Оптический
журнал

Оптическое материаловедение и технология

A polyimide-coated fiber Bragg grating sensor for monitoring of composite materials curing process

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Submitted 23.05.2019

DOI:10.17586/1023-5086-2020-87-08-72-78

In this paper, a polyimide-coated fiber Bragg grating sensor for temperature and strain monitoring of composite materials curing process in real time is proposed. New experiments have been done in much the same way as earlier, with the changes and peculiarities as follows: we demonstrate a new grating polyimide-coated fiber Bragg grating. It can resist 300 °C and the grating in the early paper can resist only 130 °C. We can measure temperature and strain at the same time in this paper. Besides, we have analyzed relative difference in this paper. The temperature and strain are calculated according to the central wavelength. For comparing the temperature results, the thermocouple has been used to monitor the temperature simultaneously. For comparing the strain results, the strain gauge has been used to monitor the strain simultaneously. The maximum relative difference of temperature between the results obtained by a polyimide-coated fiber Bragg grating sensor and the results obtained by thermocouple is 2.5%. The maximum relative difference of strain between the results obtained by a polyimide-coated fiber Bragg grating sensor and the results obtained by strain gauge is 0.2%. Additionally, a new signal demodulation scheme for experimental data processing has been used for improving the accuracy of monitoring results. The experimental results have good repeatability. The research results provide important references for the curing process optimization and technological process improvement of composite materials curing process.

Keywords: *polyimide-coated fiber Bragg grating, temperature, strain, composite materials, curing, real-time monitoring, demodulation.*

OCIS codes: *060.2370.*

Датчик для мониторинга процессов технологической обработки композитных материалов, использующий брэгговскую решётку в волокне с полиимидной оболочкой

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Предложен датчик для мониторинга в реальном времени процессов технологической обработки композитных материалов, использующий брэгговскую решётку в волокне с полиимидной оболочкой. Новая конструкция волоконного датчика позволяет работать при температурах

до 300 °С по сравнению с прежним достижимым значением лишь 130 °С. Возможны одновременные измерения температуры и деформаций на основе обработки данных об изменении длины волны максимального отражения решётки. Полученные результаты сравнивались с результатами прямых измерений термопарами и тензометрами, внедрёнными в испытуемый образец вблизи от оптических датчиков. Максимальные относительные отклонения результатов измерений составляли 2,5% для температуры и 0,2% — для деформаций. Предложена новая схема демодуляции сигнала, используемого в процессе обработки, повышающая точность результатов мониторинга при высокой их воспроизводимости. Результаты проведённых исследований открывают пути для оптимизации процессов технологической обработки композитных материалов.

Ключевые слова: *волоконный брэгговский датчик, полиимидная оболочка, композитные материалы, технологическая обработка, мониторинг технологических процессов, демодуляция.*

1. INTRODUCTION

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 [1–3] is affected.

Fiber Bragg Grating (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. Some monitoring methods using FBG during the curing process of composite materials have been reported.

The VARI (Vacuum Assistant Resin Infus ion) 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 [4–6]. 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.

In this paper, the PFBG (Polyimide-coated Fiber Bragg Grating) is used to monitor the VARI curing process of composite materials. 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

2.1. Fiber Bragg Grating [7]

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 relation is as follows:

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

where n_{eff} is the effective refractive index of the fundamental mode of the fiber core and Λ is the period of FBG. Equation (1) shows that when the measured parameters such as temperature or strain cause the changes of the period of FBG and effective refractive index, it will lead to the linear change of central wavelength of the FBG.

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:

$$\Delta\lambda_B = \lambda_B\left[(1-P_e)\Delta\varepsilon + (\alpha_f + \xi)\Delta T\right] = \\ = K_\varepsilon \Delta\varepsilon + K_T \Delta T, \qquad (2)$$

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 (2) that the $\Delta\lambda_B$ is sensitive to both temperature and strain.

2.2. Signal demodulation schemes

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

$$\Delta\lambda = K_\varepsilon \Delta\varepsilon + K_T \Delta T, \qquad (3)$$

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.

2.2.1. First signal demodulation scheme

The encapsulated FBG means normal ceramic encapsulated FBG. So encapsulated FBG is only sensitive to the temperature, the variation of the central wavelength can be expressed as follows:

$$\Delta\lambda = K_T \Delta T. \qquad (4)$$

The temperature and strain can be monitored simultaneously by combining unencapsulated FBG with encapsulated FBG. And the variation of the central wavelength can be expressed as follows:

$$\begin{gathered} \Delta\lambda_1 = K_{\varepsilon 1}\Delta\varepsilon + K_{T1}\Delta T, \\ \Delta\lambda_2 = K_{T2}\Delta T. \end{gathered} \qquad (5)$$

The changes of temperature and strain of the FBG can be calculated by equation (6).

$$\left.\begin{aligned} \Delta\varepsilon &= \frac{K_{T2}\Delta\lambda_1 - K_{T1}\Delta\lambda_2}{K_{T2}K_{\varepsilon 1}} \\ \Delta T &= \frac{\Delta\lambda_2}{K_{T2}} \end{aligned}\right\}. \qquad (6)$$

2.2.2. Second signal demodulation scheme

The changes of temperature and strain of the PFBG can be calculated by equation (7).

$$\left.\begin{aligned} \Delta\varepsilon &= \frac{\Delta\lambda - K_T\Delta T_1}{K_\varepsilon} \\ \Delta T &= \frac{\Delta\lambda - K_\varepsilon\Delta\varepsilon_1}{K_T} \end{aligned}\right\}, \qquad (7)$$

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 (7), 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:

$$\Delta\lambda_B' = \lambda_B\left[\alpha_f + \xi + (1-P_e)(\alpha_{\text{sub}} - \alpha_f)\right]\Delta T, \qquad (8)$$

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

3. EXPERIMENTAL CONFIGURATION AND PROCESS

3.1 . Raster embedding scheme

Prepreg of carbon fiber (T800*850) reinforcement medium modulus high strength epoxy composites is used. The size is 300×200 mm and the thickness of single layer is 0.1 mm. Ten layers are laid in the same direction. Seven positions are selected on the prepreg surface as the PFBG preselection points as shown in Fig.1.

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 follows.

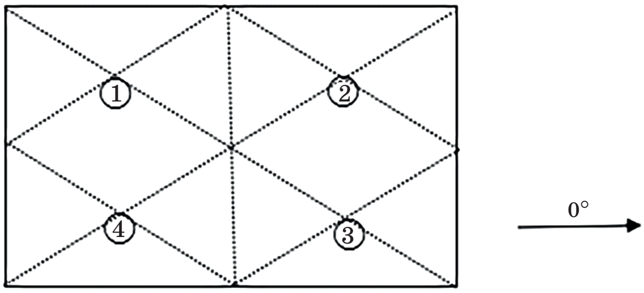


Fig. 1. Pre-embedded positions of PFBG in composite materials.

In the experiments, a high temperature resistant PFBG, a thermocouple and a strain gauge are embedded in position ②③ and 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 0 °C.

3.2 . Curing and monitoring programs

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 1 Hz and the wavelength precision is 1 pm.

4. ANALYSES OF EXPERIMENT RESULTS

4.1 . Results of temperature measurements

In the 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. 2.

The results of the experimental temperature measurements obtained from the first set of signal demodulation schemes are shown in Fig. 3a. 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.

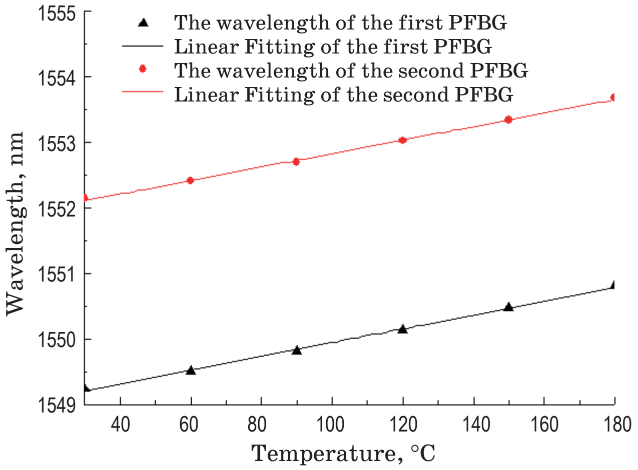


Fig. 2a. Central wavelength measurements of PFBG.

Equation	$y = a + bx$		
Adj.R-Square	0.9978	0.99802	
		Value	Standard Error
the second PFBG	Intercept	1551.80227	0.02522
the second PFBG	Slope	0.01029	2.15845E–4
the first PFBG	Intercept	1548.89273	0.02459
the first PFBG	Slope	0.01056	2.10429E–4

Fig. 2b. The parameters of the sensor fiber gratings.

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 experimental temperature measurements obtained from the second set of signal demodulation schemes are shown in Fig. 3b. Compared with the first set of signal demodulation schemes, 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 5 °C.

4.2 Results of strain measurements

The strain measurements of the experiments obtained from the first set of signal demodulation schemes are shown in Fig. 4a, b, c. The sudden drop of the strain measured by FBG is eliminated because of the use of PFBG, but the strain measured by PFBG has the opposite trend of the

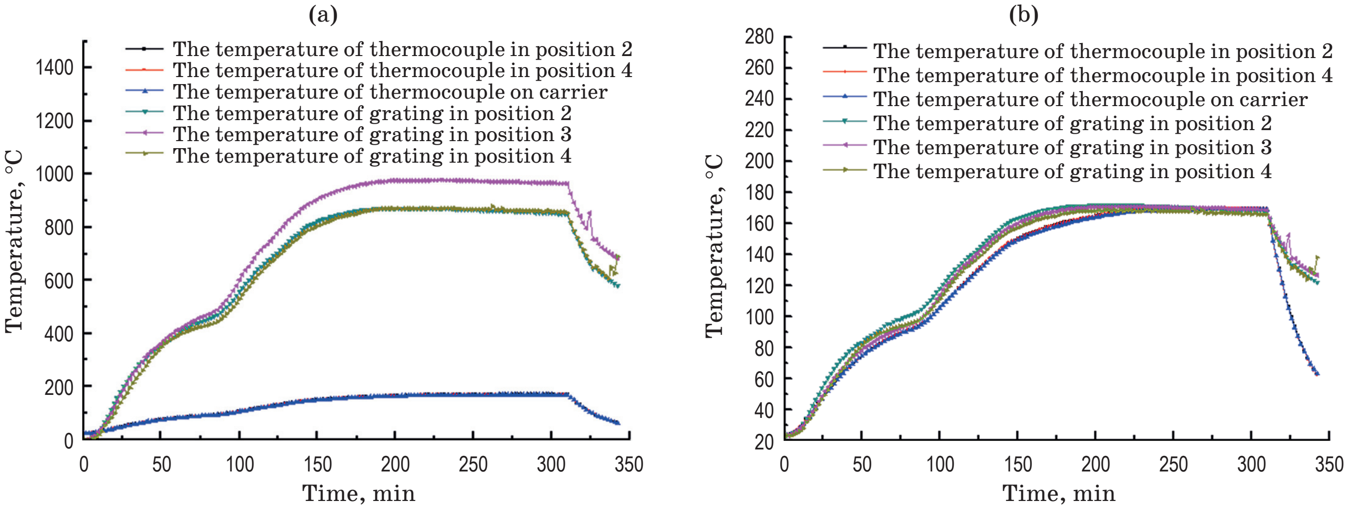


Fig. 3. The results of temperature measurements. (a) The results of the first set of signal demodulation scheme, (b) the results of the second set of signal demodulation scheme.

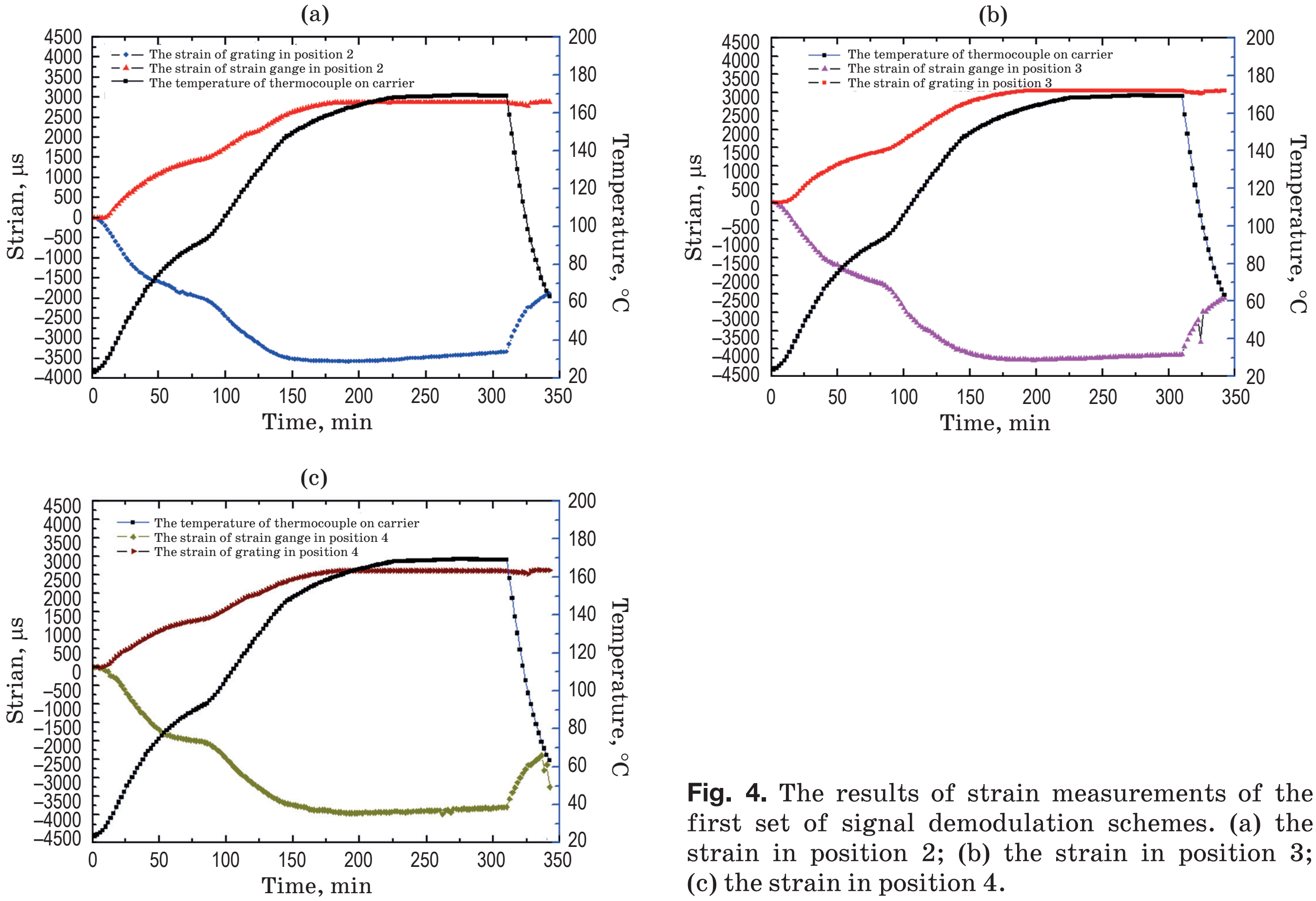
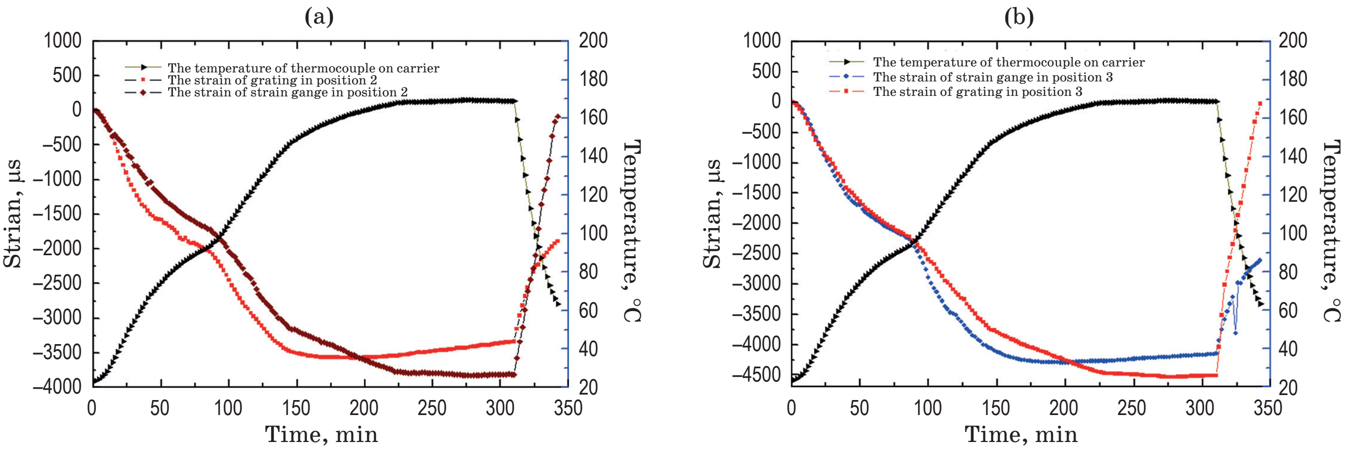


Fig. 4. The results of strain measurements of the first set of signal demodulation schemes. (a) the strain in position 2; (b) the strain in position 3; (c) the strain in position 4.

strain measured by the strain gauge. The result of measurements is quite different.

The strain measurements of the experiments obtained from the second set of signal demodulation schemes are shown in Fig. 5a, b, c. It shows that after the temperature coefficient of the PFBG is redefined, the variation trend of strain measured by PFBG has been greatly improved.



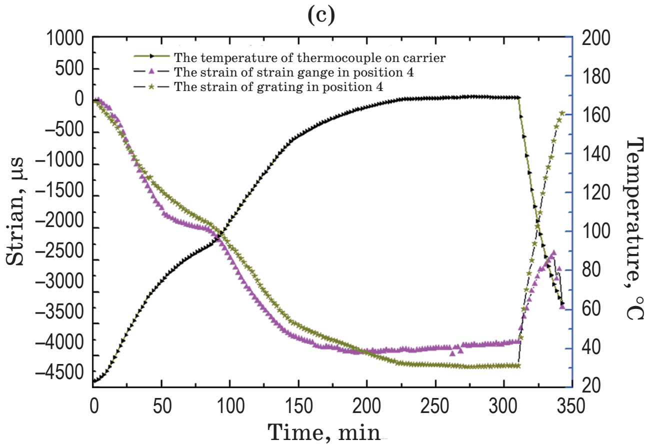


Fig. 5. The results of strain measurements of the second set of signal demodulation schemes. (a) the strain in position 2; (b) the strain in position 3; (c) the strain in position 4.

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 0.2%. 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

Whether it is common FBG or PFBG, it 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. As a result, the temperature and strain coefficient of PFBG should be redefined. The second signal demodulation scheme of the experiments is an effective model. In this paper, the high temperature resistant PFBG are used and the temperature-wavelength coefficient is redefined. The maximum relative difference of temperature between the results obtained by PFBG sensor and the results obtained by thermocouple is 2.5%. The maximum relative difference of strain between the results obtained by PFBG sensor and the results obtained by strain gauge is 0.2%. The experimental results have good repeatability.

Supported by Nonlinear Science Institute, Donghua University, and National Engineering Research Center, Shanghai Aircraft Manufacturing Co. Ltd, Open fund of Shanghai center for high performance fibers and composites.

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