Investigation of Temperature Performance of Silica Gel Covered Flexible Array Optical Fiber Temperature Probe

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ABSTRACT

This paper presents the design, fabrication and reliability testing of a novel flexible array of sensors based on fiber Bragg grating (FBG) for surface temperature sensing applications. The structure of the proposed optical fiber temperature probe (OFTP) consists of a rectangular metal base over which a room temperature cured silica gel is laid out. The FBGs pass through hollow capillary channels located in the middle of the silica gel layer. The use of the silica gel allows obtaining a tiny deformable surface that provides the capability to adapt its contact surface to better match the measured object. Based on a specific design, a silica gel of 80 mm × 80 mm × 5 mm with eight parallel arranged capillary channels is fabricated on a 15 mm-thick rectangular metal protruding platform. Two FBGs are placed into capillary channels in symmetrical positions close to a central hole, respectively. One is placed inside a Teflon capillary tube, along with a thermocouple used as a reference, while the other FBG goes directly through the capillary channel. The prototype is tightly attached to a heating plate to obtain a uniform temperature loading. The experimental results show that the designed flexible array temperature probe offers reliable and precise temperature measurements when compared to the real value at the panel. Although FBGs have been used in this proof-of-concept demonstration, distributed fiber sensing methods can also be used to obtain a distributed temperature profile.

1. Introduction

Surface temperature is an important parameter in structure health monitoring (SHM), machining process monitoring, and equipment state control and diagnosis. It can reveal the temperature of a local point or the distribution of temperature of an object, allowing for the evaluation of the rationality of processing parameters and device faults diagnose. The advantages of optical fiber temperature sensors have been recognized and their applications are steadily growing [1–3]. In these applications, temperature measurement plays a significant role in maintenance and condition safety, being utilized in applications such as the monitoring of the oil wells and pipelines. For these purposes, optical fiber sensors are typically used under different scenarios, being often inserted into metal tubes in cable form for installation at the temperature measurement site. Especially, the use of optical fiber sensors becomes an interesting alternative for monitoring the temperature of surfaces where traditional methods, such as infrared thermal imager, are difficult to use for capturing temperature distributions. Carbon fiber reinforced polymers (CFRP) have become the most relevant material to manufacture lightweight automotive and aerospace components. With the increasing demand for a large number of applications, the machining productivity of CFRP components is greatly affected by defective hole under high-speed drilling due to its stiffness and brittleness characteristics. The cutting heat is
generally recognized as the main heat source leading to a significant temperature increase in the cutting zone, eventually exceeding the glass transition temperature, and resulting in poor-quality hole walls or consequent defects. Owing to the poor thermo-mechanical properties of epoxy resin, many attempts to explore the temperature distribution have been made to optimize cutting parameters \[4\]. Recently, an effective method based on distributed optical fiber sensors (DOFSs) has been developed to obtain the two-dimensional temperature distribution adjacent to the borehole \[5\]. However, it is inconvenient to glue an optical fiber on every machined part; and therefore, the use of an external independent temperature probe emerges as a good alternative to adapt to simple installations.

In this paper, a novel flexible array of temperature sensors based on fiber Bragg gratings is proposed, in which an array of FBGs is embedded into a silica gel layer, which is tightly bonded on the surface of a metal substrate. In order to investigate the thermal conductivity of the designed temperature probe, two embedded FBGs are experimentally tested: One FBG is placed inside a Teflon capillary tube, along with a thermocouple used as a reference, and the other FBG passes through a capillary channel in the silica gel covering layer. The probe is tightly attached to a heating plate to obtain a uniform temperature distribution. The experimental results show that the designed flexible array temperature probe offers reliable and precise temperature measurements when compared to the real value at the panel. Even though FBG-based point optical fiber sensors are used in the proof-of-concept experiment presented in this paper, distributed fiber sensing techniques can also be used to obtain a two-dimensional distributed temperature profile.

2. Packaging Techniques

2.1 Design of Prototype

The proposed OFTP structure consists of a rectangular metal base over which a room temperature cured silica gel is laid out, as shown in Fig.1. The OFSs pass through hollow capillary channels located in the middle of the silica gel layer, which is used to provide a flexible surface having the possibility of easily adapting it surface to improve the contact with the measured object. Based on this concept, some silica gel was placed on the top of a rectangular metal protruding base with a group of parallel arranged capillary channels. The capillary channels are produced by firstly inserting Teflon tubes in capillary grooves existing on the base, as shown in Fig. 1, and then pouring silica gel and encapsulating the Teflon tubes. This silica gel is then cured at room temperature for about half an hour. After this, the inserted Teflon tubes are pulled out, thus forming the capillary channels where an optical fiber is then embedded in each of them.

![Figure 1. Concept design of the temperature probe](image)

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Owing to different shape and monitoring region, the optical fiber path can be made into many forms, such as orthogonal grid or spiral shape. The orthogonal grid and spiral curve with a hole in the center are designed for measuring exit temperature induced by drilling CFRP laminates. The hole is set for creating some space for the drilling bit when penetrating through the CFRP laminates. If the temperature must be measured in a whole plane, the central hole in the gel is not necessary. An optical fiber joint is placed near the end of the fabricated temperature probe to connect a bare sensing optical fiber and leading optical fibers. In order to protect that segment of bare optical fiber before splicing, two lids are covered on two ends of the base, shown in Fig.1.

2.2 Fiber Bragg grating sensors

Fiber Bragg gratings are fiber-optic components in which the refractive index of the fiber core is periodically modulated in axial direction [6]. The longitudinal period $\Lambda$ of the refractive index modulation determines the Bragg wavelength $\lambda_{FBG} = 2n_{eff}\Lambda$ (with $n_{eff}$ the effective refractive index), at which an incident light is reflected back through the optical fiber. Since the refractive index of the fiber changes with environmental variables such as temperature and strain, measuring the relative spectral shifts of the Bragg wavelength ($\Delta\lambda_{FBG}/\lambda_{FBG}$) allows for temperature and strain sensing, according to:

$$\Delta\lambda_{FBG}/\lambda_{FBG} = C_\varepsilon \Delta\varepsilon + C_T \Delta T,$$

where $\Delta\lambda_{FBG}$ is the Bragg wavelength shift, $\lambda_{FBG}$ is the Bragg wavelength at a reference condition (i.e. at known temperature and strain), $C_\varepsilon$ and $C_T$ are the strain and temperature coefficients of the FBG, respectively, and $\Delta\varepsilon$ and $\Delta T$ are the external strain and temperature changes, respectively. It must be noticed that FBGs respond simultaneously to temperature and strain variations, making it impossible to discriminate one from each other using a single measurement. Diverse strategies can be used to discriminate temperature from strain or to obtain strain-free temperature sensing.

2.3 Fabrication of Prototype

In order to verify the proposed concept of temperature sensing probe, a prototype was fabricated. Based on the design, a size of 80 mm × 80 mm × 5 mm silica gel with eight parallel arranged capillary channels is fabricated on a 15 mm-thick rectangular base, which was 3D printed instead of being manufactured by metal materials. Before pouring the liquid silica gel, two Teflon tubes were placed in two small grooves near the centre hole. Then the mixture was stirred uniformly with silica gel and curing agent at 100:1 and put it aside at room temperature for half an hour. Then carefully pull out one of the Teflon tube and a hollow capillary channel was created.

![Figure 2](image)

**Figure 2.** The details fabrication: (a) layout of the sensors, and (b) fabricated prototype

For simplicity, FBG point-type optical fiber sensor is employed instead of distributed optical fiber sensors to verify optical fiber sensing performance. Two FBGs were used to compare the temperature sensing effect of OFSs passing through hollow capillary channels located in the middle of the silica gel layer. The FBGs (marked in Fig. 2a with a pair of short dashes) are placed into capillary channels
in symmetrical positions close to a central hole, as shown in Fig. 2a. One (named FBG1) is placed inside one channel with a Teflon capillary tube, along with a thermocouple used to measure a reference temperature, while the other (named FBG2) directly goes through the capillary channel under cured silica gel, as shown in Fig. 2b.

3. Experiments

The fabricated silica gel covering the flexible optical fiber temperature probe has been experimentally tested in order to verify the reliability of the proposed structure. In order to investigate how the silica gel and Teflon tube affect the temperature sensing based on FBGs located in different packaged situations, hot-pressed plates with uniform temperature field are used for heat loading to the prototype. The prototype is tightly attached to the upper heating plate of the hot-press machine to obtain a uniform temperature loading, as shown in Fig. 3.

The thermocouple and two FBGs can obtain continuous temperature values. The hot-press also has a temperature indicator for its panel temperature, which is usually the temperature of measured surface. The experimental results (in Fig. 4a) show that the designed flexible array temperature probe offers reliable and precise temperature measurements when compared to the real value at the panel. The proportion of actual temperature attenuation under different conditions is shown in Fig. 4b.

It is noticed that, comparing with panel temperature values, the temperature attenuation of the FBG2 encapsulated only by silica gel to temperature is less than 5 percent, and the value is getting smaller as the temperature increases. In the case of FBG1 encapsulated by both Teflon tube and silica gel, the temperature attenuation ratio rises to around 15 percent. The attenuations of the thermocouple and
FBG1 in the Teflon tube are similar. Therefore, only slightly lower values compared to the panel temperature can be observed, corresponding to an acceptable bias for some engineering applications.

4. Conclusion and discussion

A novel flexible array of sensors based on fiber Bragg grating for surface temperature sensing has been proposed and experimentally investigated. The structure of proposed OFTP can be designed for different surface temperature measurement by setting parallel, orthogonal grid or spiral curves. The hollow capillary channels provide loose space for placing optical fibres that allow for temperature sensing without strain disturbance. The experimental results show that the designed flexible array temperature probe offers reliable and precise temperature measurements when compared to the real value at the panel.

Although FBGs have been used in this proof-of-concept demonstration, distributed fiber sensing methods can also be used to obtain a distributed temperature profile. The silica gel layer allows obtaining a tiny deformable surface that provides the capability to adapt its contact surface to better match the measured object. It is worth noting that, the thickness of silica gel should be optimized and fabricated to obtain best heat transmission effect. Whether to protect bare fiber with Teflon tube or not depends on the environment and temperature in specific use. In addition, a special measuring point reconstruction model is needed for arranging the sensing optical fiber by spiral path. Methods for calibration and for reconstructing the measurement points in a 2D map are still under investigation.

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References and Footnotes