Real-Time Monitoring of the Aircraft Structure Based on Fiber Bragg Grating

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Abstract. The fiber Bragg grating (FBG) sensing technique was introduced to research the real-time corrosion monitoring method for the simulation structures of aircraft during an accelerated corrosion test. The results showed that the variation of grating wavelength was able to describe the corrosion damage caused by corrosion at different times. The relationship between the corrosion damage and the variation of central grating wavelength in the process of accelerated corrosion is established.

1. Introduction

The fiber grating sensor has the advantages of small size, low weight, high temperature resistance, corrosion resistance, high sensitivity, high ability of anti-electromagnetic disturbance, etc. Thus, it is really suitable for the applications of aircraft structures. The fiber grating has been successfully used for the health monitoring for the structure of bridge, dam body, offshore platform, concrete, etc [1]. In American aerospace, effective results have been achieved for the application of FBG sensing technique in the structural health monitoring (SHM) of F-18, Boeing-777, X-33, etc.. The technique was mainly employed for the SHM of aircraft composite structures in France, Australia, Canada, etc [2,3]. In China, Yuan Shenfang developed an aircraft smart structures using FBG [4]; in the filed of corrosion sensing, Yan Yun and Simon K. T. Grattan [5] designed a corrosion sensor based on the relaxation of pre-tension stress by FBG for the reinforced concrete structure, but the sensor was only applicable for the early monitoring of rust. Montemor M F [6] adopted an optical fiber corrosion sensor with a single FBG to obtain the relationship between the grating reflected wavelength shift and the weight loss rate of rebar through experiments. However, the application of optical fiber corrosion sensor for SHM is still in its infancy in China now, especially for the corrosion monitoring of aircraft structures. Moreover, there are several technical problems, for instance, cross-sensitivity of strain and temperature, difficult grating adhesion, low survival rate, real-time monitoring with too much information, etc.

The fiber grating is characterized by corrosion resistance, high sensitivity, high ability of anti-electromagnetic disturbance, etc. Given that, the paper carried out a corrosion monitoring technique research on the perishable aircraft structure using FBG strain sensing technique. The relationship between the corrosion damage size and the variation of grating wavelength was investigated as well.

2. Monitoring test based on fiber Bragg grating

2.1. Specimen

The structure of aluminum alloy sheet and steel bolt was studied. 7B04 aluminum alloy, which is the main force bearing structural material of aircraft structures, and 30CrMnSiA alloy steel were adopted as the aluminum alloy sheet and steel bolt respectively. XM-33 sealant was spread on the fastener holes to enhance the corrosion resistance. The structural simulation specimen is shown in Figure 1.
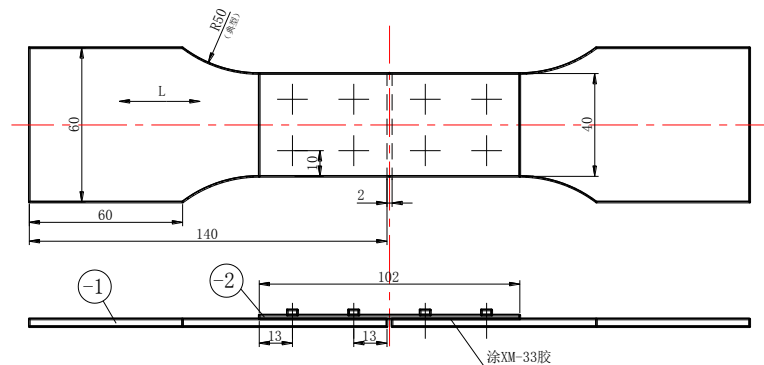

Figure 1. The simulation specimen of the dissimilar metal joint structure

2.2. Sticking method of FBG

The sm125-500 FBG demodulator made by American Micron Optics Inc. (MOI) was employed. Its main parameters are as follows: four optical channels; the wavelength range is 1510~1590 nm; the accuracy is 1 pm; the stability is 1 pm; the scanning frequency is 2 Hz and the dynamic range is 50 db. The programming can be redeveloped to obtain a user operation interface for multipoint strain display. The FBGs used and the key parameters are displayed in Table 1.

Table 1. The key parameters of the FBGs involved

NO.	Wavelength / nm	Bandwidth / nm	Peak value reflectivity/ db
FBG19	1546.094	0.24	18.82
FBG28	1531.512	0.22	21.49
FBG11	1540.414	0.21	18.61

Loctite E-30CL epoxy resin glue was utilized to paste the three FBGs (FBG 11, FBG 19 and FBG 28) adopted in the simulation specimen of the dissimilar metal joint structure. In order to stick firmly, something with proper weight was hung on the fibers to make them close to the surface of specimen. And then they were covered by appropriate epoxy resin glue, Loctite E-30CL. When the glue was solidified after being dried for 24 hours in the air, additional E-30CL epoxy resin glue was smeared on the pasted parts to make the fibers firmer. The welding equipment, TYPE-81C, was used to weld the three gratings (see in Figure 2).
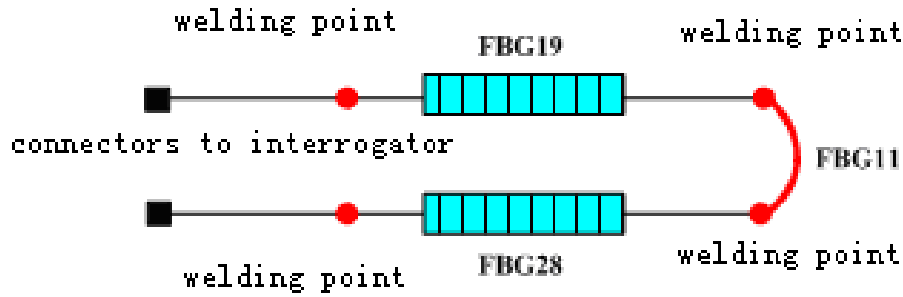
Figure 2. Grating welding

2.3. Monitoring test

An accelerated corrosion test was conducted to the simulation specimen of the aircraft dissimilar metal joint structure. The paper also took the corrosion environment of coastal airports and the energy spectrum analysis results for the external corrosion products of aircraft aluminum alloy into consideration. As a result, the density of exfoliation corrosion (EXCO) solution used in the corrosion test was adjusted to 50% according to Criteria G34 of American Society for Testing and Materials (ASTM). For the purpose of real-time monitoring of corrosion, the paper monitored the grating wavelength of the specimen. Figure 3 illustrate the reflection spectrums of FBG at the beginning of the test (0 hour) and at 320th hour. During the test, the temperatures of the solution changed with the air temperature in the range of 21 ℃~26.5 ℃.
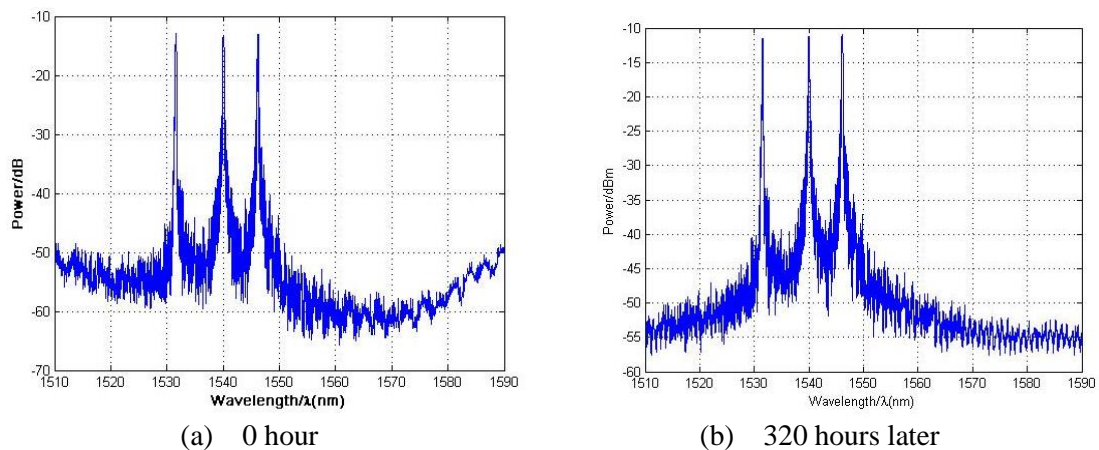

(a) 0 hour   (b) 320 hours later

Figure 3. The reflection spectrums of FBG at different corrosion times

3. Theoretical analysis method

The central wavelength of FBG reflected light λ_B is associated with the change period of grating refractive index and effective refractive index.

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

The grating has no strain in stressless condition. When the temperature changes, the paper explores the change law of the period of grating which is induced by thermal expansion and temperature effect of FBG. When the external temperature changes, Formula (1) can be expanded and the relative wavelength shift caused by the temperature variation ΔT will be:

$$\Delta\lambda_B = 2\left[\frac{\partial n_{eff}}{\partial T}\Delta T + \left(\Delta n_{eff}\right)_{ep} + \frac{\partial n_{eff}}{\partial a}\Delta a\right]\Lambda + 2n_{eff}\frac{\partial \Lambda}{\partial T}\Delta T \tag{2}$$

where $a_n = \dfrac{1}{n_{eff}}\dfrac{\partial n_{eff}}{\partial T}$ represents the calorescence coefficient of FBG; $\left(\Delta n_{eff}\right)_{ep}$ means the

elasto-optical effect brought by thermal expansion; $\dfrac{\partial n_{eff}}{\partial a}$ is the wave-guide effect led by the change

of fiber core diameter which is caused by the thermal expansion; and $\alpha_\Lambda = \dfrac{1}{\Lambda}\dfrac{\partial \Lambda}{\partial T}$ stands for the coefficient of linear thermal expansion. So Formula (2) is rewritten as:

$$\frac{\Delta\lambda_B}{\lambda_B \Delta T} = \frac{1}{n_{eff}}\left[n_{eff}\alpha_n + \left(\Delta n_{eff}\right)_{ep} + \frac{\partial n_{eff}}{\partial a}\times\frac{\Delta a}{\Delta T}\right] + \alpha_\Lambda \tag{3}$$

Therefore, the complete expression of the temperature sensitivity coefficient of fibers can be obtained:

$$S_T = \frac{\Delta\lambda_B}{\lambda_B \Delta T} = \frac{1}{n_{eff}} * \tag{4}$$

$$\left[n_{eff}\alpha_n - \frac{n_{eff}^3}{2}\left(p_{11}+2p_{12}\right)\alpha_\Lambda + S_{wg} + \frac{\Delta\alpha}{\Delta T}\right] + \alpha_\Lambda \tag{5}$$

in Formula (4), S_{wg} is the coefficient of Bragg wavelength shift and p_{11}, p_{12}, n_{eff}, α_n and α_Λ are the material constants. It can be seen that the temperature sensitivity coefficient of FBG is almost the same as material constants if the material is determined. In theory, it demonstrates that the temperature sensor made of FBG has good linear output.

4. Corrosion monitoring based on FBG

After the corrosion test, a corrosion bulge in the area of 24 mm×30 mm and in the thickness of 0.91 mm is formed on the specimen of structure. The specimen was 5.21 and 6.13 mm in thickness before and after the corrosion. The paper took the thickness of the bulge as a quantification parameter to measure the corrosion damage size. The monitoring results show that simulation structure changes slightly at the early stage with the increasing corrosion time, while the change intensifies obviously in the medium term and becomes gentle at the late stage. The results are consistent with the actual measurement. Wavelength variation of grating, as the characteristic parameter for describing the corrosion damage, provides valuable information of corrosion damage (see in Figure 4). The method is simple and intuitive; it shows good real-time performance and eliminates the external temperature influence. Therefore, it provides guidance for overall corrosion monitoring in future.
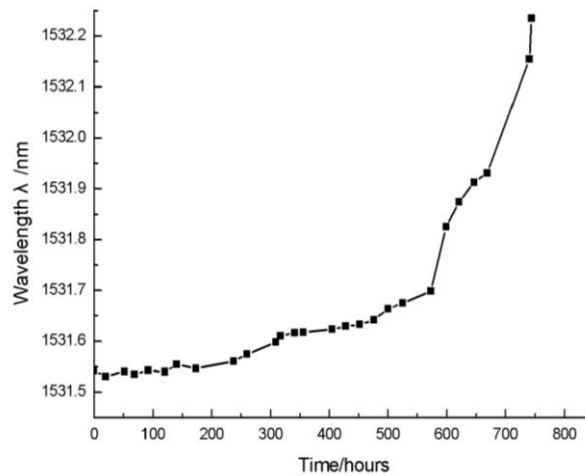
Figure 4. Relationship between the corrosion damage size and corrosion time

5. Conclusion

FBG strain sensing technique has great significance and promising application in the real-time monitoring for early corrosion in lap joints and the development law of corrosion. Meanwhile, the paper established the relationship between the corrosion damage and the variation of central grating wavelength in the process of accelerated corrosion. The treating mode was changed from currently passive find it-fix it mode into an active mode, find it sooner-the evaluate-plan-fix.

6. Reference

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