Advanced fiber grating corrosion sensors for structural health monitoring

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ABSTRACT: Sensors for monitoring metal materials corrosion are of much significance for civil engineering structures. By using the strain-sensitive characteristics of fiber Bragg gratings, a metal corrosion sensor is proposed and demonstrated in this paper. The device was made of a fiber grating, a steel spring and some mechanical parts, and was packaged under pre-strained condition of the spring. The peak wavelength of the grating was red-shifted for 3.2nm in stretch-strain and the spring was pressed after packaging. The device was then put in an atmosphere with hydrochloric acid. The peak wavelength was monitored every day, and was found to be blue-shifted little by little; showing the elastic coefficient of the spring was decreased gradually that was caused by the corrosion of the spring material. The accelerated corrosion process lasted 1315 hours until the spring was broken, and an average etching rate was estimated to be 5 μm/day. The experiment showed that the device can be used as a sensor for metal corrosion if it is put in the same ambient as the engineering structure. Temperature effect of the FBG, friction in the device and other factors related to its practical use are discussed in the paper.
KEY WORDS: Metal corrosion sensor; fiber Bragg grating; steel spring; elastic coefficient

1 INSTRUCTION

Sensors based on fiber Bragg grating (FBG) and long-period grating (LPG) have attracted considerable interest because of their wide range of applications, including monitoring temperature, strain, loading, bending, pressure, and vibration of many engineering systems and structures. [1-3] Nowadays, there is a growing demand for structure health monitoring of civil infrastructures in order to increase safety as well as efficiency. One of the most promising solutions is using FBG as an intrinsic sensor for strain, vibration, temperature and other measurands of interest in such monitoring applications. FBG sensors have a number of significant technical advantages, such as lightweight, resistant to corrosion and fatigue, immunity to electromagnetic interference. They can be multiplexed, embedded in composite materials, applied in harsh environment.

2 PRINCIPLES

Fiber Bragg grating (FBG) is widely used as filters and sensors in communication and sensor field. The resonant wavelength of FBG satisfies the phase-matching condition: $\lambda_B = 2n_{eff}\Lambda$, [4] where n_{eff} is the effective index of fundamental mode in fiber, Λ is the period of gating. n_{eff} and Λ are both relative to the temperature and stress of the fiber, which can be wrote as a line function in the first order approximation: $\Delta\lambda_B = \alpha\Delta\varepsilon + \beta\Delta T$, where α is stress coefficient, β is temperature coefficient. In experiment, we have measured that α=1.2pm/με, β=11pm/°C [5] for the fiber around 1550nm. With the strain-sensitive and temperature-sensitive characteristics, FBG can be used as stress sensors and temperature sensors.

In order to detect the corrosion of material by using the characteristics described above, we should design a mechanical device, in which spring was packaged under pre-strained condition. When the structure suffered from corrosion, the stress of fiber would change. By observing the changes of peak wavelength of FBG, we can get the information of corrosion.

In this paper, we have designed a FBG corrosion sensor based on a spring structure to detect the corrosion of metal. Fig. 1 is the profile of the sensor structure.

In this structure, a steel spring was fixed between two corrosion proof mounts. There was a copper brace inside the spring, to ensure the spring keep straight while being pressed. Two ends of FBG were glued in the holes of mount, and when the FBG was glued, the spring was in the condition of compressed. Therefore, after FBG and spring were glued, FBG was in the condition of drawn. As the elastic coefficient of spring is relative to the radius of steel wire, it would change when the steel wire was corroded. Then the pulling force of FBG would change, which let us know the extent of corrosion from the change of the peak wavelength of FBG.

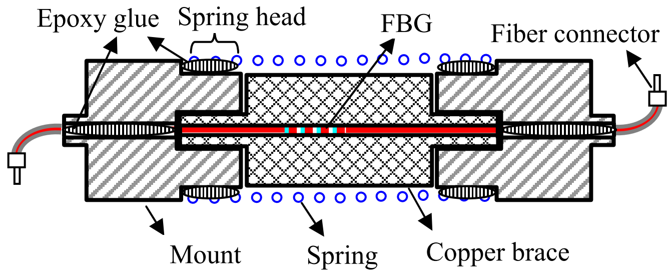

Figure 1. Profile of the sensor structure

This structure can be analyzed from stress balance. After the FBG was installed and fixed, the elasticity of spring and the resilience of the FBG became equal:

$$F = E_f A\varepsilon_g + k\varepsilon_S = 0 \quad (1)$$

where E_f is Young's modulus of fiber, A is the horizontal area of fiber, ε_g is the stress of fiber; κ is the relative elastic coefficient; ε_s is the stress of spring. According to the analysis of Mechanics of materials, we know that:

$$k = Gpr^4/(4R^3) \quad (2)$$

where G is the shear modulus of metal, p is the screw-pitch, r is the radius of metal wire, R is the radius of the loop of spring. We can see from (2) that when the other conditions keep invariable, the elastic coefficient is in direct proportion to r^4. It's obvious that as the corrosion of metal, the radius of metal wire will become thinner, and then the elasticity of spring will become weaker.

According to formula (1), we can gain that $E_f A\delta\varepsilon_g + k\delta\varepsilon_S + \varepsilon_S \delta k = 0$. When the elasticity of spring changed, the deformation of FBG and spring is equal in numeral but opposite in direction. So their stresses are relative, and have the relation: $\delta\varepsilon_S = (l/s)\delta\varepsilon_g$. Where l is the distance between the two glued points of FBG, s is the length of spring except two heads. From here, we can deduce the relation between the relative change of the stress of FBG and the relative elastic coefficient of spring, which is :

$$\frac{\delta\varepsilon_g}{\varepsilon_g} = \frac{sE_f A}{sE_f A + lk}\frac{\delta k}{k} = \frac{4sE_f A}{sE_f A + lk}\frac{\delta r}{r} \quad (3)$$

So, we can see that in the first order approximation, the change of the peak wavelength of FBG is in direction proportion to the change of the radius of spring metal wire.

In practical application, we put the device onto the relevant position of the building structure, and it can be corroded as the metal of building. Then we can get the information of corrosion of metal from the changes of the peak wavelength of FBG.

3 EXPERIMENTAL METHODS AND RESULTS

According to the principles described above, we have designed a sensor to detect the corrosion of metal. The key problem of designing this structure was to choose proper elasticity and proper length of spring, in order to reach high sensitivity but not break off the FBG. From calculation and experiment, we have chosen a spring whose external diameter is 6mm and internal diameter is 4.8mm. In our experiment, We have measured the elastic coefficient of this spring, which is 740με/g. The relative elastic coefficient is about 13N/ε. The mount of the device is made of copper which is corrosion proof. Then we used a copper brace to drill through the center of spring whose internal diameter is matched with the external diameter of copper brace. FBG was drilled through two mounts and the copper brace, and glued in the holes of two mounts when the spring was in the condition of compressed. After the epoxy glue became solidification, we released the pressure on the spring, then the resilience of spring would act on FBG.

In this experiment, the effective length of spring (spring except two heads in Fig. 1) is 20mm after pressed. The length of FBG is 10mm, and the length of fiber between the two glued points is 30mm. The initial peak wavelength of FBG is 1552.126nm. The peak wavelength moved to 1555.334nm after the sensor had been installed, in the same time we have noted the temperature, which is 17°C. So, the peak wavelength increased about 3.2nm. We can estimate the stress that the FBG suffered is about 3200pm/(1.2pm/με)=2670με.

According to Young's modulus (~7×10^{10}N/m^2) and the radius of FBG, we can gain that the stress the FBG suffered is about 2.2N. The initial length of spring is 34mm, two heads are glued to the mounts, which is 2×5mm. So, the effective length is 24mm. When the spring is installed, it will be pressed to 20mm, corresponding to the stress is 0.17. According to the experiment, the relative elastic coefficient is about 13N/ε, which give a stress of 2.2N to spring. It is obvious that the FBG and the spring have reached a balance.

In order to demonstrate the sensor that has been designed above, we took an accelerated corrosion experiment. The concrete method is: Put the sensor into a copper tube in which there were many holes at center, then put the copper tube into the middle part of an acid proof container horizontally. There was a certain amount of dense hydrochloric acid in the acid proof container. The sensor was put above the dense hydrochloric acid, and suffered corrosion of the acid. In our experiment, we monitored the peak wavelength regularly. And in the purpose of correct the excursion of the peak wavelength induced by temperature, we measured the temperature simultaneously. The whole experiment lasted about 50 days until the spring was broken. Fig. 2 is the variation of the peak wavelength of FBG and temperature versus time.

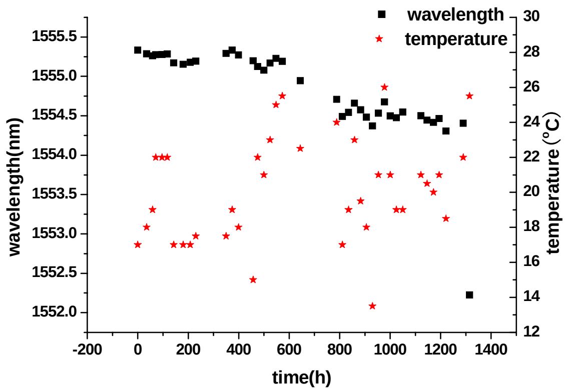

Figure 2. Variation of the peak wavelength of FBG and temperature versus time

The last experiment data was measured at 1315 hours in Fig. 2, and the wavelength was 1552.225nm, temperature was 25.5 °C. If we deducted the influence of temperature, the wavelength was almost same to the initial wavelength, which indicted that the spring was

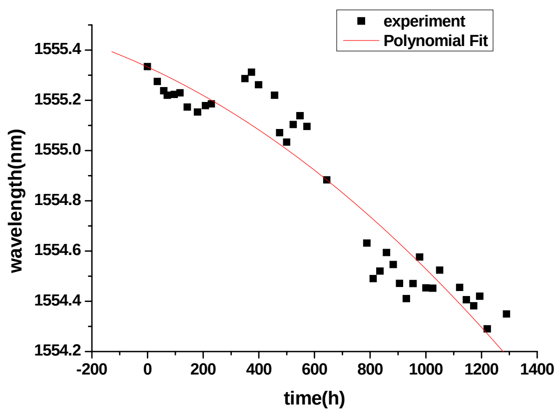

Figure 3. Variation of the peak wavelength of FBG and fit curve versus time after eliminate the temperature factor

broken. Then we opened the container, and found that the spring was really broken. We dealt with all the datum, deducted the influence of temperature by using temperature coefficient β=11pm/°C. In Fig. 3, we have dawn a fit curve of all the datum. From the fit curve, we could estimate the velocity of corrosion was 5 μm/day.

4 ANALYSIS AND DISCUSSION

From the experiment, we can see that the peak wavelength became shorter as the stress of mechanical organization became subside, which indicates our principle is reasonable and feasible. Further more, with the corrosion of the steel wire, the change of speed that the peak wavelength of FBG has the tendency to accelerate, which accords with behaviors described of formula (3).

From Fig. 2, we also can see that the environment temperature has a direct influence on the experiment data, which can be solved by installing temperature compensation FBG. From Fig. 3, the variation of wavelength is not smooth, some times there are fluctuations. There may be caused by some reasons, but we can conclude that the friction between the spring and copper brace is an important reason. Because the steel wire is corroded by some pieces of invariable speed, but the products corroded will not come off immediately and simultaneously, which may hinder the deformation of spring in a certain extent, even if the primitive mechanical device of the sensing head have good sliding cooperate.

If we want to make it as a metal corrode sensor for practical use, there are several problems should be solved. First, the sensitivity should be improved. It can be realized by using spring that made of thin steel wire, but it will reduce the measurement range. Second, we should solve the influence of friction, which can be solved by optimization in machinery.

5 CONCLUSION

We have demonstrated a corrosion sensor based on the strain-sensitive characteristics of fiber Bragg gratings. In the accelerated experiment, we know that the average velocity of corrosion is about 5 μm/day from the movement of the peak wavelength of FBG. Our experiment has reached the anticipated purpose and showed that FBG has a wide prospect in detecting corrosion in metal structure.

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