

Process Monitoring and Damage Detection in Composites Using FBG Sensors

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Abstract—The residual strain will be generated during the prepreg curing process when the composite materials were manufactured, and the residual strain in the composites will markedly influence the quality of the composite materials. In order to realize on-line monitoring the prepreg curing process and on-time detecting the damages in the composites, optical fiber Bragg grating (FBG) sensors were embedded inside the laminated composites when the composite plates were produced. The changes of the Bragg wavelength of the FBG sensors were measured using an optical fiber spectrometer. The strain changes during the prepreg curing process were monitored with the FBG sensors, and then the progress of the composite solidification process was analyzed. The reflection spectra of the FBG sensors were measured, and the internal damages in the composite specimens were monitored according to the spectrum measurement results. Experiment results indicate that the FBG sensing technology is feasible for monitoring prepreg curing process and detecting the interior damages in the composites.

Keywords—optical fiber Bragg grating; composite materials; curing; residual strain; interior damages

I. INTRODUCTION

Nowadays more and more fiber reinforced composites are used in the manufacture of aerospace structures^[1]. The composites possess the many advantages over metal materials, such as higher fatigue strength, lighter weight, and ease in shaping complicated components. Particularly, after FBG sensors can be embedded in the composite materials during the production process of the composites, the health of the composite structures can be real-time on-line monitored and the performance of the composites can be tested. But resin-matrix composites have some disadvantages, such as low damage tolerance, poor resistance to impacts and poor stability in damp and hot environments. Moreover, interior damages in the process of flying by such accidents caused by the bird collision, metal tools' impact and so on are not easily detected and will probably lead to catastrophic accidents. So real-time on-line monitoring on aircraft structures is particularly important. Using FBG sensors to realize structure healthy monitoring (SHM) is an important research direction of intelligent materials and structures^[2]. By embedding FBG sensors into composites, it is possible to detect the deformations, impacts, failures of the structures in environmental parameters. The research scope includes aerospace, also include military field in civil engineering. At

the same time, composite material quality and performance are closely related to prepreg curing process. From the composite material beforehand products manufacturing and curing, to finally made, if the FBG sensors can track distribution and changes of interior strain or stress, it will have very good guarantee to control composite material performance. Therefore, composite materials solidification process monitoring and structure on-line detecting are an important guarantee for safety of the aircraft. The FBG sensors, owe to small size, good repeatability, stable performance in product quality, have become the focus of research of fiber intelligent sensors^[3]. Monitoring of prepreg composite curing process and detecting of interior damages of the composite materials were studied applying the FBG sensor in the article.

II. OPTICAL FIBER BRAGG GRATING SENSOR

The basic principle of the FBG sensor is that process of using doping fiber photosensitive properties and using 240-248 nm UV exposure in the optical fiber makes photon and the doped fiber particles inside core interact with one another, which produces the core index periodic permanent change along the axial, and forms space phase grating. When injecting broadband light into the grating, reflective spectrum of Bragg wavelength appears at the entrance of the fiber. The FBG wavelength can be determined by the following formula^[4]:

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

Here λ_B is the FBG wavelength. Λ is Bragg grating period interval. n_{eff} is the effective refractive index of fiber core. It can be seen that changes in Λ or n_{eff} can lead to change of Bragg grating wavelength. When the surrounding temperature or stress changes, the FBG period Λ and the effective refractive index n_{eff} will change. Thus this causes wavelength of the FBG to change too. The FBG sensor parameter can be determined by testing the change of wavelength of the FBG. Change of wavelength of the FBG is given by:

$$\Delta\lambda_B = \lambda_B(1 - P_e)\Delta\epsilon + \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \quad (2)$$

Order $K_\epsilon = \lambda_B(1 - P_e)$, and $K_T = \lambda_B(\alpha_\Lambda + \alpha_n)$. Here P_e is effective strain elastic-optic coefficient; α_Λ is thermal expansion coefficient of optical fiber; α_n is thermal-optic coefficient. K_ϵ represents strain sensitive coefficient; K_T stands for temperature sensitive coefficient. Working principle diagram of the FBG sensor is shown in Fig. 1:

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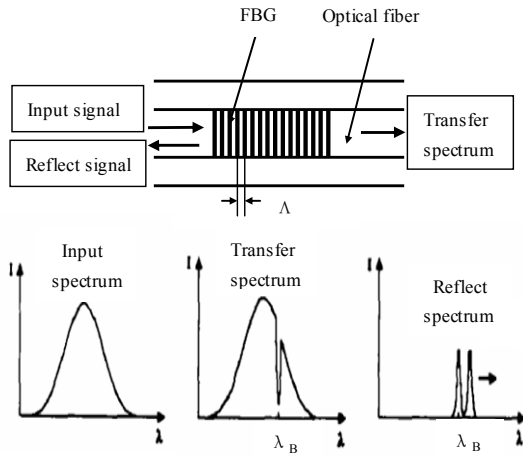


Figure 1. Basic principle of optical fiber grating sensor

III. PREPREG CURING PROCESS MONITORING AND INTERIOR DAMAGE DETECTING

1 Optical fiber grating sensing properties

In order to conduct prepreg composite curing process monitoring, strain response, namely strain sensitivity coefficient, of fiber grating embedded inside the resin must be known. Therefore tensile test of composite specimen embedding the FBG sensor was carried out in the material testing machine. The laminate configuration was $[0_2/\text{FBG}/0_2]$. Resistance strain gauge was fixed on the surface of the specimen. The fiber Bragg wavelength draft and value of resistance strain gauge were recorded simultaneously during the test. Specimen was loaded using material testing machine (Instron, 3382, USA). Response curve of fiber grating strain sensor embedded inside the composite is shown in Fig. 2. To fit the curve, strain sensitivity coefficient of the FBG embedded inside the composite materials is $1.0935 \text{ pm}/\mu\epsilon$. Bragg wavelength shift and the strain show a good linear relationship. The temperature compensation should also be considered in strain measurement. For the sake of obtaining strain change of prepreg materials in curing process, fiber grating temperature sensitivity coefficient can be measured firstly.

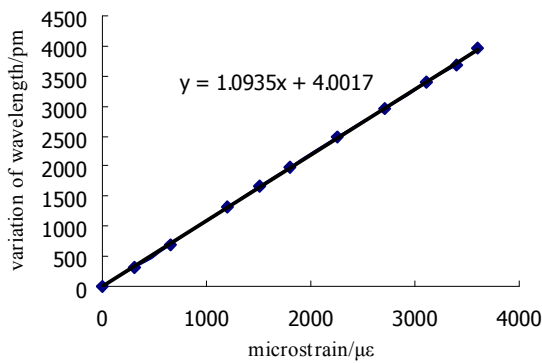


Figure 2. Variation curve of strain sensing

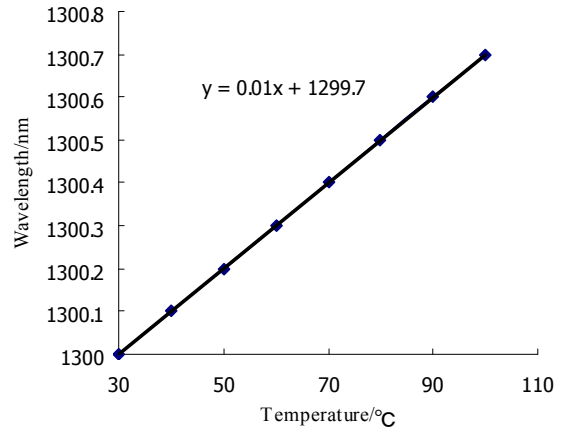


Figure 3. Curve of temperature sensing

Then according to formula (2), strain can be obtained via subtracting the excursion of wavelength drift from general drift of Bragg wavelength by temperature change. To this end, it is necessary to implement temperature sensing property of fiber grating experiment for temperature sensitivity coefficient. A free state of fiber grating must be made in the experimental process. Experimental result is shown in Fig. 3. Temperature sensitivity coefficient is $10 \text{ pm}/^\circ\text{C}$. A good linear relationship is presented between wavelength and temperature.

2 Composite solidification process monitoring result

With the strain sensitivity coefficient, prepreg curing process monitoring of composites was implemented. Application of the FBG sensor, interior strain in 0° and one-way laminated plate material was measured. Design of one-way laminated plates was $[0]_8$. Fiber grating sensor was located in layer 4 and 5 layers and sensor was located in the center position of prepreg layer. This reduces the effect of edge. Monitoring result of curing process is shown in Fig. 4.

The effect of temperature was considered in experiments. As can be seen from Fig. 4 that laminated plate strain curve appears to fluctuate in different degree. This has to do with gradual softening of the resin in heating process and the resin softening led to weensy displacement of reinforcing fibers. At

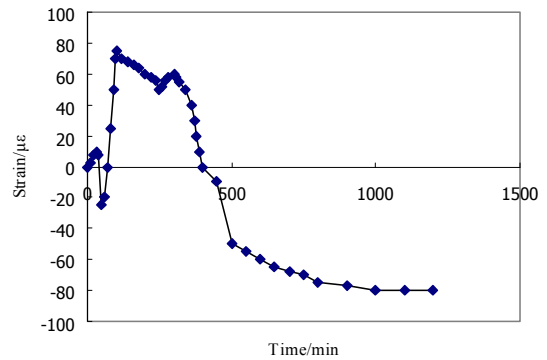


Figure 4. Curve of prepreg composite curing

first, resin viscosity fluid state gradually transforms into viscoelastic solid state. The force of the transfer of fiber grating increases; fiber grating presents positive strain state. In natural cooling stage, resin produces thermal shrinkage; measuring strain of the FBG as resin thermal deformation reduces gradually. After cooling, fiber grating shows negative strain state, and value remains constant. Solidification process has come to an end. Therefore, by monitoring the FBG strain change, composite material progress of the solidification process can be obtained.

3 Damage monitoring inside composite specimens^[5]

Specimens of embedding the FBG in composite materials were pre-produced. The laminate configuration was $[0_2/90_2/0_2]$. A specimen was depicted cracks in the thickness direction, as shown in Fig. 5. Sizes of the tested specimen in the length, the width, and the thickness are 200 mm, 25 mm, 3 mm respectively. Fiber grating sensor was located in layer 2 and 3 layers. Then tensile test was carried out in the Instron testing machine. Reflecting spectral of optical fiber grating was recorded using AQ6317 spectrometer. Fig. 6 and 7, respectively, showed results excluding and containing the edge crack. Fig. 6 demonstrates that when specimen without edge cracks carries out tensile test, the center wavelength just moves to the right, without any change in peak shape. This indicates that the damage does not appear within the composite specimen. When the specimen containing the edge cracks goes through tensile test, edge cracks extend to the grating position, and the specimen gives rise to stress state changes. This results in changes of the FBG reflection peak. Fig. 7 shows that the height of grating reflection peak gradually lower from left to right, the width wider, and the emergence of multiple peaks.

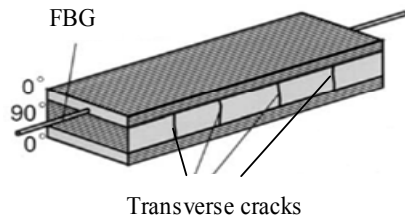


Figure 5. Embedding of a FBG sensor into a composite whose laminate configuration is cross-ply $[0_2/90_2/0_2]$

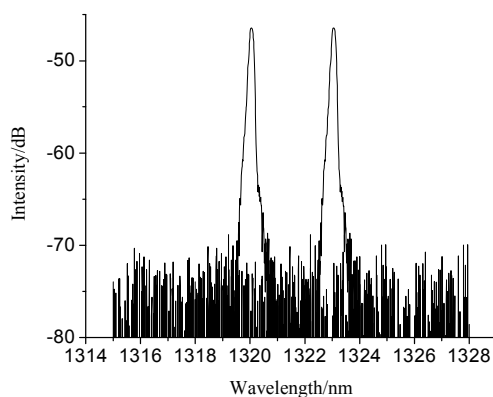


Figure 6. Reflected spectra of specimen without edge crack

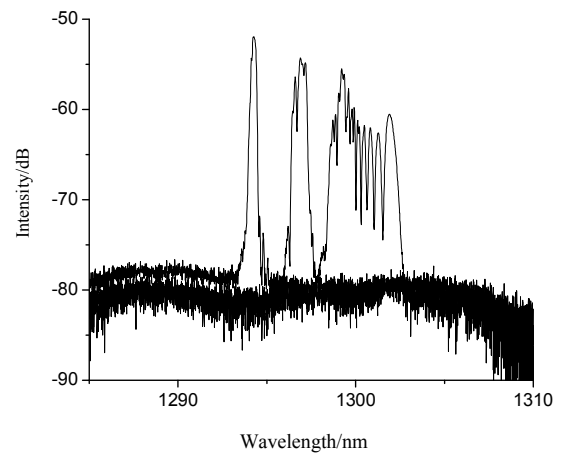


Figure 7. Reflected spectra of specimen with edge crack

This indicates that the damage cracks within the composite are the reasons leading to changes of the FBG peak shape. Therefore, this characteristic can be used to on-line monitor the existence of damage in composite materials.

IV. SUMMARY

The FBG sensor before curing was embedded into composite prepreg layer. In a fiber, on-line monitoring status of interior strain and damages were realized in the curing process inside materials. The results indicate that monitoring of solidification process of laminated composite plates and detecting of its interior damage are feasible using the FBG sensors. It can be good method for the FBG sensors to monitor composite curing process and internal damages, and plays an important role in guaranteeing the health status of structures in the composite materials.

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