Application of the embedded Optical Fiber Bragg Grating sensors in curing monitoring of Gr/Epoxy laminated composites

Liren Tsai¹, Tsung-Chieh Cheng¹, Chih-Lang Lin² and Chia-Chin Chiang¹*
¹Department of Mechanical Engineering, National Kaohsiung University of Applied Sciences, 415 Chien Kung Road, Kaohsiung 807, Taiwan (R.O.C.)
²Institute of Biomedical Engineering and Material, Central Taiwan University of Science and Technology, No.11, Buzih Lane, Beitun District, Taichung City 40601, Taiwan (R.O.C.)

ABSTRACT

The curing monitoring of polymeric composite materials has attracted wide interests recently. Monitoring the curing process is necessary to improve the performance of Gr/Epoxy composites, especially for the characterization of residual strains after manufacture. This paper aimed on exploring the use of embedded fiber Bragg grating (FBG) to monitor the characterizations of the curing process in a Graphite/Epoxy composite. The curing development and residual stress measurement were assessed through changes in the shape of the optical spectra, intensity attenuation and shifts in wavelengths in the optical fiber sensors. The curing caused residual stress was presented and analyzed systematically in this paper.

Keywords: Gr/Epoxy Composite; Optic Fiber Sensor; Fiber Bragg Gratings

1. INTRODUCTION

Carbon fiber reinforced plastics (CFRP) have good specific stiffness/strength, corrosion resistance, and are used in various fields such as aircrafts and aerospace applications [1-2]. It is important to monitor the curing process and residual stress to ensure the reliability of CFRP materials [3-4]. The curing monitoring of the polymeric composite materials has attracted wide interests recently [3,5-6]. Monitoring the curing process is necessary to improve the performance of Gr/Epoxy composites, especially for the characterization of residual strains after manufacture.

A number of attempts have been made for composite curing monitoring, including Copper wire sensing method[7], dielectric analysis[8-9], nuclear magnetic resonance[8] and Differential Scanning Calorimetry (DSC)[8,10]. However, these methods are not available for in situ and on-lining curing monitoring.

A Fiber Bragg Grating (FBG) is one of such candidate that finds increasing applications as a sensor in aerospace, structural, medical and chemical applications for vibration, temperature, strain, impact and general structural health monitoring [2,11-13]. These sensors are light, have small size, good sensitivity, good long-term stability, corrosion resistance and are immune to magnetic and electromagnetic interferences. FBG sensors are small and compatible with common polymeric materials. They can be easily embedded close to the internal sensing site in a composite structure without introducing significant defects. In the past few years, several articles [2,14-15] have been devoted to the study of using embedded FBGs for curing monitoring. Recent studies [3,16] discovered that when FBG sensors are embedded in CFRP laminates, the reflection spectrum from the FBG sensors splits into two peaks because of the non-axisymmetric thermal residual stresses. This deformation of the spectrum was considered defective as it will lead to misinterpretation in strain measurements or crack detection in the laminates [4-5,8].

*Email: ccchiang@cc.kuas.edu.tw; Phone: +886-7-381-4526 ext5340; Fax: +886-7-383-1373
This paper aimed on exploring the use of embedded fiber Bragg grating (FBG) to monitor the characterization of the curing process in a Graphite/Epoxy composite. The curing development and residual stress measurement were assessed through changes in the shape of the optical spectra, intensity attenuation and shifts in wavelengths in the optical fiber sensors. The curing caused residual stress was presented and analyzed systematically in this paper.

2. PRINCIPLE OF FIBER BRAGG GRATING SENSORS

Fiber Bragg grating (FBG) consist of a section of periodic variation in refractive index in the optical fiber core. When a broadband light spectrum encounters the Bragg gratings, a narrow band spectrum at the Bragg wavelength ($\lambda_B$) will be reflected. The Bragg reflection wavelength is obtained:

$$\lambda_B = 2n_{eff}\Lambda$$  \hspace{1cm} (1)

The grating pitch ($\Lambda$) will be modified by physical elongation or contraction modifies. Fiber refractive index will be changed by strain optics coefficient. So it is affected by photoelastic and photothermal effects. For plane stress condition, we can obtain the strains by measuring the two wavelength shifts. The relation between Bragg wavelength and stresses is described as following:

$$\begin{bmatrix} \frac{\Delta\lambda_B}{\lambda_B} \\ \frac{\Delta\lambda_B}{\lambda_B} \end{bmatrix} = \begin{bmatrix} K_1 & K_2 \\ K_1 & K_3 \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \end{bmatrix} + K_T \Delta T \{I\}$$  \hspace{1cm} (2)

where

$$K_1 = \frac{1}{E} \left[1 + \frac{n_0^2}{2} \left\{ \nu(p_{11} + p_{12}) - p_{13} \right\} \right]$$

$$K_2 = \frac{1}{E} \left[1 + \frac{n_0^2}{2} \left\{ 2
nu p_{12} - p_{11} \right\} \right]$$

$$K_3 = \frac{1}{E} \left[1 + \frac{n_0^2}{2} \left\{ \nu(p_{11} + p_{12}) - p_{13} \right\} \right]$$

$$K_T = \frac{\xi}{n_0} \left[1 - \frac{n_0^2}{2} \left\{ \nu(p_{11} + 2p_{12}) \right\} \right]$$

and $\{I\}$ is the unit matrix. The transverse stress $\sigma_x$ can be obtained from Eq. 2:

$$\sigma_x = \frac{\frac{\Delta\lambda_B}{\lambda_B} \lambda_B - \frac{\Delta\lambda_B}{\lambda_B}}{K_2 - K_3}$$  \hspace{1cm} (3)

So we can obtain the plan stress fields by observation the FBG spectra. In this paper, we proposed an embedded FBG sensor in the composite laminate to measure the residual stress during the composite cure process. By monitoring and analyzing the spectra of FBG, the curing residual stress and glass transition temperature will be studied.

3. EXPERIMENTAL SETUP

3.1 Fabrication fiber Bragg grating sensors

The FBG involved was fabricated in the Ge-B co-doped single cladding photosensitive fiber using the side writing method. The photosensitive fiber is produced by Fibercore Co. Ltd. (PS1250/1550). The FBGs are photoimprinted in photosensitive optical fiber by 248-nm UV radiation from a KrF Excimer laser. The impulse frequency of laser is 10 Hz. To avoid burning the phase mask, the laser power should be <500 mJ/cm². Along the fiber core, the FBG has a periodic refractive index modulation with a period of 1.05–1.08 μm, obtained by using phase masks (Lasiris Co. Ltd.) with different periods. This resulted in a peak Bragg reflecting wavelength of 1540–1564 nm. The reflectivity of the resulting FBG was about 99% and the FWHM (Full width Half Maximum) of the FBG is about 0.175 nm.

3.2 Preparation of composite materials with embedded FBG sensors

8 layer cross-ply T300/3501 Graphite Epoxy were laid up in the stacking sequences [0/90/0/90], (Fig. 1). The FBG sensor was placed in the interface of two central 90° carbon fiber of prepeg lamina. The prepreg has nominally 61% by volume of graphite fiber, and is 125μm thick. The stacks were fabricated at 140°C under 6 kg/cm² pressure 30 mins in a
diaphragm type forming mold (Fig. 1) according to the conditions (Fig. 2). And then air cooling of the formed laminates was inside the hot forming mold to room temperature. Pressure over the diaphragm was maintained during the curing process. The dimensions of the composite lamina was 60 mm width and 120 mm length. We recorded the FBG spectra during the curing process by using the Optical Spectrum Analyzer (OSA) for composite curing monitoring in Fig. 3.

Fig. 1. The diaphragm forming method for the composite curing process with the embedded FBG.

Fig. 2. The condition for composite curing process.
Fig. 3. Schematic diagram of the composite curing monitoring with embedded FBG sensor.

4. RESULTS AND DISSCUSSIONS

4.1 Temperature calibration of FBG sensors

The Bragg wavelength of a FBG [3-5] is affected by the temperature. The FBG was put in an oven and allowed to expand freely when the temperature is raised. Fig. 4 shows the variation of the Bragg wavelength of the FBG with temperature. Spectra were measured with the OSA. The wavelength-temperature relationships are quite linear (R-squared=0.996759) so that these gratings can easily be used as temperature sensor. The temperature coefficient of the wavelength shift of the FBG is 10.66 pm/°C.
4.2 Curing monitoring

Monitoring the curing process is necessary to improve the performance of Gr/Epoxy composites. The curing process includes heating, isothermal and cooling stages. The temperature rises from 25°C to 140°C at heating stage. The glass transition temperature ($T_g$) is in this region. When the temperature is rising higher than $T_g$, the epoxy matrix begin to vitrify. During the vitrification state of the composite, physical quantities such as the viscosity, thermal expansion and refractive index will change dramatically. We proposed using embedded FBG sensor for composite curing monitoring to detect the glass transition temperature of the composite laminate. When the lay-up prepegs with the embedded FBG sensor is in the forming mold with 6 kg/cm$^2$ air pressure, the reflected light intensity is very low and the reflected spectra cannot be observed below 55°C in Fig. 5. This phenomenon indicted the high pressure under the laminate let the light signal become weak. As the temperature is rising in curing process, the reflected light intensity is increasing. The viscosity of the epoxy matrix is increasing progressively with temperature. When temperature between room temperature and $T_g$ during the curing process, the higher viscosity of the matrix makes the optical fiber well embedded in the lamina along the carbon fiber direction without forming the matrix rich region in Fig. 6. Therefore, the most pressure loading will be taken by carbon fiber and epoxy matrix. Therefore, the light intensity begins to grow up intensively. This phenomenon is observed by the spectra of the embedded FBG in Fig. 5. The spectra of FBG are greatly increasing below 95°C.

When the curing temperature is between 95°C to 140°C, the reflected light intensity is increasing gently. We can find the slope change of the fitting line of FBG peak intensity is at 95 °C(Fig5). Consequently, the 95°C of the curing process is related to the vitrification of the composite. The glass transition temperature detected by the slope change of FBG intensity curve is 95 °C which is in agreement on the product specification.
4.3 Residual strain after curing process

The FBG sensor is embedded into the central interface of composite laminate to monitor the residual stress variations. The FBG spectra recorded continuously during the curing process. By observing the reflective spectra we can measure the curing residual stress of Gr/Epoxy laminated composite due to the different thermal expansion coefficients of the graphite fiber and the epoxy. During the heating stage of curing process, the epoxy expands but the graphite fiber concentrates. On contrary, during the cooling process, the epoxy concentrates but the carbon fiber expands. Therefore, residual stress appears at the interface between the graphite fiber and the epoxy. Fig. 7 shows Spectra embedded FBG sensor after curing process. The spectrum is split into two peak and shift to the left side of the original wavelength. This phenomenon is caused by the non-uniaxial stress condition. The residual stress acts in a transverse direction on the optical fiber and makes the FBG spectra split into two speaks. By calculating the Splitting span of FBG spectrum (Fig.7) and shift of central wavelength using Eq. 3, the residual stresses are obtained. The transverse residual stress is about 63.6MPa in the central lamina.
In Fig. 8, we monitor the FBG spectra during the cooling stage of curing process. The FBG spectrum begins to split into two peaks at about 95°C. This phenomenon is relative to the glass transition temperature. When the temperature cooling below to the $T_g$, the epoxy matrix is under curing induced shrinkage and induced non-uniaxial stresses.
5. CONCLUSION

In this paper, we successfully monitor the curing process of composite laminate by embedded FBG sensor. In our experiment, we find out that the glass transition temperature is about 95°C which has agreement with product specification. By calculating the Splitting span of FBG spectrum using Eq. 3, the residual stresses are obtained. The transverse residual stress is about 63.6MPa in the central lamina. Moreover, we monitor the FBG spectra during the cooling stage of curing process. The FBG spectrum begins to split into two peaks at about 95°C. This phenomenon is relative to the glass transition temperature.

ACKNOWLEDGEMENT

This work is supported by the National Science Council under contracts NSC 97-2221-E-151-016 and NSC 96-2221-E-151-035. We are also indebted to Professor S. K. Liaw of NTUST for some of the equipment support and advice.

REFERENCES