Technology and test of fiber Bragg grating in composite materials

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Abstract. In this process, the processing flow of fiber Bragg grating (FBG) embedded carbon fiber reinforced composites are prepared by means of pressurized film forming and end-surface elicitation. Firstly, the development of composites in aerospace field is introduced. Then, according to the principle of FBG sensor, a scheme for embedding fiber grating into carbon fiber composites is designed. There are three key steps involved in this process, namely, laying the bare fiber parallel to the carbon fiber cleavage direction, applying the end-surface elicitation method with the use of stainless steel thin tubes and Teflon fine tubes for protection, and pasting the rubber strip tile on the end to prevent the curing of the fiber break. After processing, a 260x60x3mm surface intact product is made according to the design scheme. There is no deformation in Carbon fiber surface and the end-surface is intact. Experimental tests show that this product has good temperature and strain response.

1. Introduction
After the 1960s, because of the low modulus, non-ideal heat resistance, it is difficult for glass fiber resin matrix composites to meet the material high specific modulus and high specific strength requirements for the aerospace vehicle. Therefore, the development of carbon fiber, boron fiber and other high-strength, modulus, low-density fiber materials has been promoted. The United States successfully applied boron fibers on the tail of the F-111 aircraft in the late 1960s. However, these materials has been gradually eliminated because of their complex production process and high cost. [1] After nearly half a century, carbon fiber composites are more mature in mechanical properties and applications, and are leading to other new materials with the advantages of high strength and high modulus. [2]

Composites are mainly used in the combustion chamber adiabatic shell structure of aerospace solid rocket engine, discontinuous structure of missile and launch vehicle, liquid hydrogen tank structure, instrument module structure, missile and satellite fairing structure, missile heat-proof material and various satellite structures. [3] The application of advanced composites to the starting machine shell can achieve significant weight reduction effect. The mechanical properties and ground storage life of spacecraft are important indexes to be referred to in spacecraft design. [4] How to prolong the ground storage life and how to launch quickly are the hotspots that spacecraft workers are paying close attention to. Based on the development of sensor network structure health monitoring, the mechanical deformation under each state of the shell can be monitored by embedding the sensor inside the spacecraft shell. [5] The traditional strain sensor is mainly based on the application of resistance strain
gauges. However, it’s measuring sensitivity and accuracy is poor because of its vulnerability to humidity, magnetic field and other factors. Therefore, it can’t meet the application needs up to now. In addition, the compatibility of resistance sheet and composite structure is poor. When used generally affixed to the surface of the object under test, it is difficult to bury the inside of the composite material for real-time monitoring.[6] Because of its small radius, the fiber Bragg grating (FBG) is more convenient to be embedded in carbon fiber, and the fiber optic protection layer and composite materials have good compatibility, so as to meet the need to bury the sensor inside the material.[7,8] At the same time, the optical field reviews show that FBG sensing technology is an effective method for structural health monitoring.[9] However, because the optical fiber diameter is small and the whole is easy to break, how to effectively protect it in the process of embedding is the premise that the FBG sensor can work.[10]

Researchers in various countries have done a lot of research on fiber embedded composites, and the research shows that it is feasible to bury FBG bare fiber into composites. However, no complete process description has been seen in the literature. In this experiment, the FBG was embedded into carbon fiber composites by the preparation method of pressurized film forming. The practical method of stainless steel and Teflon casing are used to protect the elicitation of FBG, and its technological process is described in detail.

2. FBG sensor principle

FBG was first proved by Hill[11], who used the photosensitivity of optical fiber core materials doped with germanium plasma to form a reflector etched at the core of optical fibers by irradiation such as ultraviolet light. It reflects the light in the incident wavelength that satisfies the Bragg diffraction and transmits all other light. (Figure 1)

![Figure 1. Principle of FBG](image)

The cylindrical body of the fiber optic center is a fiber core, and the circular outer layer near the core is called the cladding layer. Fiber cores and cladding layers are usually made of quartz glass with different refractive index. The refractive index of the fiber core is greater than that of the cladding layer.[12] Each FBG definition has a unique central wavelength, and the refraction surface in the fiber grating is called the Bragg surface, which is produced when two opposite light sources interfere constructively. The tensile fiber grating (sensitive to mechanical or thermal strain) causes the refractive index of the sensor to change. As shown in Figure 1, when a wavelength tunable laser transmits light through a fiber grating, the narrow bandwidth of the laser is reflected back, while other light is transmitted. The FBG strain comes from the Bragg wavelength, which is located at the center of the reflection wavelength range and can be expressed as [13,14,15]

$$\lambda_b = 2n\Lambda_b$$  \hspace{1cm} (1)

In equation (1), $n$ is the effective refractive index of the fiber core, $\Lambda_b$ is the spacing of the Bragg surface. When the Bragg grating sensor is induced to produce strain, the reflection wavelength hanges. Because of the temperature change $\Delta T$ and strain $\varepsilon$ in the fiber direction, Bragg wavelength displacement can be expressed as:
\[
\frac{\Delta \lambda_b}{\lambda_b} = (1 - P_s) + (\alpha_s + \alpha_f) \Delta T
\]

When \( \lambda_b \) is a non-strain Bragg wavelength, \( P_s \) is the strain light coefficient, \( \alpha_s \) is the thermal expansion coefficient of the fiber, and \( \alpha_f \) is the thermal light coefficient. Because of the influence of temperature and strain on the reflection wavelength of fiber grating, temperature compensation should be introduced in order to measure the strain accurately.

3. Processing and testing

3.1 Temperature strain sensitivity analysis

As known by formula (2), the sensor is sensitive to temperature and strain at the same time, and when strain measurement is carried out, it is usually necessary to introduce a temperature compensation sensor near the strain sensor. Therefore, these two sensors have the same response to temperature changes, even if the shift of the center wavelength of the sensor is only related to strain. At this point, the strain of the material can be expressed as:

\[
\Delta \varepsilon = \frac{\Delta \lambda_b - \Delta \lambda_T}{k \varepsilon}
\]

The \( \Delta \lambda_T \) is the Bragg central wavelength shift of the temperature compensation sensor.

It has been shown that the diameter of the encapsulated temperature compensated grating fiber sensor is significantly larger than that of the carbon fiber, and the local stress concentration may be caused by encapsulating the composites, which can destroy the microstructure of the composites.[16] However, when the number of fibers embedded in the fiber is very few, the effect on the mechanical properties of the composites is not obvious. At the same time, too many optical fiber quantities easily lead to fiber winding in carbon fiber, affecting the mechanical properties after curing. Therefore, it is necessary to minimize the number of fibers embedded in the composites, and to make the length of the fiber as close as possible to the length of the material laminate.[17]

3.2 Fiber embedded composites scheme

The design is based on the embedded scheme as shown in Figure 2, and the length, width and height of the carbon fiber laminates are 260 mm, 60 mm and 3 mm respectively. Bury the fiber in the middle layer at 1.5 mm. Stainless steel tubes and Teflon fine tubes are used at the interface for elicitation protection.

Figure 2. Diagram of fiber embedded composites
3.3 Optical fiber end-surface elicitation protection scheme

There are generally two kinds of elicitation methods in embedded fiber, namely, surface elicitation and end-surface elicitation. Surface elicitation, that is, optical fiber piercing directly from the surface of the composite material and light path bending in the production process that may affect structural properties and surface integrity. The optical fiber induced by the end-surface elicitation is in a straight line state in the carbon fiber laminate, which is helpful to improve the compatibility between the embedded fiber and the laminates. However, this method in the curing process will lead to the flow of resin, not conducive to demoulding. Therefore, it is necessary to protect the optical fiber at the elicitation site when the end-surface is introduced.[18]

The experimental process uses the method of end-surface elicitation and the protection of stainless steel pipe, rubber pad, Teflon pipe, etc, and the schematic diagram is shown in Figure 3. Sealant was used on both sides of the stainless steel tube, and the parts connected with it were further protected with Teflon (PTFE) fine tubes. The rubber pad is pasted on the upper and lower surface to avoid the bending of fiber during the curing process.

3.4 Machining process

The laminated 1.5 mm thickness carbon fiber composites are cut into two pieces of 260 mm × 60 mm according to the design size, and the 260 mm length is the parallel cleavage direction of carbon fiber. Take one of the cropped carbon fibers, and lay two bare fibers protected with stainless steel pipe in the distance of 20 mm on both sides of the long edge respectively. So that the bottom carbon fiber is divided into three rectangular patterns with equal area. The contact vertical end-surface between optical fiber and carbon fiber is fixed with the use of tape. Place the other carbon fiber laminate with a thickness of 1.5 mm on top of it. The rubber strip with a length of about 60 mm is cut and placed on the upper and lower surface of the end-surface of the plate, and the elicitation fiber is protected to prevent the optical fiber from breaking when the end-surface is induced when the heating and pressurization are cured. Put the plastic film on the surface of the upper carbon fiber and fix it with insulating tape to further protect it. Then put it into the processing platform and further push them into the large vulcanization equipment for heating (220℃) and vacuum. The machining flowchart is shown in Figure 4.
3.5. Experiment and analysis
In order to test the overall performance of high temperature composites embedded in FBG, two sets of comprehensive experimental devices were constructed. These two sets of devices include the strain property test device of embedded FBG composite material and the high temperature performance test device of embedded FBG composite material. As shown in Figure 5.

![Figure 5. FBG strain and temperature testing device embedded in composite materials](image)

3.6. Experiment of FBG strain performance
During the strain performance test of the composite embedded with FBG, pulse force and step force are applied to the composite respectively to measure the response of the composite under the strain action and the accuracy of the embedded FBG sensor.

The test results show that the FBG sensor embedded in the composite material and completely survived can complete the strain measurement of the composite material. This measurement has high time sensitivity (< 0.5s) and good repeatability. However, further analysis shows that the accuracy of strain measurement of multiple gratings embedded in the composite is not consistent, as shown in Fig. 6. The difference in the preparation process of FBG is due to the different residual stress. The specific reason needs further measurement and confirmation.

![Figure 6. Different FBG measurements](image)

3.7. FBG experiments at high temperatures.
The high temperature test of FBG buried in composite material is divided into two parts. First of all, the maximum temperature of 250 degrees Celsius temperature test, FBG's high temperature
performance evaluation, and then the maximum temperature of 700 degrees Celsius of the standard high temperature test. The high temperature measurement results are compared with the thermometer measurements in real time. The test results for medium to high temperature performance are shown in Figure 7. The test results for the high temperature performance of the standard are shown in Figure 8.

![Figure 7. The results of the high temperature experiment in FBG.](image)

![Figure 8. FBG high temperature experimental results.](image)

From the test results, it can be seen that under the conditions of medium-high temperature and high temperature test, FBG buried in composite materials can measure the temperature with high accuracy, and the measurement accuracy is about 1.1 pm/℃. At the same time, it can be learned from the experimental results that FBG buried in composite materials can be well tracked during temperature increase, temperature decrease and thermal cycle, and the response time is less than 0.5 seconds.

4. Summary
This paper introduces the principle of fiber grating sensor, and designs and processes the process of burying carbon fiber composite materials into FBG. The lead-out process of this process uses side-led, stainless steel tubes for export protection. The finished laminate and fiber are complete, and there is no fiber break or carbon fiber deformation. We systematically designed the strain test and high temperature test of FBG buried in high temperature composites. We thoroughly tested the integrity, usability, testing capability and accuracy of the sensor at high temperatures. The test results show that the accuracy of the embedded sensor is about 1.1 pm/℃, the applicable temperature range of the sensor head is greater than 700 ℃, and it can perform distributed measurement of strain and temperature.
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