An optical fiber multi-parameter sensor for temperature and strain real-time monitoring in different structures

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An optical fiber grating multi-parameter sensor for temperature and strain real-time monitoring has been proposed. Based on a polyimide fiber Bragg grating (PFBG), the system can be used for high temperature (100-300℃) monitoring, except for common temperature (-20~100℃) and strain monitoring in composites curing process simultaneously. The PFBG is embedded into composites for VARI (Vacuum Assisted Resin Infusion) curing process. The temperature and strain are calculated according to the central wavelength. Different materials and structures are used in this paper. The results provide references for curing process optimization and technological process improvement of composites curing process.

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1. Introduction

FBG sensors are more and more widely used to monitor the curing process of composite materials due to their advantages, such as good electrical insulation, no electromagnetic interference, low disturbance to measured field and good compatibility with matrix materials [1.2.3].

Carbon fiber reinforced resin matrix composites has been widely used in aerospace, automotive industry and civil engineering because of excellent specific strength, specific stiffness, fatigue resistance and good design ability. It is of great value to monitor the curing characteristics of composite materials and analyze the evolution of temperature and strain during the curing process. In recent years, monitoring of composite materials curing process in real time has become a hot topic. Traditional temperature and strain monitoring methods are largely influenced by matrix. Besides, these methods have poor compatibility with composite materials. So the accuracy of monitoring results [4.5.6] is affected.

Some monitoring methods using FBG during the curing process of composite materials have been reported. Parlevliet et al. [7] embedded FBG to monitor the effect of curing shrinkage and solidified residual stress. Takuhei Tsukada et al. [8] embedded FBG to monitor the influence of residual strain in thermo-curing process of unidirectional lamination of carbon fiber / polyphenylene sulfide at different cooling rates. M. Mulle et al. [9] embedded transverse and longitudinal FBG in different positions of glass fiber reinforced polypropylene (glass-fiber-reinforced polypropylene (GFPP) laminates) to monitor the strain evolution during hot press curing. R. brain Jenkins et al. [10] embedded a FBG array in carbon fiber/epoxy resin composite materials to measure the surface and internal temperature changes of the composite materials at the same time. Qin Wei [11]and Tian Heng [12]et al. used FBG to realize the strain monitoring during the curing process of composite materials in RTM curing process and hot pressing tank molding process respectively, and this method has received extensive attention at present. Its development and application can not only reduce the manufacturing cost of aerospace composite materials with large size and volume but also bring positive effect to the development of aerospace composite materials [13.14.15.16].

The VARI molding manufacturing technology uses vacuum negative pressure to the composite materials and avoids the use of hot pressing tank in curing process or natural state solidification curing process at higher temperature in the oven. The VARI molding manufacturing technology has large potential due to the low cost and high performance advantages [17.18.19]. The United States once used VARI molding manufacturing technology to manufacture the structural integral parts of composite aircraft, and it was successfully tested for the first time in 2009. It is a milestone for VARI molding technology in large-volume and large-area aeronautical manufacturing.

The PFBG is used to monitor the VARI curing process of composites. Temperature and strain are two important parameters that need to be monitored. It is necessary to use a certain method to distinguish the temperature effects and strain effects because the conventional FBG is sensitive to both temperature and strain. In this paper, the PFBG is embedded in the structure of preimpregnated carbon fiber/epoxy resin laminates to monitor the temperature and strain of composite materials in real time. In addition, the conventional FBG is used to compare with the PFBG.

2. Experimental principle

FBG is an optical structure in which the optical fiber with photosensitivity is exposed directly by ultraviolet laser and the refractive index changes periodically on the core. When the broadband light travels in it, the light that meets the conditions is reflected.

The relationship between the variation of temperature (ΔT), the variation of strain ($\Delta\varepsilon$) and the variation of central wavelength of FBG ($\Delta\lambda_B$) are as follows:

$$\begin{aligned}\Delta\lambda_B &= \lambda_B[(1-P_e)\Delta\varepsilon + (\alpha_f + \xi)\Delta T] \\ &= K_\varepsilon \Delta\varepsilon + K_T \Delta T\end{aligned} \tag{1}$$

where P_e is elasto-optical coefficient of optical fiber, α_f is the coefficient of thermal expansion of optical fiber, ξ is the thermo-optical coefficient of the optical fiber. And K_T is the temperature sensitivity coefficient of the FBG, K_ε is strain sensitivity coefficient of FBG. It can be seen from equation (1) that the $\Delta\lambda_B$ is sensitive to both temperature and strain.

The PFBG is proved to be of high temperature resistance. The variation of the central wavelength can be expressed as follows:

$$\Delta\lambda = K_\varepsilon \Delta\varepsilon + K_T \Delta T \tag{2}$$

where $\Delta\lambda$ is the relative shift of central wavelength of PFBG. K_T and K_ε are the temperature sensitivity coefficient and strain sensitivity coefficient of PFBG, respectively.
The changes of temperature and strain of the PFBG can be calculated by equation (3).

$$\left.\begin{aligned}\Delta\varepsilon &= \frac{\Delta\lambda - K_T \cdot \Delta T_1}{K_\varepsilon} \\ \Delta T &= \frac{\Delta\lambda - K_\varepsilon \cdot \Delta\varepsilon_1}{K_T}\end{aligned}\right\} \tag{3}$$

where ΔT_1 is the change of temperature measured by the thermocouple, $\Delta\varepsilon_1$ is the change of strain measured by strain gauge. From equation (3), the temperature and strain can be calculated according to the wavelength shift, temperature sensitivity coefficient and strain sensitivity coefficient of the PFBG. The T type thermocouple and resistance strain gauge are embedded near to the buried PFBG. In the meanwhile, the temperature and strain can be measured by thermocouple and strain gauge. The measured results are used to compare with the results obtained by PFBG.

During the curing process, heat expands the epoxy resin in the composite materials. Thermal expansion of base materials will cause the change of wavelength drift. The following model is deduced for demodulation:

$$\Delta\lambda_B' = \lambda_B\left[\alpha_f + \xi + (1-P_e)(\alpha_{sub} - \alpha_f)\right]\Delta T \tag{4}$$

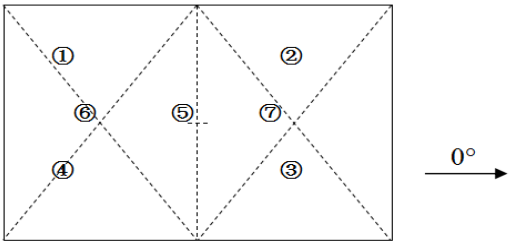
where α_{sub} is the coefficient of thermal expansion of epoxy resin.

3. Experimental configuration and process

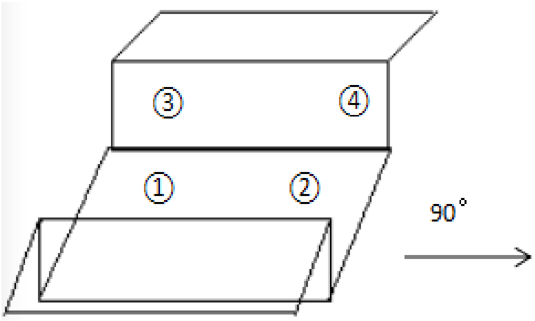
3.1 Raster embedding scheme

Different materials is used in our experiments. UD prepreg of carbon fiber (T800*850) reinforcement medium modulus high strength epoxy composites is used in the first and second series of experiments. UA2433-125 woven (90°) carbon fiber of fabric composites is used in the third series of experiments.

Different structures are used in our experiments. The material size is 300mm ×200mm and the thickness of single layer is 0.1mm in the first and second series of experiments. Besides, the way of [$0°_{10}$] is used to lay the layers and seven positions are selected on the prepared surface as the PFBG preselection points. In the third series of experiments, the material size is 600mm ×600mm and the thickness of single layer is 0.1mm.The laying direction is [$90°_{10}$].



(a)



(b)

Fig.1 Pre-embedded positions of PFBG in composite materials (a) in the first and second series of experiments (b) in the third series of experiments

The temperature sensitivity coefficient and the strain sensitivity coefficient of FBG and PFBG are measured before the experiments. In this paper, three series of experiments are introduced, and the embedding schemes of each series of experiments are described detailedly as Fig.1. Fig. 1 (a) is the laying scheme of the first and second series of experiments. Fig.1 (b) is the laying scheme of the second series of experiments.

In the first series of experiments, each position is embedded with a FBG string. The FBG string is welded by a bare FBG and an encapsulated FBG. All FBGs are embedded between the fifth and sixth layers. Two pairs of FBGs are embedded at positions ①and ②respectively. The laying direction of the FBGs is 0°.

In the second series of experiments, a new glass encapsulated FBG is embedded in position ②and a common FBG string is embedded in position ③and ④respectively. A thermocouple and a strain gauge are embedded in position ②,③and ④respectively. And the laying direction of the thermocouple is parallel to that of the FBGs. All the FBGs are embedded between the 5th and 6th layers, and the laying direction of the FBGs is 0°.

In the third series of experiments, a high temperature resistant PFBG, a thermocouple and a strain gauge are embedded in position ②, ③and ④ respectively. The laying direction of the thermocouple is parallel to that of the PFBGs. All the PFBGs are embedded between the 5th and 6th layers, and the laying direction of the PFBGs is 90°.

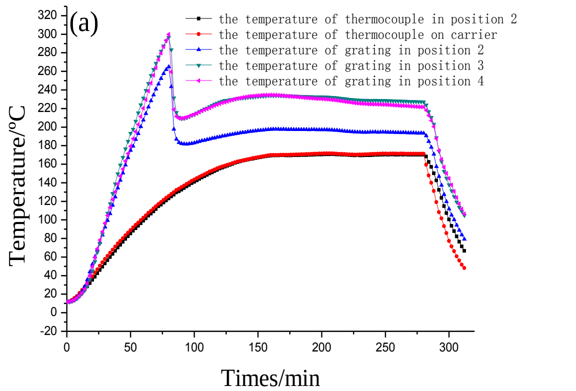
3.2. Curing and monitoring programmes

The VARI is used and the curing pressure was -0.099 MPA in all experiments. The VARI curing process includes three stages: (1) raising the temperature of the oven to 180 °C , (2) keeping the temperature at 180° C for 2 hours, (3) closing the oven heating device and keeping the temperature decreasing at the rate of 5°C/min. The metal plate carrier is used in the experiments. The FBG sensor demodulator is the SM125 of MOI company. The sampling frequency is 1Hz and the wavelength precision is 1pm.

4. Analyses of experiment results

4.1. Results of temperature measurements

In the first series of experiments, the temperature measurements results of the FBG are shown in Fig. 2 (a).



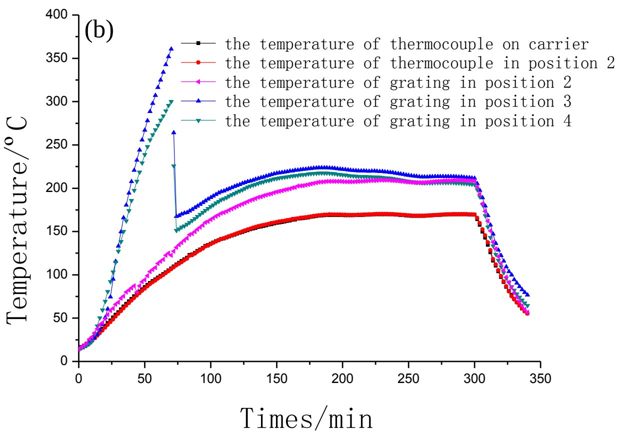


Fig. 2. The results of temperature measurements (a)in the first series of experiments (b)in the second series of experiments (color online)

It can be seen that the temperature measured by FBG and thermocouple are consistent, so the temperature measured by FBG varies along with the change of ambient temperature. In the temperature holding stage, the temperature measured by FBG is consistent with that measured by thermocouple, and the difference between them is stable. The difference between the temperature measured by FBG and the temperature measured by thermocouple is reduced in the cooling stage. When the ambient temperature reaches to 130 °C , the temperature curve measured by the FBG has a sharp drop.Because when the temperature rose to 130 ℃ , the elastic coefficient and thermal expansion coefficient of the grating changed, resulting in the discontinuity of the measurement curve.

In the second series of experiments, a new type of glass encapsulated FBG is used to replace the common FBG at position ② The new glass encapsulated FBG is affected only by temperature. The results of temperature measurement are consistent with the results of thermocouple measurement. There is a temperature gradient in the numerical value. The results of measurement are shown in Fig. 2 (b).

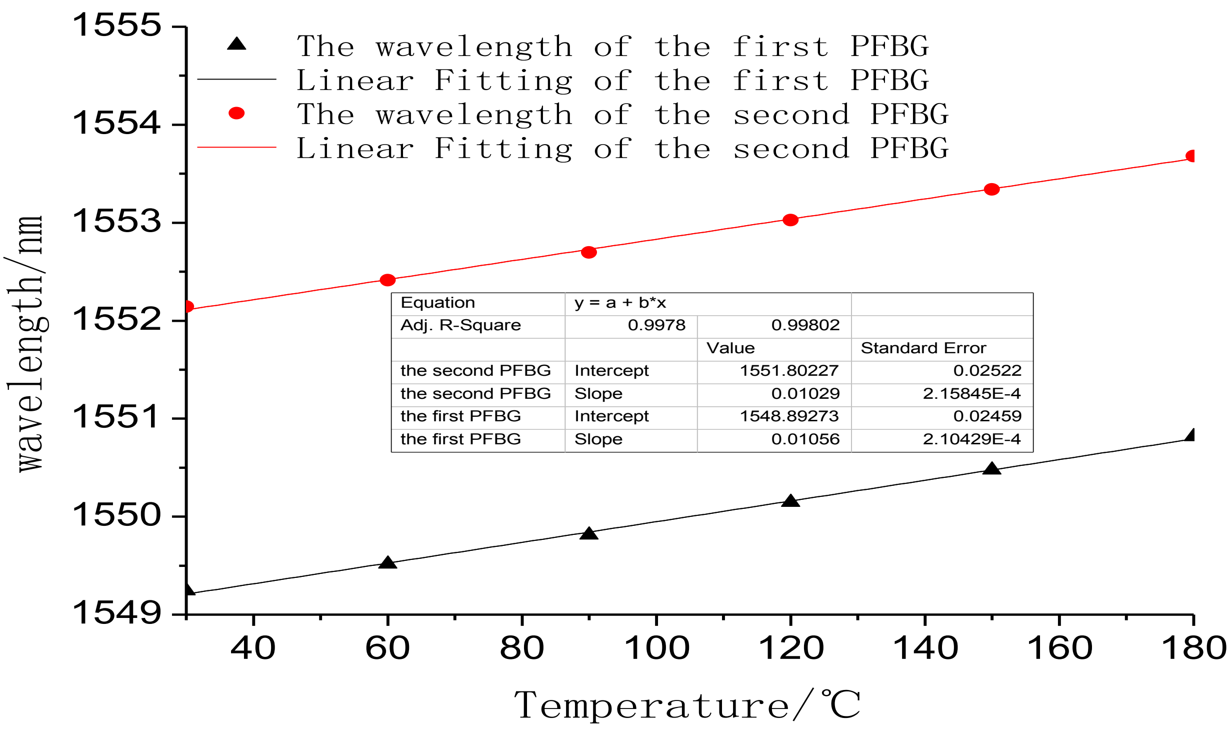


Fig. 3. Central wavelength measurements of PFBG

In the third series of experiments, the PFBG is used to verify whether it can withstand 300 °C in the composite materials curing process. The high temperature resistance of the PFBG is measured by using a thermostat and spectrometer before the experiment. The test results are shown in Fig. 3.

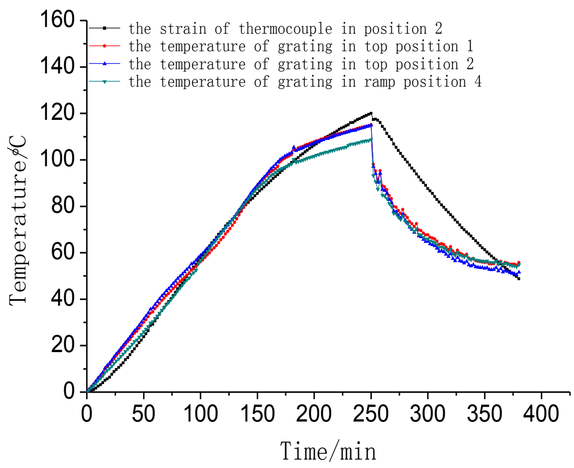


Fig. 4. The results of temperature measurements in the third series of experiments (color online)

It can be seen from the Fig. 3 that the central wavelength of PFBG has a good linear relationship with temperature. The temperature-wavelength coefficient of the first PFBG is 0.01056 and the linearity is up to 0.99802. The temperature-wavelength coefficient of the second PFBG is 0.01029 and the linearity is up to 0.9978.

The results of the third series of experimental temperature measurements are shown in Fig.4. It can be seen that the temperature curve measured by the PFBG is smooth and has no defects. The temperature measured by the PFBG is similar to that measured by the thermocouple, but the difference in value becomes even bigger. It shows that thermal expansion of base materials will cause the change of wavelength drift during the curing process of composite materials, and the temperature-wavelength coefficient of the PFBG needs to be redefined.

The results of the third series of experimental temperature measurements are shown in Fig. 4. Compared with the first and second series experiments, the temperature data of the high temperature resistant PFBG is in good agreement with the temperature data of the thermocouple. The difference between them becomes smaller and the lowest value is 4º C.

4.2. Results of strain measurements

The results of the first series of experiments are shown in Fig. 5(a). In this series of experiments, strain gauges are embedded near the FBG at various positions to verify the accuracy of the FBG strain measurements.

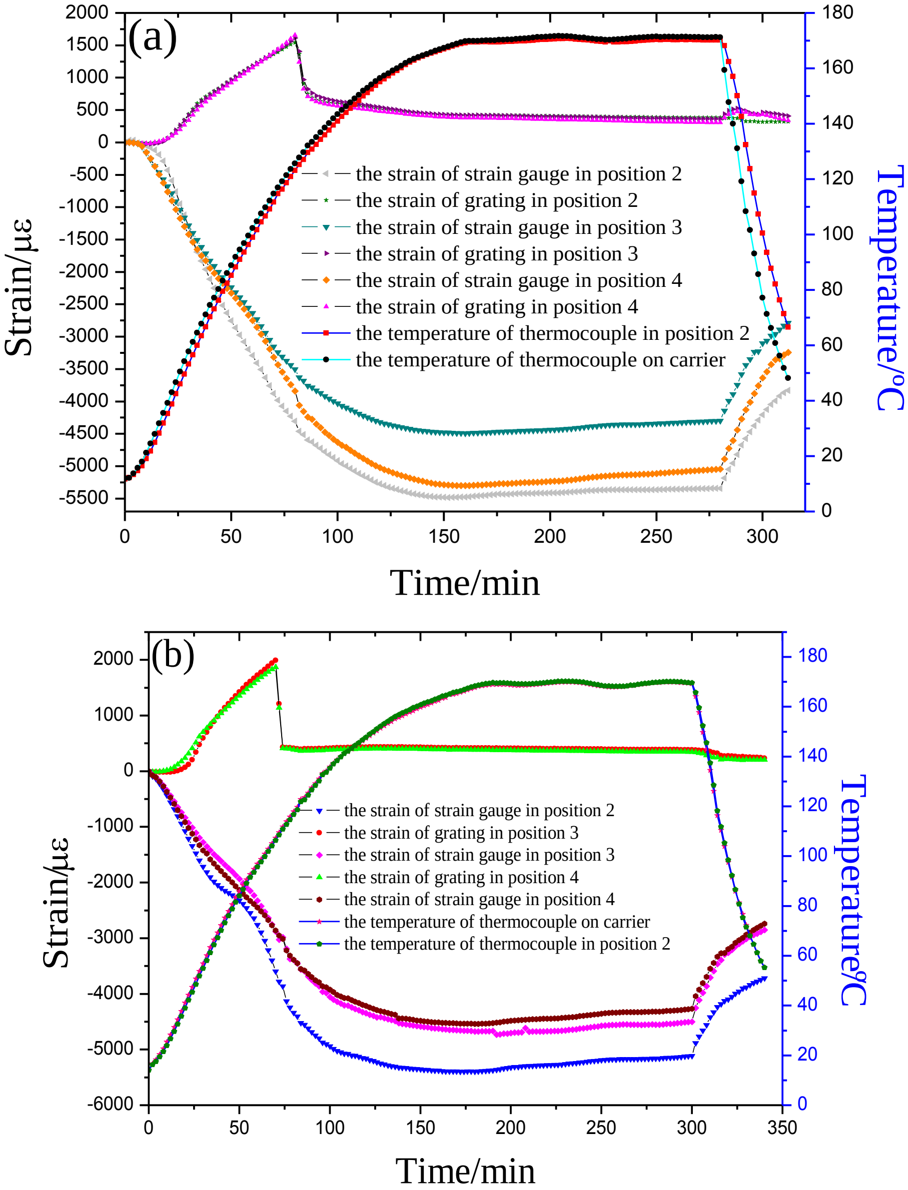


Fig. 5. The results of strain measurements (a)in the first series of experiments (b)in the second series of experiments (color online)

It can be seen from the diagram that the measured results of strain gauges show a downward trend with the increase of temperature. It shows that there are compressive stresses in the curing process of composite materials. In the temperature holding stage, the measured results of strain gauges remain unchanged. In the cooling stage, the results of strain gauge measurements show an upward trend that the residual strain in the composite materials decreases gradually, and the system is in a recovery state. The strain measured by FBG is opposite to that measured by strain gauge, and the difference of stress is big. The strain curve measured by FBG drops sharply when the curing temperature is about 130º C. The results of the second series of experiments are shown in Fig. 5 (b). In this series of experiments, a new type of glass encapsulated FBG is used to replace the common FBG string at position ② The strain curve measured by the FBG drops sharply when the curing temperature is about 130º C.

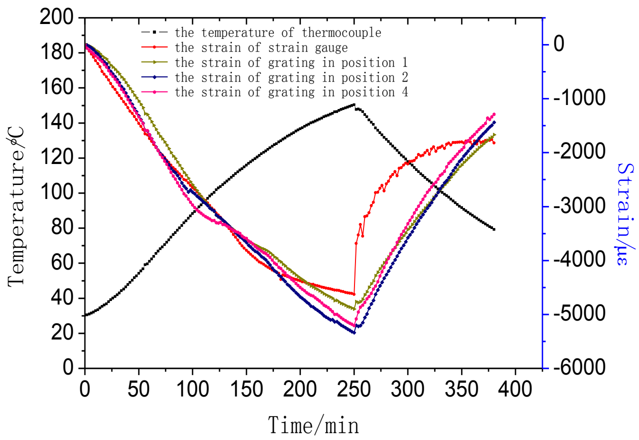


Fig. 6. The results of strain measurements in the third series of experiments (color online)

In the third series of experiments, the model of flying beam made of composite materials is used. This model is different from the previous model of laminated plate. Meanwhile, new materials-UA2433-125 woven (90º) carbon fiber of fabric composites was used in this series experiments. The strain measurements of the third series of experiments are shown in Fig. 5. It shows that after the temperature coefficient of the PFBG is redefined, the variation trend of strain measured by PFBG has been greatly improved. It is consistent with the variation trend of the strain measured by strain gauge. The difference between the two values becomes smaller, the maximum relative error is 0.18%. It’s smaller than the value of laminated plate. The results show that the strain sensor of PFBG is subjected to compression stress and the strain increases negatively during the curing process of the composite materials.

5. Conclusion

In this paper, we used two models. The model of laminated plate is used in the first and second series of experiments. In the third series of experiments, a new model is used. This new model is the flying beam. Common FBG and PFBG can be used to monitor the temperature and strain during the curing process of composite materials in real time. When the temperature is not too high, the temperature and strain can be measured in real time by using the ordinary FBG. But when the temperature is high, PFBG should be used. In high temperature environment, using PFBG can accurately measure temperature and strain in real time. The research results provide important references for the application of PFBG in monitoring the temperature and strain simultaneously during the curing process of composite materials.

In the process of signal demodulation and data processing, the transfer effect of substrate materials (such as epoxy resin) on the strain and temperature of PFBG should be considered, and the thermal expansion coefficient of substrate materials will affect the PFBG. So the temperature and strain coefficient of PFBG should be redefined.

In this paper, the high temperature resistant PFBG are used in three series experiments. In the first and second series of experiments, the same materials and structure is used. In the third series of experiments a new material and structure is used. The new material is UA2433-125 woven (90º) carbon fiber of fabric composites. The new model is the flying beam. The maximum relative difference of temperature between the results obtained by PFBG sensor and the results obtained by thermocouple is 2.5% in the first and second series of experiments. The maximum relative difference of strain between the results obtained by PFBG sensor and the results obtained by strain gauge is 0.2% in the first and second series of experiments. In the third series of experiments, the maximum relative difference of temperature is 2.3% and the maximum relative difference of strain is 0.18%. The experimental results have good repeatability.

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