Experimental study on cement sheath integrity based on fiber Bragg grating technology

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Abstract. Fiber Bragg grating (FBG) sensing technology is a new structure monitoring technology. Aiming at the influence of hydration and cyclic casing pressure on cement sheath integrity in real wellbore conditions, firstly, the temperature and strain variation regularities of cement sheath in setting stage are investigated by FBG and a test device for evaluating cement sheath integrity. Then the circumferential strains of cement sheath and casing under cyclic casing pressure are studied. Furthermore, the applicability of FBG technology is verified. The results show that the temperature and strain of cement slurry change rapidly in 5 hours after pouring. In cyclic casing pressure stage, circumferential strains of cement sheath and casing are both tensile strains. In addition, circumferential strain of cement sheath and casing increases with the increase of casing pressure. The FBG sensors have high sensitivity that can reflect the change of casing pressure in time. The FBG technology is a scientific temperature and strain monitoring method for cement sheath. The results of this study are of great significance to the application of FBG technology for cement sheath integrity.

Keywords. Cement sheath integrity, Fiber Bragg grating, Casing-cement sheath-formation system, Temperature monitoring, Circumferential strain

1. Introduction

The cement sheath integrity is directly related to the quality of well cementing. Annulus between casing and formation is completely filled with cement sheath, cement sheath is mainly to prevent the fluids out of formation in completion and production stages and to support the casing (Vralstad et al., 2019). However, cement sheath integrity is facing more severe challenges, because stress state and working condition of cement sheath are getting more complex and worse in the development of new energy and deep formations resources. The failure modes of cement sheath integrity mainly include the following two forms (Goodwin and Crook, 1992; Saint-Marc, 2008): one is the tensile or shear failure of cement sheath. The other is the generation of microannulus at the first interface (casing-cement sheath) or the second interface (cement sheath-formation). Generally, volume shrinkage of cement caused by hydration during setting stage, the changing internal pressure of casing in hydraulic fracturing, in addition, high temperature in deep part of wells will make contribution to these failures (Bois et al., 2011; Lura and Jensen, 2003). The real stress-strain state of cement sheath is the key
connecting the failures and reasons, however, due to complexity of practical conditions, it is difficult to obtain. This problem restricts further development of research to some extent.

In view of this, studies and experiments were conducted by some scholars to investigate cement sheath integrity. In research of numerical model calculation, Lian et al. (2020) established a casing-cement sheath-formation analytical model based on the formation mechanical parameters to calculate cement sheath stress under cyclic casing pressure, and failure modes of cement sheath were also studied. Liu et al. (2018) developed an analytical model in which the influence of stress state of cement sheath at completion stage was considered, results showed that fluid pressure in casing was the main reason for failure of cement sheath integrity. The cement sheath integrity during different stages was studied by Hu et al. (2019), and failure modes of cement sheath in each stage were also analyzed. In research of experiments and tests, Jackson and Murphey (1993) conducted an experiment to study integrity of cement sheath under different casing pressure, generation and development of microannulus were reflected by degree of gas channeling. Zeng et al. (2019) designed a test device for evaluating integrity of cement sheath. Then, failure mechanism of cement sheath under cyclic casing pressure was studied by comparing experiment results with numerical model results. The radial displacement of casing under cyclic casing pressure was measured by Li et al. (2010). These researches and studies mentioned above were mainly focused on numerical analysis of cement sheath integrity, and strain measurement was only limited to the casing. The strains of cement sheath in real conditions were not obtained. Therefore, it is necessary to find a method that can solve this problem.

In this paper, FBG technology (Nascimento et al., 2020; Lindner et al., 2021; and Konstantaki et al., 2021) is used to obtain temperature and strain of cement sheath and casing in different conditions, circumferential strains of cement sheath and casing under cyclic casing pressure are discussed. Finally, the applicability of FBG technology is verified.

2. Materials and Methods
2.1. Principle of the FBG sensor

FBG is made by photosensitivity of fiber, the refractive index of germanium-doped fiber is changed by a periodically changing ultraviolet laser source, gratings with uniform distribution are formed in the fiber. The grating can reflect the incident light with a certain wavelength, but the other wavelengths will be not. Then, the reflected spectrum will show a peak at center wavelength (\(\lambda_B\)), the center wavelength \(\lambda_B\) is determined as (Rao, 1997):

\[
\lambda_B = 2n_{\text{eff}}\Lambda
\]

(1)

Where \(\lambda_B\) is center wavelength, \(n_{\text{eff}}\) is effective refractive index, and \(\Lambda\) is grating period.

According to elastic mechanics, the effects of strain and temperature for the variation of central wavelength are expressed as:

\[
\Delta\lambda_B = 2n_{\text{eff}}\Lambda \left\{ \left[ 1 - \left( \frac{n_{\text{eff}}}{2} \right)^2 \right] \left[ P_{12} - \mu(P_{11} + P_{12}) \right] \Delta\varepsilon + (\alpha_s + \xi_s)\Delta T \right\} = \lambda_B (P\Delta\varepsilon + K\Delta T)
\]

(2)

Where \(P_{11}\) and \(P_{12}\) are elastooptic Coefficients, \(\mu\) is Poisson's ratio, \(\Delta\varepsilon\) is variation of axial strain, \(\alpha_s\) is coefficient of thermal expansion, \(\xi_s\) is thermo-optic coefficient, \(\Delta T\) is variation of temperature, \(P\) is coefficient of strain sensitivity, and \(K\) is coefficient of temperature sensitivity.

According to Equation (2), the variation of central wavelength of FBG is linear with the variation of strain and temperature. In practical application, the strain and temperature of test sample can be obtained by measuring the center wavelength.

2.2. Materials

The material used in this experiment is class G cement, water-to-cement ratio of cement slurry is 0.44, and density of cement slurry is 1.92 g/cm³.

2.3. Monitoring test for cement sheath

A test device for evaluating cement sheath integrity (test device for short) is used to investigate temperature and strain of cement sheath in setting stage and under cyclic casing pressure, as shown in
Fig. 1. (a) Test device for evaluating integrity of cement sheath and (b) profile of casing-cement sheath-formation system

Table 1. Geometrical properties of casing-cement sheath-formation system

|                | Inner casing | cement sheath | Outer casing |
|----------------|--------------|---------------|--------------|
|                | Inner diameter | Outer diameter | Inner diameter | Outer diameter | Inner diameter | Outer diameter |
| D/mm           | 125.4        | 139.7         | 139.7        | 163.7         | 163.7         | 263.7         |
| L/mm           | 1000         | 1000          | 1100         |

Fig. 2. Layout of FBG sensors in the annulus

The process of monitoring test are as follows. The cement slurry is poured into the annulus and make sure that the FBG sensors are completely immersed. Cement slurry in the annulus is cured at 48
℃ for 72 hours. Then, the cyclic casing pressure test is started, the pressure varied from 5 to 10 MPa, and the number of cycles is 20. The temperature and strain of cement sheath during these stages are captured by computer.

2.4. Monitoring test for outer casing

The strain of outer casing can reflect the stress-strain state of casing-cement sheath-formation system under high cyclic casing pressure, the monitoring test for outer casing is also conducted. The FBG sensor is installed on the outer wall of outer casing in the circumferential direction with glue and tape, the distribution of sensor on the outer casing is shown in Fig.3. The glue has the best bonding effect after 24 hours, then the cyclic casing pressure is loaded, the pressure in this test varied from 5 to 50 MPa, and the circulation times are 5. The circumferential strain of outer casing is also captured by computer.

3. Results and Discussion

3.1. Temperature and strain of cement sheath

(1) Sitting stage

Fig.4 illustrates the temperature and circumferential strain of cement sheath during the setting stage. The circumferential strain of cement sheath in the setting stage is tensile strain, which is the result of thermal expansion of the inner casing and outer casing and the strain of cement slurry in hydration process. Besides, for the first 5 hours after pouring, the temperature and circumferential strain increase rapidly, and then remain stable. The peak value of circumferential strain is about 400με.

(2) Loading stage

The circumferential strain curve of cement sheath under low cyclic casing pressure varied from 6 to 10 MPa are shown in Fig.5. It can be found that the circumferential strain of cement sheath is tensile strain, and the circumferential strain increases with the increase of internal casing pressure, the peak value of circumferential strain is about 38με. Besides, the circumferential strain is reduced to 0 when the casing pressure is completely unloaded, that means the circumferential strain under low cyclic casing pressure is elastic strain. Moreover, the trend of circumferential strain curve is consistent with the casing pressure curve, the FBG sensor has high sensitivity that can reflect the change of measured physical quantity in time.

3.2. Circumferential strain of outer casing

The circumferential strain curve of outer casing under cyclic casing pressure varied from 6 to 50 MPa are shown in Fig.6. It can be found that the circumferential strain of cement sheath is tensile strain, and the circumferential strain increases with the increase of internal casing pressure, the peak
value of circumferential strain is about 120με. The trend of circumferential strain curve is also in a good agreement with casing pressure curve.

Fig.4. The temperature and circumferential strain curves of cement sheath in the setting stage

Fig.5. The circumferential strain curves of cement sheath under cyclic casing pressure
4. Conclusions

In this paper, the temperature and strain of casing-cement sheath-formation system in setting stage and cyclic casing pressure are obtained based on the FBG sensing technology. The main conclusions are as follows:

In setting stage, the temperature and strain of cement sheath increases rapidly after pouring, reaching a peak value at 5 hours, and then remain stable. The circumferential strain of cement sheath in test device is tensile strain and the maximum value of circumferential strain is $400 \mu e$.

The circumferential strains of the cement sheath and outer casing under cyclic casing pressure are both tensile strains and increase with the increase of casing pressure. The FBG sensor has high sensitivity that can reflect the change of casing pressure in time, the correctness of FBG sensing technology is verified. This study can provide a reference basis for the study of cement sheath integrity in setting stage and under cyclic casing pressure.

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