Failure Analysis of Stainless Steel EH Tubing Used in Power Plant

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Abstract. The EH fuel pipe of stainless steel used in a power plant was cracked. The crack and leakage of stainless steel fuel pipe were detected and analyzed by alloy composition analysis, EDS, microhardness and metallographic structure. Results show that the alloy components conform to the requirements of the standard stainless steel EH fuel pipe’s microstructure is normal, but EDS results show that Cl and S ions were detected in the crack aperture. The microhardness test found that the closer the hardness value is to the crack, the lower it is. Combined with the operating environment of EH tubing, the main reason for tubing cracking is that it absorbs moisture in the air and free Cl ions in a humid working environment, forming a corrosive medium. Under the action of working pressure and residual stress, stress corrosion cracking that expands from outside to inside occurs.

1. Introduction
The fuel supply system is one of the three main body systems of steam turbines in thermal power plants [1], of which the EH oil system occupies half of the fuel supply system. Once the EH oil system fails, it will seriously affect the normal power generation and cause unnecessary economic losses. The main parts of the EH oil system include the oil supply part, the execution part, the emergency shielding part and the oil pipeline part. According to the power plant maintenance procedures, regular maintenance of the fuel supply part, the executive part and the emergency shelter system is required. The most common failure of EH oil system is the pipeline part, including flange gasket aging failure [2], welding defect failure [3], tubing rupture failure [4–7] and so on. This paper will take a power plant’s EH oil pipeline failure case as a model, analyze its failure causes, and put forward corresponding suggestions for subsequent maintenance.

A thermal power plant discovered a large amount of oil leakage in an EH tubing of unit 1\# in November 2020, which affected the production of the rolling mill. Since the start of production is imminent, in order to ensure the safety of production and operation, it is necessary to accurately identify the cause of the leakage in a relatively short period of time. So as to provide reference for the
normal use of other pipelines and avoid similar accidents.

The design material of EH tubing is 304 steel, the design specification is 20×2.5mm, the cumulative operating time is about 70,000 hours since it was put into use, the operating pressure is 14MPa, the operating temperature is 21~55℃, and the medium is steam-resistant fuel oil.

2. Experimental program
According to the macroscopic morphology, the type of EH oil pipeline cracking characteristics is judged. Determine the material composition by analyzing the alloy composition of the tube wall. Sampling of failed EH oil pipelines, after polishing, polishing, and then corroding with dilute aqua regia. The metallographic structure of the cracked tubing was analyzed by the LSM700 laser confocal microscope, and the crack development changes were judged according to the crack direction. Use the MHVS-30V microhardness tester to measure the hardness of the sample after the metallographic observation, and obtain the hardness change data. Direct sampling, ultrasonic vibration and drying, the chemical composition of the oxide in the crack is obtained by energy spectrum analysis (EDS).

3. Experimental research

3.1 Macroscopic morphology analysis
The macro morphology of the EH tubing sample is shown in Figure 1. The box in the figure is an enlarged view of the partial area of the back arc of the elbow. There are obvious macro cracks at the side arc of the elbow, and there are small branches of varying degrees near the main crack. The entire crack is intermittent, and the longest crack length is about 30mm. In addition to cracks, there are slight scratches and wear marks on the outer surface of the EH tubing, and the outer wall of the pipe has different degrees of pitting corrosion, especially the corrosion area on the back arc side is gradually continuous, as shown in the circle in Figure 1.

![Figure 1. Macroscopic morphology of EH fuel pipe](image)

3.2 Alloy composition analysis
The alloy composition analysis is carried out on the wall of the EH tubing sample tube, the implementation standard: DL/T991-2006, the instrument model: NitonXL2 alloy analyzer.

The results of alloy composition analysis are shown in Table 1. Table 1 also lists the standard values of 06Cr19Ni10 (304) steel in GB/T 20878-2007. The alloy composition of the EH tubing sample meets the requirements of the 06Cr19Ni10 (304) steel standard.

| Sample name       | Chemical elements (mass fraction) (%) |
|-------------------|---------------------------------------|
|                   | Mn      | Cr   | Ni     |
| EH tubing sample  | 1.490   | 18.213 | 8.110  |
| 06Cr19Ni10 (304)  | ≤2.00   | 18.00~20.00 | 8.00~11.00 |

3.3 Microhardness test
Using MHVS-30V microhardness tester, the microhardness test is carried out from the vicinity of the crack to the distance away from the crack. The test parameters are: load 200 g, load time 10 s, the
The indenter type is square pyramid diamond, and the measurement data are shown in Table 2. The data in Table 2 shows that the closer to the crack position, the smaller the hardness value. The hardness value of the base material of EH tubing away from cracks is 225 HV, which meets the requirements of DL/T 438-2016 "Metal Technical Supervision Regulations for Thermal Power Plants".

| Sample position | Distance (mm) | Hardness value (HB) |
|-----------------|---------------|---------------------|
| crack           | 0.25          | 183                 |
|                 | 0.50          | 186                 |
|                 | 0.75          | 193                 |
|                 | 1.00          | 219                 |
|                 | 1.25          | 226                 |
|                 | 5             | 225                 |

3.4 Metallographic inspection

Sampling is performed on the back arc of the elbow with cracks. After grinding and polishing the sample, it is corroded with dilute aqua regia. Observe the cross-section of EH tubing with a laser confocal microscope. Figure 2 is the metallographic morphology of the cross section of the tubing, and Figure 2 (a) is the metallographic morphology of the entire cross section. The entire crack macroscopically develops inward from the vertical pipe wall, and the total length of the crack is about 2.1mm, accounting for about 84% of the entire wall thickness. The crack is formed from the outer wall and gradually expands to the inner wall. Figure 2(b) and Figure 2(c) are partial enlarged views of the crack middle position and the crack tip position respectively. The figures show that there are many small cracks around the main crack, which are distributed in a dendritic manner, especially near the crack tip. No obvious corrosion and oxidation products are seen in the cracks in Figure 2. The metallographic phase of the matrix far from the crack position is austenite, the structure is uniform, and there is no obvious carbide precipitation on the grain boundaries [5-7].

Figure 3 is the metallographic structure of the box in Figure 2 (c) after being partially magnified 200 times, which is uniform austenite. There are two types of cracks: transgranular cracks and intergranular cracks. No obvious precipitates and aging phenomena are seen on the grain boundaries.

| Element | C   | O   | P   | S   | Cl  | Cr  | Fe  | Ni  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Atlas 5 | 12.57 | 41.12 | 0.16 | 0.36 | 8.73 | 22.91 | 12.91 | 1.24 |
| Atlas 7 | 11.34 | 19.66 | 0.43 | /   | 1.93 | 14.81 | 47.62 | 4.21 |

Table 2. Microhardness Value Near the Crack Edg

Table 3. EDS Testing Results, WT.%

Figure 2. The cross section metallographic morphology of EH fuel pipe

Figure 3. Metallographic structure near crack tip of EH fuel pipe
3.5 Energy spectrum analysis

In order to more accurately understand the content and change trend of corrosion products in EH tubing, the middle position of the crack and the position near the crack tip are respectively selected for energy spectrum analysis. The corresponding detection positions are shown in Figure 4 and Figure 5. Figures 4 and 5 are the positions of the energy spectrum analysis results corresponding to the positions of the spectrogram 5 and the spectrogram 7. The specific numerical results of the energy spectrum analysis are shown in Table 3. It can be seen from the results of energy spectrum analysis that the presence of chloride ions can be detected in both cracks, and 0.36 Wt.% of sulfur is detected at the position of the spectrogram 5, and the content of Cl and O are both high. It is worth noting that chloride ion is the sensitive element that induces intergranular corrosion of austenitic stainless steel [8,9].

![Figure 4. Distribution of taking points in the middle of the crack](image1)

![Figure 5. Distribution of taking points of the crack tip](image2)

4. Reason analysis and suggestions

The EH test results show that the composition of the tubing alloy meets the standard requirements, the metallographic structure of the matrix is austenite, and there are no obvious precipitates at the grain boundaries. A comprehensive macroscopic display of the distribution of pitting pits on the outside of EH tubing, the appearance of tree-rooted multi-branch cracks, and the detection of Cl and S elements by the energy spectrum, this feature belongs to stress corrosion cracking [5].

There are three specific conditions for stress corrosion cracking of metals: 1) the sensitivity of the metal material itself to SCC; 2) the specific organizational environment (including corrosive media, concentration, and temperature); 3) the tensile force that causes stress corrosion cracking.

a) In the energy spectrum analysis of the corrosion products inside the crack, there are halogen elements such as Cl and S in the crack. Austenitic stainless steel is very sensitive to halide elements. In addition to chlorine and halogen elements, oxygen must also be present to produce stress corrosion [10]. The oxygen content in the position of Figure 5 is as high as 41.12 Wt.%, which is confirmed by the higher content of oxygen detected in the cracks.

b) The external environment of the EH oil pipes submitted for inspection is relatively closed, and the operating temperature is higher than room temperature. When the oil pipes have a little leakage, it is easy to form a relatively humid environment. In addition to a small amount of water in EH oil, there will also be a very small amount of impurity ions, such as Cl [11]. When a humid environment is formed, corrosion pits (pitting pits) are first formed on the surface of the tubing. As the running time increases, the corrosion pits will gradually absorb moisture in the air and free Cl and S elements to form local Cl and S solutions [12]. According to the energy spectrum analysis, the mass fraction of Cl ions near the outer wall crack No. 5 position is up to 8.73%, and the content of sulfide ions is 0.36%. The mass fraction of Cl ion at No. 7 position is as high as 1.93%, and there is no sulfide ion. This result shows that the Cl content in the early cracks is significantly higher than the Cl ion content near the crack tip. Cl and S elements have concentrated and accumulated at the crack tip (or the bottom of
the pitting pit), and the accumulation of time makes the environment at the crack tip (or the bottom of the pitting pit) meet the medium conditions of stress corrosion.

c) The cracks are mainly distributed in the back arc position of the elbow, indicating that there is residual stress in the forming process at the back arc position [13,14]. The tensile stress on the outer wall of the pipe will be caused by the working internal pressure of the oil pipe.

In summary, the cause of EH tubing cracks is due to the long-term humid working environment. Pitting corrosion pits are formed first, and then corrosive media are formed, resulting in stress corrosion cracking that expands from the outside to the inside.

The microhardness shows that the closer to the crack, the lower the hardness value of EH tubing. The content of C and Cr detected in the crack is higher than the normal structure, indicating that C-Cr compounds are precipitated at the crack [9]. The common carbide in austenitic stainless steel is Cr23C6 [7,9]. The precipitation of carbides along the grain boundaries leads to a decrease in the Cr concentration in adjacent grains, breaking the original balance between the grain boundaries and the grains, resulting in insufficient chromium content in the grains and reducing the corrosion resistance of the material. Such reciprocation will cause a network of intergranular corrosion at the grain boundaries under the action of stress corrosion, that is, the formation of small root-like cracks around the main crack.

The following recommended measures for stress corrosion of EH tubing:

a) A leak in the EH oil system should be repaired as soon as possible.

b) Keep the operating environment of the oil pipeline clean and ventilated to avoid the formation of a humid environment.

c) Regular non-destructive testing of EH oil pipelines, inspection of pipeline welding positions and stress concentration positions, to prevent pipeline cracking and other defects.

5. Conclusions
The reason for the leakage of EH oil stainless steel pipe is that the working environment of this section of pipeline is humid. Under the action of bending residual stress and working internal stress, it absorbs moisture and Cl ions in the air to form a corrosive medium. The stress corrosion cracking that spreads from the outside to the inside is produced, which eventually leads to the cracking of the stainless steel EH tubing.

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