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Application of Optical Fiber Sensing Technology in Internal Characteristics Monitoring and Safety Management of Cast Explosive

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Abstract

To monitor the changes in the internal structure and characteristics of the cast explosive during the molding process and storage, thereby reducing the safety risks, a system is designed to monitor the internal temperature and strains of cast explosives in real-time based on optical fiber sensing technology. First, the basic structures, sensing principles, and sensor classifications of the Fabry-Perot(F-P) sensor and the Fiber Bragg Grating(FBG) sensor are introduced and analyzed. Second, different sensors are prepared and reasonably packaged by chemical etching, discharge welding technology, and precision cutting technology. Finally, the FBG sensor suitable for explosive monitoring is selected through comparative analysis. On this basis, a reasonable and effective real-time monitoring system is constructed, the strain/temperature monitoring experiments are carried out during the internal molding and storage process of the cast explosive, and the temperature and strain regularities during the molding and storage process of the cast explosive are analyzed. The results show that in the low-temperature stage, there is a certain linear relationship between the strain of the cast explosive and the temperature, which also proves the feasibility and reliability of the optical fiber sensor for the measurement of the internal structure and characteristics of the cast explosive. The discovery has important reference value for the application of optical fiber sensing technology in real-time monitoring of the internal characteristics and safety management of cast explosives.

Keywords: *optical fiber sensing technology; cast explosive; temperature/strain monitoring; optical fiber Fabry-Perotsensor; Fiber Bragg Grating sensor;*

1. Introduction

At present, the cast explosive is widely used in the military, and the casting technology of explosives is the most commonly used forming method, both of which are widely applied in various countries' military and national defense fields. In general, casting explosives are obtained by mixing gelatinous adhesives, curing agents, and other materials into the explosives [1].Due to the process of heating curing or vulcanization molding, the resulting explosive strength is extremely high, so that it can be applied to many charges on a large scale. In recent years, military weapon technology has continued to be advanced and perfected. Therefore, relevant ammunition charging technology is supposed to be constantly updated and developed in variety and quality as well. Under this circumstance, the research on charging technology with higher accuracy and the higher level becomes the top priority, and the requirements for the structural design of the charging technology and the ammunition quality have also been greatly improved [2].

In addition, themolding process of explosives is the result of many complex physical quantities. Many related issues are involved in the procedure such as thermodynamics and multiphase flow. Therefore, various factors may lead to the destruction of its structure. Specifically, there are the following aspects: first, if the explosive internal state of matter changes, it will affect the internal structure of the cast explosive to a large extent; second, if the stability of the materials used during casting is not high, problems such as inclusions, pores and delamination will appear at the end, which will affect the structure and usage of the explosive; third, during storage or transportation, due to the appearance of aging, moisture and corrosion of the ammunition, the structure of the explosive will also be affected, resulting in damages such as cracks and bubbles inside [3].These internal defects, on the one hand, reduce the explosive energy and mechanical function of explosives, resulting in the reduction of the ability to destroy in battle; on the other hand, these structural damages will bring huge safety hazards, which are extremely dangerous in the process of storage and transportation of explosives.

To improve the performance of cast explosives as much as possible and reduce the safety risks and hidden dangers, it is necessary to monitor the changes in the internal characteristics of cast explosives effectively, grasp the real-time dynamics of its internal structure, and make corresponding safety management. Therefore, the goals are achieved based on optical fiber sensing technology. First, the sensoris prepared and tested. Then, the strain and temperature during the internal molding and storage process of the cast explosive are monitored in real-time, and the temperature and strain regularities during the storage process are analyzed. So, explosive performance and safety management can be strengthened and improved. In summary, the research has certain reference value for the stability of explosive characteristics and quality safety management in national defense security and military science and technology.

2. Methods

2.1 Introduction of the basic principles of optical fiber sensors

(1) Introduction of the optical fiber Fabry-Perot(F-P) sensor

The schematic diagram of the optical fiber Fabry-Perot sensor is shown in Figure 1.

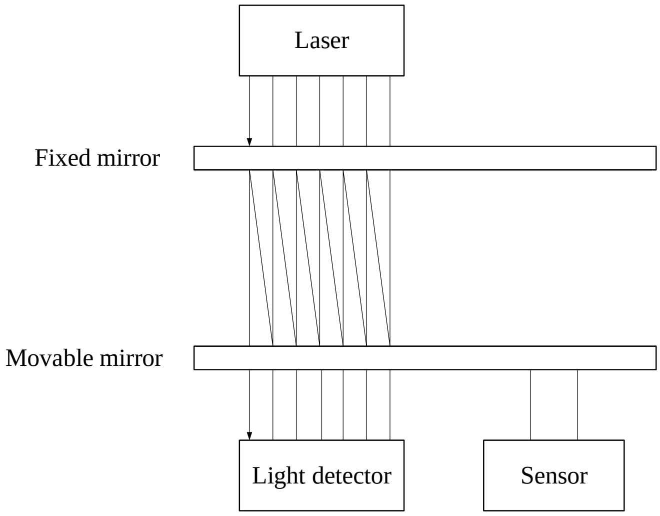

FIG. 1 Schematic diagram of F-P interferometer

Figure 1 shows that the F-Psensor cavity is composed of two plates, one is fixed and the other is movable. Reflective films are respectively coated on the surfaces of the two plates to form two mirrors, following the parallel law in optics [4].The light beam is emitted from the laser and enters the F-P cavity; then it will reflect several times between the two plates, which is optical resonance. Also, a part of the light transmits from the reflector will be absorbed by the photodetector. Each transmission ratio of the light beam is relatively constant.

If the half-wave loss is not considered, the optical path difference between two adjacent beams of transmitted light will be:

$$\Delta L = 2nd\cos\theta \quad (1)$$

In (1), n refers to the refractive index between the two mirrors; d refers to the distance between them, and θ represents the reflection angle between the light and the mirror. The phase difference between two adjacent beams can be expressed by equation (2).

$$\varphi = \frac{4\pi}{\lambda} nd\cos\theta \quad (2)$$

In (2), λ represents the wavelength of the incident light. But in general, if the light beam enters the sparser medium from the denser medium, its reflection does not have half-wave loss, nor does its transmitted light[5]. However, if light enters a denser medium from a sparse medium, the half-wave loss will occur. At this time, the optical path difference between two adjacent beams can be expressed by equation (3).

$$\Delta L' = \Delta L \pm \frac{\lambda}{2} \quad (3)$$

It can be seen that in two mirrors, the phase difference between two adjacent rays can be expressed by equation (4) or equation (5).

$$\varphi = \frac{4\pi}{\lambda} nd\cos\theta \text{ (without considering half-wave loss)} \quad (4)$$

$$\varphi = \frac{4\pi}{\lambda} nd\cos\theta \pm \pi \text{ (considering half-wave loss)} \quad (5)$$

In the F-P interferometer, each light beam is superimposed, and the output intensity of the reflected light and transmitted light are expressed as follows:

The reflected output light intensity I_r is shown in equation (6).

$$I_r = \frac{F\sin^2\frac{\varphi}{2}}{1+F\sin^2\frac{\varphi}{2}} I_i \quad (6)$$

The transmitted output light intensity $I_t$is shown in equation (7).

$$I_t = \frac{I_i}{1+F\sin^2\frac{\varphi}{2}} \quad (7)$$

The equation (8) can be obtained by simplification.

$$F = \frac{4R}{(1-R)^2} \quad (8)$$

In (8), I_i represents the intensity of incident light, R refers to the reflectivity of the two mirrors, and F refers to the accuracy of the instrument.

When R is 4%, 20%, and 40%, the relationship between I_r and phase difference φ is shown in Figure 2.

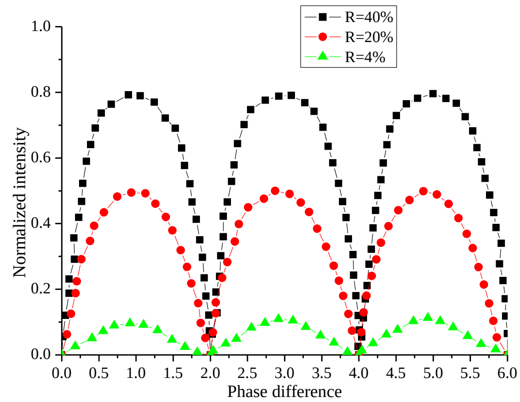

FIG. 2 Relationship between the intensity of reflected light and phase in the F-P cavity

I_t and φ are complementary to the above figure, and the extreme value and period of I_r and I_t only depend on the phase difference φ. When φ=2kπ,I_r takes the minimum value; when φ=(2k+1)π, I_r takes the maximum value. Among the equation, k is an integer.

In the Extrinsic Fabry-Perot Interferometer (EFPI) sensor, R between the quartz glass surface and the air interface is about 4%, so the F-P interferometer has excellent low-resolution. There are the following relationships:

$$(1-R)^2 \approx 1 \quad (9)$$

$$\left(1+4R\sin^2\frac{\varphi}{2}\right)^{-1} \approx 1-4R\sin^2\frac{\varphi}{2} = 1-2R(1-\cos\varphi) \quad (10)$$

Therefore, it can be concluded that:

$$I_t = \left[1-2R(1-\cos\varphi)\right] I_i \quad (11)$$

$$I_r = 2RI_i(1-\cos\varphi) \quad (12)$$

In (12), I_r presents a cosine change trend with the change of phase difference. When both R and F are relatively low, only two or more low-intensity reflections can occur in EFPI, which has almost no influence on interference. Therefore, in this sensor, the interference phenomenon of the reflected beam is called "double beam interference" [6].

When the light enters the air cavity vertically (θ=0, n=1), the reflected light intensity can be expressed by equation (13).

$$I_r = 2RI_i\left[1-\cos\left(\frac{4\pi h}{\lambda}\right)\right] \quad (13)$$

In (13), h represents the distance between two mirrors in the F-P cavity. The interference fringe contrast can be expressed by equation (14).

$$\gamma = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (14)$$

In (14), I_{max} refers to the maximum value of the output light intensity, and I_{min} refers to the minimum value.

Among the optical fiber F-P sensors, the F-P cavity is used to detect changes in the external environment. The F-P cavity includes an air cavity and an interference cavity. The F-P cavity will change with the change of the external environment. On this basis, the phase difference will be changed, and the intensity of the interference light will also change, thereby completing the sensing task.

Therefore, the sensing is realized by monitoring the change of the F-P reflected light intensity generally, and only one optical fiber is used in this sensing, which has a very high interference contrast.

(2) Introduction of fiber grating sensors

Diffraction gratings are used to form mirrors that can reflect specific wavelengths. By changing the refractive index of the core, the diffraction gratings can be written into the cores, prepared into fiber gratings, and coupled with the fiber systems. According to the differences in the characteristics of the grating, they can be divided into three categories, as shown in Table 1.

Table 1 Fiber gratings classified by period and uniformity

Grating names	Long-period grating(LPG)	Short period grating(SPG)	Chirped grating
Periods(μm)	>100	0.5-1.6	nonconstant
characteristics	Transmissive band stop filter	Narrow band filter	Electronic Dispersion Compensation (EDC)

The Fiber Bragg grating (FBG) sensor is selected [7]. The center wavelength of the sensor will change as the external environment changes, therefore FBG sensor can modulate the wavelength, and its characteristics areas follows: (1)strong anti-interference ability. Its conductive fiber cannot interfere with the frequency of light, and itcan also avoid the interference caused by various light intensity fluctuations; (2) the simple and small structured probe which has a wide range of applications; (3) the measurement results with good repeatability and reliability; (4) various forms of sensor networks; (5) absolute measurement of external parameters; (6) convenience of large-scale output.

The change of the external environment causes changes in the period of the Bragg grating and its refractive index, which changes its reflection spectrum and transmission spectrum. Therefore, the relevant external information can be directly observed from its spectral changes. The sensing principle of fiber grating is shown in Figure 3.

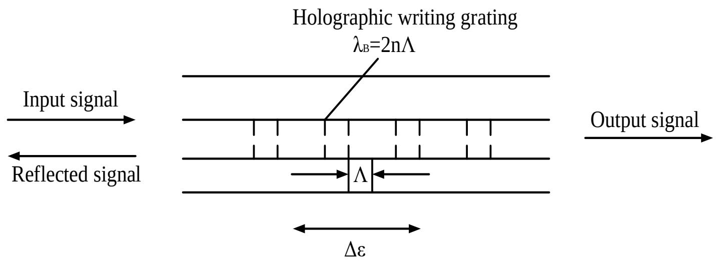

FIG. 3 Schematic of FBG sensing

Assuming that the broad-spectrum light with a center wavelength of λ enters the grating, the reflected monochromatic light is λ_B.

$$\lambda_B = 2n_{eff}\Lambda \quad (15)$$

In (15), λ_B refers to the center wavelength of the reflected light; Λ represents the grating period. Differentiate the above equation to get equation (16).

$$\Delta\lambda_B = 2n_{eff}\Delta\Lambda + 2\Delta n_{eff}\Lambda \quad (16)$$

In (16), n_{eff} represents the refractive index of the core ;the displacement of λ_B is related to n_{eff} and Λ;n_{eff} and Λ are related to temperature and strain. Therefore, when the center wavelength produces a displacement of $\Delta\lambda_B$, the measured parameter can be observed by the fluctuation of the grating reflection spectrum.

2.2 Preparation and packaging of optical fiber sensors

(1) Preparation of optical fiber F-P sensor.

For a comprehensive and systematic experiment, the following two fiber optic F-P sensors with different structures are prepared.

(a) Optical fiber F-P sensor based on the microcellular structure.

The fiber material selected for the preparation of this type of sensor is SiO_2. The outer diameter and the inner diameter of the single-mode optical fiber are120μmand 7μm. Moreover, the multi-mode fiber has an outer diameter of 120μm and an inner diameter of 100μm.

This type of sensor is small in size and thin in the bubble wall. It can be damaged easily due to changes in material properties or operational errors during experiments. Therefore, it is necessary to take appropriate measures to encapsulate it. To retain its performance, the polydimethylsiloxane (PDMS)is used, which is a glue, a mixed liquid silicone that will form a transparent elastomer evenly attaches to the sensor surface after curing to protect the sensors well [8].

(b) Optical fiber F-P sensor based on the axisymmetric structure.

This type of sensor is made of single-mode fiber and glass tube fiber. It is an axisymmetric structure with a smooth reflection surface, whose cavity length is between 50-70μm. Besides, the minimum displacement of the cavity length can be manually changed to 3μm. Its two reflecting surfaces are parallel, and its cavity is filled by air.

The sensor is obtained on an adjustable fiber cutting platform with extremely high accuracy. It has short cavity length, sensitive strain capability, and great freedom in terms of the spectral range.

(2) Packaging of optical fiber FBG sensor.

The sensor is obtained by writing a single-mode fiber into a grating. The fiber is quite slim and much easier to be broken after writing the grating. If the bare grating is directly used in the monitoring experiment, the grating will be destroyed and the center wavelength will also be affected [9]. To obtain effective experimental data, the temperature sensor and strain sensor must be packaged separately.

The temperature sensor employs a ceramic tube with an outer diameter of 2.0mm and a length of 65mm. The bare fiber is put into it, and the gap between the two is filled with proportioning PDMS glue to fix the fiber. The reason for choosing the ceramic tube as the protective shell is that its heat transfer effect is small and it is not easy to be interfered with by the heat of other parts. Therefore, the temperature measured by the grating is the real temperature, and the measurement effect is more accurate.

The strain sensor uses a capillary steel tube with an inner diameter of 2.0m, an outer diameter of 3.0mm, and a length of 90mm. It is sleeved on the grating, and the gaps are filled with PDMS proportioning glue to fix the grating and avoid the influence of airflow. The reason why the capillary steel pipe is selected is that it is more sensitive to stress changes and the measurement results are more accurate.

Through the comparison of different encapsulated sensors and the verification of the calibration experiment, the analysis shows that the FBG sensor has a better linear fit after encapsulation, which makes it more suitable for the monitoring experiment of explosive casting.

3. Results and discussion

3.1 Experimental results and discussion of the explosive casting process

The metal tank of the cast explosive is put into a constant temperature oven at 66°C. This temperature is very suitable for curing the cast explosive [10]. The monitoring can be divided into two steps: one is to monitor the curing process of the explosive, and the other is to monitor the low temperature (-20°C) storage process after curing.

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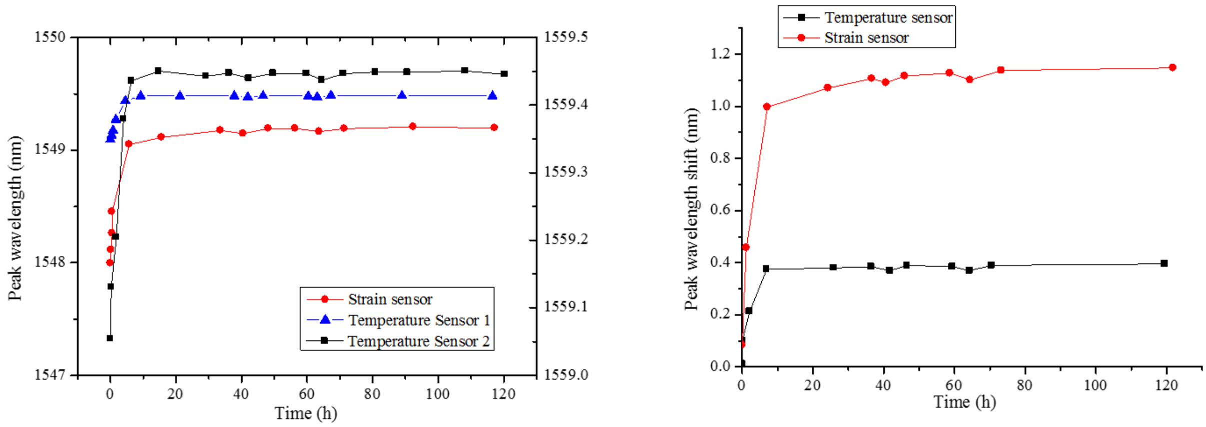
To monitor the changes in the internal characteristics of explosives at the same time, two temperature sensors and one strain sensor are used to monitor temperature and strain, respectively. Among them, the two temperature sensors can mutually verify the feasibility of the experiment.

To obtain accurate data results, the demodulator records once every second, and the obtained data is stored in the designated folder. The data results are compared through Origin, Matlab, etc., and the relevant graphs are created.

Figure 4 (a) shows the raw data of the temperature and strain changes of the cast explosive embedded with the grating sensor from entering the constant temperature oven to the later stage of slow curing. When the temperature rises, the cast explosive gradually solidifies. Figure 4(b) shows the law of spectral peak off set over time. During the curing process of the explosive, the spectral peaks of all three sensors show an increasing trend, and the variation range is between 0-1.2nm.At this stage, the strain sensor is subject to the dual interference caused by temperature and strain, so it changes greatly; mean while, the temperature sensor has only one interference factor of temperature, and its change is very small. Moreover, two grooves appear while temperature and strain are in the range of about 40-70 hours; then, they become stable again. The reason is that the solidification inside the explosive is not uniform, resulting in the subtle changes in the sensor.



(a) (b)

FIG. 4 The original data of the solidification process of the cast explosive

Figure 5(a) analyzes the relationship between time and the internal temperature of the cast explosive calculated by using two temperature sensors. After the proportioned explosive is put into a 66°C oven, the internal temperature increases slowly until it is uniform with the temperature in the oven. During the curing process, the shape of the explosive is gelatinous, and the thermal diffusion rate of this form is slightly faster. So, after about 7 hours, the temperature inside the explosive can be the same as the temperature of the oven.Also, during this process, the internal structure temperature of the explosive experiences a rise from 25°C to 66°C, and the change range is between 0-41°C. The data fluctuations sensed by the two temperature sensors are coincident, which also proves the authenticity and credibility of the experiment from the other perspective. Figure 5(b) analyzes the relationship between the internal strain of the cast explosive monitored by the strain sensor over time. The changing trend shows that this explosive also produces a corresponding stress change during the curing process. Before the temperature inside the explosive reaches 66°C, its internal stress undergoes a change from 0-700με, which indicates the initial stage of solidification. Also, the fluctuation of its internal stress is so obvious that it only takes about 10 hours for such a huge change. Once the temperature inside the explosive rises to 66°C, the stress fluctuation becomes very slow. It takes nearly 30 hours to change from 700με to 800με. After about 75 hours, it almost stabilizes and no longer changes. According to the observation results, when the temperature inside the explosive is in the rising stage, its stress fluctuation is significant; when the temperature does not change anymore, the stress fluctuation is gradually gentle, and finally, tends to be stable. Therefore, there is a certain relationship between strain and temperature. This discovery provides a reference for the optimization and improvement of the explosive casting process and the control of risk factors. Through the study of temperature and stress changes, the degree of solidification of cast explosives can be judged.

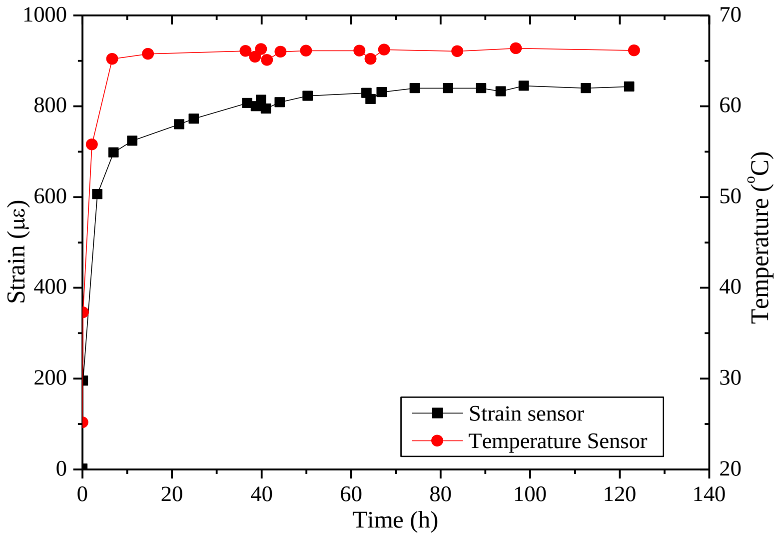


FIG. 5 Changes in internal temperature and strain of cast explosive

3.2 Experimental results and discussion of the explosive storage process

In general, after the explosives are produced and prepared, they will not be put into use immediately. If it is not in the time of the war, the explosives will be stored for a long time. It is the same for the cast explosives. After the projectile is injected into the explosives, the explosives are supposed to be stored when they are not in use. In the long-term storage process, explosives may face problems like invalidation or quality and safety. Moreover, in serious cases, safety risks may also occur. Therefore, this is an important problem, and distinguishing the change of the states of the cast explosives during the storage process becomes a top priority in research [11]. At this time, the strain situation is analyzed by changing the internal temperature of the explosive, and the relationship between the internal temperature and strain of the explosive is explored, which can provide a method for judging whether the explosive is ineffective [12].

The specific experimental method is similar to the explosive curing process, but the difference is that the cast explosive metal tank with a built-in optical fiber temperature sensor and strain sensor is placed in a refrigerator with a temperature of -20°C. By monitoring the temperature and strain of the explosive in the storage state, the state change of the explosive is analyzed. Figure 6(a) illustratesthat during the temperature decrease of the cast explosive, the grating spectrum peaks of the temperature sensor and the strain sensor have a blue shift trend, which is the opposite of the curing process. In Figure 6(b), the blue shift amplitude of the strain sensor is greater than that of the temperature sensor, indicating that the internal strain is shrinking during the cooling process.

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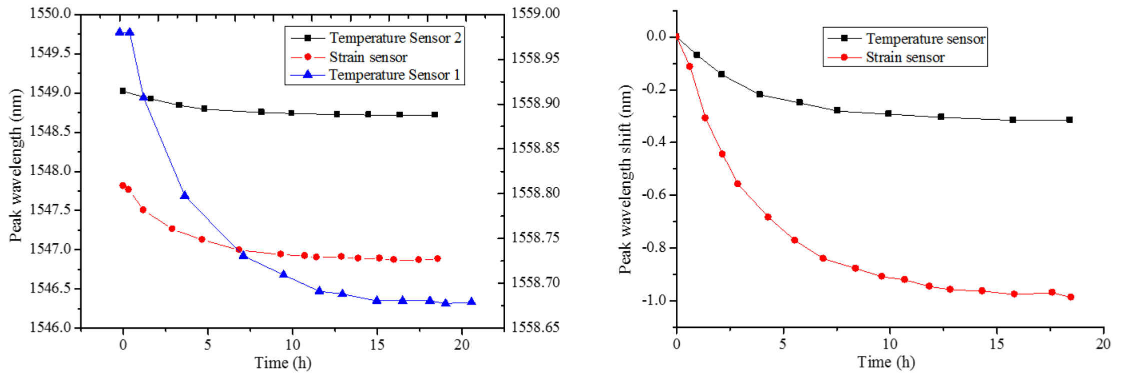

（a） （b）

FIG. 6 Raw data graph of FBG sensor experiment under storage environment

Figure 7 shows the internal temperature change trend of two temperature sensors during the storage state of the cast explosive. Their temperature changes are highly consistent, which indirectly verifies the correctness of the experiment. When the temperature decreases from 25°C to -20°C, the internal strain of the explosive decreases from -400με to approximately -850με. In 0-8 hours, the temperature and strain decline rapidly; after 8 hours, the decreasing speed of the two slows down and gradually stabilizes. When the temperature changes drastically, the strain changes drastically as well, indicating that temperature change plays an important role in the internal strain change of the explosive and also proving that maintaining a constant temperature environment plays an important role in the storage of explosives.

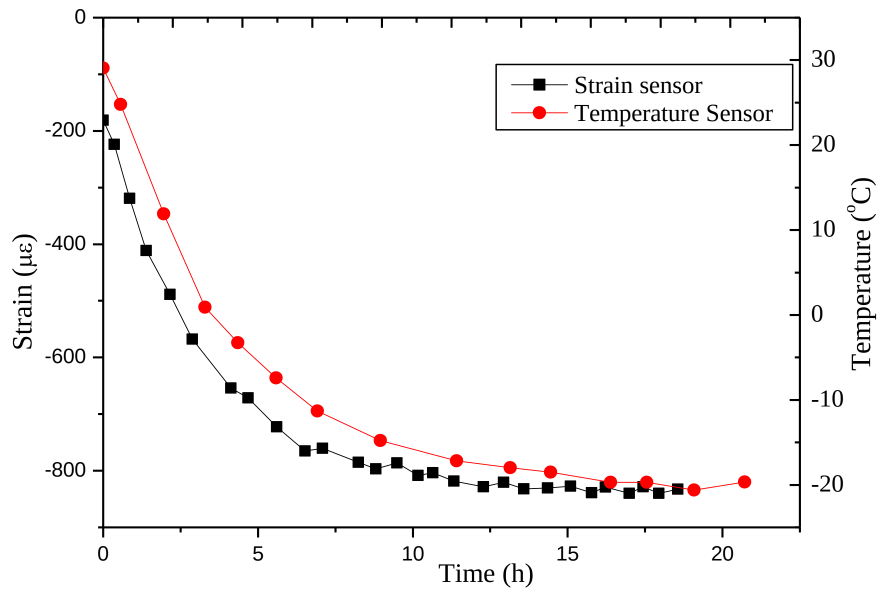

FIG. 7 Changes of internal strain and temperature of cast explosive with time during a low-temperature experiment

Figure 8 calculates the variation curve of internal strain with the temperature of cast explosives in the storage state. The two follow a very regular linear proportional relationship, whose slope is 8.88201με/°C. It should be informed that there is a certain correlation between the specific strain/temperature linear relationship and the specific cast explosive ratio. But in certain ratio, the linear relationship of this function is relatively clear. Therefore, for cast explosives stored for a long time,

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the performance changes and failures of the explosives can be judged by detecting the curvature of the strain change within the range of temperature fluctuations. More importantly, the fiber grating sensor has good working stability, and its performance can remain stable for decades, so it is very suitable for long-term storage of cast explosive performance testing.

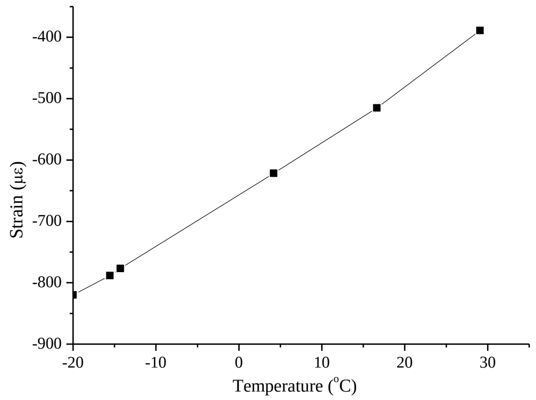

FIG. 8 Changes of the internal strain of cast explosive with temperature during the low-temperature experiment

The experimental results provide a scientific and effective method for monitoring the change of the characteristics of the explosive casting process, analyzing the long-term stability, and monitoring the failure of the explosive.

4. Conclusion

As China attaches great importance to the cause of national defense, issues such as explosive molding technology, explosive quality, and safety have taken up a more and more important position. During the molding process of explosives, changes in temperature and stress have a great impact on their quality and characteristics; during the storage process, the changes will also seriously threaten the quality and safety of explosives. Therefore, real-time monitoring of changes in the internal characteristics of explosives is essential. Given the inflammable and explosive characteristics of cast explosives, the advantages of optical fiber sensors reemployed to construct an internal temperature/strain monitoring test system for cast explosives. Compared with other sensors, the optical fiber sensor is small in size, high in sensitivity, resistant to electromagnetic interference, and harmless to the explosive structure during monitoring. Then, based on the physical characteristics of the cast explosive, a real-time temperature and stress monitoring system for the solidification and storage of the cast explosive with the FBG sensor is designed, and Matlab and Origin software are used to process and analyze the stress and temperature changes in the simulation and the explosive casting experiment. The linear law between the temperature and stress of the cast explosive is obtained.

However, due to limited time and conditions, there are many shortcomings and problems to be solved in some aspects. For example, it is necessary to study the preparation technology of FP sensors and FBG sensors to prepare sensors with specifications that can be mass-produced, which is conducive to the application and popularization of this technology in monitoring the internal characteristics of cast explosives. In addition, the encapsulation method of sensors also needs to be further studied and improved to find a reliable encapsulation method to avoid damage to the sensor structure due to operational errors during packaging and experiments.

REFERENCES

[1] Leung C K Y, Wan K T, Inaudi D, et al. Optical fiber sensors for civil engineering applications. Materials and Structures, 2015, 48(4), pp. 871-906.
[2] Hong C Y, Zhang Y F, Li G W, et al. Recent progress of using Brillouin distributed fiber optic sensors for geotechnical health monitoring. Sensors and Actuators A: Physical, 2017, 258, pp. 131-145.
[3] Seshadri D R, Li R T, Voos J E, et al. Wearable sensors for monitoring the internal and external workload of the athlete. NPJ digital medicine, 2019, 2(1), pp. 1-18.
[4] Zhu H H, Shi B, Zhang C C. FBG-based monitoring of geohazards: current status and trends. Sensors, 2017, 17(3), pp. 452.

July - August 2020
ISSN: 0193-4120 Page No. 4397 - 4406

[5] Wang X, Wolfbe is O S. Fiber-optic chemical sensors and biosensors (2013–2015). Analytical chemistry, 2016, 88(1), pp. 203-227.
[6] Xu Y, Wu X, Guo X, et al. The boom in 3D-printed sensor technology. Sensors, 2017, 17(5), pp. 1166.
[7] Gandhi M S, Chu S, Senthilnathan K, et al. Recent advances in plasmonic sensor-based fiber optic probes for biological applications. Applied Sciences, 2019, 9(5), pp. 949.
[8] Taheri S. A review on five key sensors for monitoring of concrete structures. Construction and Building Materials, 2019, 204, pp. 492-509.
[9] Pawar D, Kale S N. A review on nanomaterial-modified optical fiber sensors for gases, vapors and ions. Microchimica Acta, 2019, 186(4), pp. 253.
[10] Sun X, Wang Y, Lei Y. Fluorescence based explosive detection: from mechanisms to sensory materials. Chemical Society Reviews, 2015, 44(22), pp. 8019-8061.
[11] Lu Y, Biswas M C, Guo Z, et al. Recent developments in bio-monitoring via advanced polymer nanocomposite-based wearable strain sensors. Biosensors and bioelectronics, 2019, 123, pp. 167-177.
[12] Tao Z, Zheng X, Zhu C, et al. Framework and Application of a Big Data Monitoring System for Mining with a Pillar-Free Self-Forming Roadway. Applied Sciences, 2019, 9(10), pp. 2111.