Failure Analysis on Fiber Reinforced Thermoplastic Pipe

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Abstract. In recent years, fiber reinforced thermoplastic pipe (FRTP) has been widely used in oil fields of China due to its excellent corrosion resistance and coiling performance. With the further expansion of application scope, some failure accidents have occurred. Based on the inspection of the wall thickness, chemical composition and physical properties of a failed FRTP in the western oilfield of China, the causes are systematically analyzed. The results show that the main cause of the sample fracture is the decrease of the strength of FRTP due to the oil and gas media constantly penetrate into the lining and reinforced layer during the long-term service. Moreover, it is found that the outer sheath is worn and penetrated to the reinforced layer which further reduces the bearing pressure performance of FRTP and finally causes the fracture failure.

Keywords: FRTP, cracking, lining, reinforced layer, outer sheath, failure analysis.

1. Introduction

As oil and gas exploration deepens, corrosion and scaling of steel pipe have been common problems which lead to a series of adverse effects, such as shutdown or decrease yield, loss and waste of oil and gas resources, serious pollution of the ecological environment, rising costs of maintenance and pollution control, and life threatening caused by H2S leakage, etc[1-3]. Therefore, FRTP has become one of the important solutions to solve the corrosion problem of gathering pipe due to its high pressure resistance, corrosion resistance, light weight, good flexibility and coiling transportation performance[4-5]. It is a three-layer structure of composite pipe in which the fiber is tightly wound around the outer wall of the plastic liner, and the plastic outer sheath is mounted on the outer wall of the fiber layer. The lining pipe is used for anti-corrosion, the reinforced layer is used for bearing the internal pressure, and the outer sheath is used to protect the fiber from wearing. Moreover, FRTP has become the fastest increase in the consumption of non-metallic pipe under the advocacy of “vigorously enhance the exploration and development and benefit construction requirements in the next few years” in china[6-7].

In the end of 2018, the leakage of a buried FRTP occurred in western oilfield of china after 8 years and 2 months service. Fig. 1 shows the on-site photo of failed FRTP after excavation and the basic information as shown in Table1. The leakage point is located at 9 o’clock of the pipe body, about 400mm away from the end of the steel casing which used to protect FRTP during crossing the highway.
Table 1. Information of FRTP.

| length | specifications | design temperature | operating temperature | design pressure | operating pressure | medium | production standard |
|--------|----------------|---------------------|------------------------|-----------------|-------------------|--------|---------------------|
| 0.8km  | DN80           | 60 °C               | 60 °C                  | 2.5MPa          | 1.5 MPa           | oil and gas | SY/T 6662.2 2012[8] |

2. Experimental Analysis

2.1. Macroscopic Fracture Detection

Fig. 2 presents the macroscopic morphology photo of the perforation of FRTP sample which is a typical three-layer structure flexible composite pipe, namely the outer sheath, reinforced layer and lining. Outward opening cracking of three-layer structure indicates obvious plastic deformation. Fig. 3 presents the macroscopic morphology photo of the outer sheath of FRTP sample. The outer sheath has undergone significant deformation and fracture (Fig. 3a), and the fracture direction is mainly along the fiber winding direction (Fig. 3b). On the yellow circle as shown in Fig. 3a exists clearly traces of wear and concave deformation (red box in Fig. 3c) where the wall thickness becomes thinning, and the fracture edge is flat which is different from other fracture edges with obvious plastic deformation. Meanwhile, there is a small hole, a length of about 8 mm triangular hole and a "extrusion edge" which should be formed after repeated extrusion (yellow circle in Fig. 3c). And no abnormality is observed on the dorsal surface of the fracture.

Fig. 4 is the macroscopic morphology photo of the reinforced layer which is composed of two layers of winding. It is observed that the fiber has become dark brown and hard tactile feeling.
Figure 4. The macroscopic morphology photo of the reinforced layer.

Fig. 5 shows the macroscopic morphology photos of the lining which the outer wall is smooth and the direction of the fracture is at a certain angle with the longitudinal direction of the pipe body. The length of the fracture is about 250mm, and the maximum opening width is about 50mm. There is a defect at the edge of the fracture (yellow box in Fig. 5b) which is also located under the triangular hole in the outer sheath (Fig. 5c). After the lining was cut longitudinally along the fracture (Fig. 6d), it can be seen that the inner wall is smooth, but the color is black and brown which is different from the color of the outer wall.

Figure 5. The macroscopic morphology photo of the lining.

2.2. Wall Thickness Measurement

Fig. 6 shows the location map of wall thickness measurement at the edge of the fracture with a vernier caliper (accuracy 0.02mm). Table 2 shows the obtained results, which the ‘g’ and ‘f’ point is the smallest (2.70mm and 2.72mm). It is observed that the wall thickness gradually increases along this two points to both ends.

Table 2 shows the thickness measurement results in four directions along the annulus of the two ends of the sample which are 6.58–6.80mm, indicating that the wall thickness of pipe body is relatively uniform.

Figure 6. The location map of wall thickness measurement (mm).

Table 2. The thickness measurement results at the fracture (mm).

| location | a  | b  | c  | d  | e  | f  | g  | h  | i  | j  |
|----------|----|----|----|----|----|----|----|----|----|----|
| thickness| 6.48 | 5.52 | 5.68 | 5.00 | 5.30 | 2.72 | 2.70 | 5.98 | 6.12 | 6.50 |
Table 3. The thickness measurement results of the two ends of the sample (mm).

| location | 3 o’clock | 6 o’clock | 9 o’clock | 12 o’clock |
|----------|-----------|-----------|-----------|------------|
| left end | 6.68      | 6.70      | 6.58      | 6.76       |
| right end| 6.80      | 6.76      | 6.78      | 6.68       |

2.3. **Infrared Spectroscopic Analysis**

A sample of 10mm×10mm×t (t represents wall thickness) was manually sawn down the lining layer and a small bundle of reinforcement layer fibers was selected which were analyzed by Fourier transform infrared spectrometer. Fig. 7 illustrates the obtained results, which the similarity between the infrared spectrum of the tested lining and the standard spectrum of polyethylene (PE) is 97.8%, the similarity between the infrared spectrum of the tested reinforced layer and the standard spectrum of polyester is 95.32%. It is indicated that the lining is PE and the reinforced layer is polyester.

![Infrared spectroscopic analysis results.](image)

2.4. **Vicat Softening Temperature Testing**

Three samples of 20mm×20mm×t were manually sawn down the lining layer to test vicat softening temperature by RV-300FW vicat softening temperature testing machine according to the standard of GB/T 1633-2000 of B50 method (50N, 50℃/h) [9]. Table 4 shows the obtained results, which the vicat softening temperature of lining is 62.23℃, greater than the operating temperature.

Table 4. Vicat softening temperature test results.

| Sample | Initial temperature (℃) | Vicat softening temperature(℃) | Average of vicat softening temperature (℃) |
|--------|--------------------------|-------------------------------|--------------------------------------------|
| 1#     | indoor temperature       | 61.77                         |                                            |
| 2#     | indoor temperature       | 62.74                         |                                            |
| 3#     | indoor temperature       | 62.18                         |                                            |

2.5. **Hardness Testing**

Six samples (20mm×20mm×t) were taken from the lining layer by hand sawing, and hardness tests were carried out on the inner wall and the outer wall respectively by TIME5410 Shore durometer according to GB/T 2411-2008[10]. Table 5 shows the obtained results. It is observed that the hardness of the outer wall is greater than that of the inner wall.

Table 5. Hardness test results.

| Sample | Hardness (HD) | Average of hardness (HD) |
|--------|---------------|--------------------------|
| Inner wall |               |                          |
| 1#    | 44.0          |                          |
| 2#    | 46.8          |                          |
| 3#    | 49.4          |                          |
| Outer wall |            |                          |
| 4#    | 52.2          |                          |
| 5#    | 53.8          |                          |
| 6#    | 56.7          |                          |

2.6. **Density Testing**

Three 1g~2g flake samples were taken from the lining layer for density measurement by ET-120SL electronic densitometer according to GB/T 1033.1-2008 of liquid pyknometer method[11]. Table 6
Table 6. Density test results.

| Sample | Density (g/cm$^3$) | Average of density (g/cm$^3$) |
|--------|-------------------|-----------------------------|
| 1\textsuperscript{o} | 0.942 |                  |
| 2\textsuperscript{o} | 0.948 | 0.945          |
| 3\textsuperscript{o} | 0.945 |                  |
| SY/T 6662.2-2012 | ≥0.930 |               |

3. Discussion
In order to analyze and find the cause of FRTP failure, the following analysis will be made from three aspects: lining, reinforced layer and outer sheath.

3.1 Lining Analysis
Under the long-term operation of FRTP (8 years and 2 months), the oil and gas medium keeps spreading to the lining matrix. The macro inspection also found that the color from the outer wall to the inner wall is getting darker and darker (Fig. 8), which will lead to significant swelling of the lining and decrease its pressure bearing capacity and heat resistance [12]. Further hardness test results show that the hardness of the inner wall is less than that of the outer wall, which verifies that the strength of the lining has decreased. Once the fiber layer is loosened or fractured locally, it will crack at this point of the lining.

3.2 Reinforced Layer Analysis
The reinforced layer has turned dark brown in color and has a hard touch, indicating that oil and gas media has penetrated into the reinforcement layer. Generally, the polyester fiber is usually white and soft (Fig. 9a), it is composed of linear macromolecules of partial crystallization of polymer. With the infiltration of oil and gas media, the interaction between the macromolecules of the fibers is weakened, so that the distance between molecules increases, the pore increases, and the fiber tensile strength will decline[13-14]. In addition, when the reinforced layer fibers at the fracture are bent by hand, partial fracture occurs (Fig. 9b), further indicating that the bearing pressure performance of the reinforced layer fibers decreases. As fiber reinforced layer is the most important pressure bearing part of FRTP, once its strength decreases, the pipe will burst when the internal pressure cannot be carried.

3.3 Outer Sheath Analysis
Because of inserting into the steel casing pipe, outer sheath has two holes along with the severe wear marks and compression marks in that it is easy to cause scratches and wear in the process of
construction installation and operation vibration. Since the fracture at the wear place is flat and the other parts of the fracture show typical plastic deformation characteristics of PE material, it can be judged that the fracture at the wear place is the most original. Furthermore, when the outer sheath is worn out and the reinforced layer is broken, the bearing capacity of FRPT will be significantly reduced.

4. Conclusions and Recommendations
(1) The lining of FRTP is PE and the reinforced layer is polyester fiber. However, the hardness of the inner and outer wall of the lining is significantly different, showing uneven distribution of hardness. In addition, obvious wear marks and defects appeared on the surface of the outer sheath.
(2) In the long-term operation of FRTP, the oil and gas medium constantly infiltrates into the lining and reinforced layer, resulting in the decrease of the strength of the reinforced layer. In addition, the outer sheath wears and penetrates into the reinforcing layer, further reducing the pressure performance of the pipe and finally causing fracture failure.
(3) It is recommended to test the permeability of lining and reinforced layer to oil, gas and water media during the procurement of FRTP, especially to evaluate whether the strength of lining and reinforced layer decreases after infiltration for a period of time. Meanwhile, the oil and gas permeability resistance of lining and reinforced layer can also be included in the relevant product standards.

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