Cause analysis of cracking and leakage of T91 steel tube in hydraulic test of Supercritical Boiler

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Abstract. When the 660MW supercritical boiler installed water pressure test, the last stage superheater T91 pipe of #1 boiler cracked and leaked. Chemical composition analysis, mechanical property test at room temperature, metallographic structure observation, SEM analysis and energy spectrum analysis were carried out for the failed steel pipe. The results show that the main reason for the cracking and leakage of the final stage superheater is that the inner wall of the steel tube has longitudinal linear defects in the process of hot rolling and cold drawing, and the stress concentration is formed at the defect tip. During the hydraulic test, the defect tip opens to form cracks and expands to open cracks, resulting in the leakage of the final stage superheater.

1. Introduction
During the installation stage of a supercritical 660MW unit in Inner Mongolia, the boiler hydraulic test was carried out. When the pressure rose to 15.8mpa, the final superheater steel tube of #1 boiler cracked and leaked. The boiler model is SG-2141/25.5-M972, and the outlet temperature of superheated steam is 571℃. The final superheater tube that was ruptured and leaked was A213-T91.

2. Physical and chemical analysis
In order to find out the cause of cracking and leakage of steel tube, a total of 27 sampling tubes were taken from the final superheater of #1 boiler and #2 boiler, all of which were sa213-t91 in material and 38 × 7mm in size. The #1 sampling tube is the #1 boiler hydraulic test cracked tube, whose position is from the #1 boiler right side number 7 behind the screen furnace number 4, the elevation of leakage position is 68m. The sampling tube of #2 ~ #11 is taken from the first screen to the eighth screen, the 15th screen and the 20th screen on the right side of the final superheater of #1 boiler; the sampling tube of #12 ~ #23 is taken from the first screen to the 12th screen on the right side of the final superheater of #2 boiler; the sampling tube of #24 ~ #27 is taken from the boiler plant with the final superheater in the same batch of T91 spare parts tube.

Both boilers are in the construction period and have not been put into operation, and the selected sample tubes have not been affected by high-temperature operation.

2.1. macroscopic appearance
No obvious mechanical damage is found on the outer wall of No.1 sampling pipe, and there is a
longitudinal straight crack with small opening. According to the cross section, the crack has penetrated along the direction of pipe wall thickness, as shown in Figure 1. No mechanical damage was found in the macroscopic inspection of #2 ~ #27 sampling tube. There were no transverse and longitudinal defects in the inner and outer walls and port sections.

Penetrant inspection of the inner wall and cross section of #2 ~ #9 sampling tube and #12 ~ #27 port and no crack exceed the standard defect display. Through the penetration test of the inner wall of the #10 sampling tube and the #11 sampling tube port, it is found that there are many straight linear defects along the axial direction, and the length is about 40mm. The results of #10 sampling tube port inner wall are shown in Figure 2.

![FIG.1 Photos of macro morphology of cracking](image1)

![FIG.2 Linear defect display of #10](image2)

### 2.2. chemical composition test

The chemical composition of 27 sampling tubes was detected by SPECTROLAB type direct reading spark source atomic emission spectrometer. The data of some sampling tubes are shown in Table 1. The results show that the content of each element in the chemical composition of the sampling tube meets the requirements of the standard.

### 2.3. mechanical property test

The mechanical properties of #1, #10, #12 and #27 sampling tubes were tested at room temperature, flattening ductility test and flaring test by using CMT5305 electronic universal testing machine and Tukon2500-6 Wilson type microhardness tester. The results show that the yield strength, tensile strength and Vickers hardness of the four tubes all meet the requirements of relevant standards.

In the flattening ductility test of four sampling pipes, the longitudinal cracks are clearly visible at 12 o'clock (top) or 6 o'clock (bottom), and the length of the cracks is 60mm, as shown in Figure 3. After the expansion test of four sampling pipes, longitudinal cracks appeared on the inner wall, as shown in Figure 4.

### Table 1. Chemical composition test results of some sampling tubes

| Detection elements | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  | V   | Nb  |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| ASTMA213/A213M-2010| 0.08| 0.20| 0.30| ≤0.020| ≤0.010| 8.00| ≤0.40| 0.85| 0.18| 0.06|
| Measurement of #1 | 0.10| 0.29| 0.40| 0.012| 0.005| 8.47| 0.07| 0.92| 0.23| 0.07|
| Measurement of #10| 0.09| 0.26| 0.43| 0.010| 0.002| 8.51| 0.07| 0.90| 0.19| 0.071|
| Measurement of #11| 0.08| 0.25| 0.43| 0.009| 0.003| 8.51| 0.05| 0.95| 0.18| 0.068|
2.4. inspection and analysis of microstructure

The microstructure of the #1 sample tube is equal tempered martensite with uniform distribution. It is not abnormal, as shown in Figure 5. The crack has penetrated the pipe wall thickness, and there is oxide inside the crack, as shown in Fig.6. There are several linear defects with parallel distribution and crack like shape on the inner wall of the pipe, as shown in Figure 7.

No linear defects were found in the inner wall of #24, #26 spare sample tube and #2 boiler #20 sampling tube. There are longitudinal linear defects with different length on the inner wall of the remaining 24 sampling pipes, the defect rate is 88.9%, and the depth statistics of the linear defect wall thickness direction is shown in Table 2. The linear thickness of the inner wall of the #10 sampling tube is 0.228mm in thickness direction. As shown in Fig.8, the linear defect wall thickness direction of the #11 sampling tube is 0.256mm, as shown in Figure 9.
2.5. *Micro area morphology and composition analysis*

Using Hitachi scanning electron microscope S3700, the linear defects in the inner wall of the #1 sampling tube shown in Fig.7 are analyzed by scanning electron microscope. It is evident that the oxide cracks in the inner wall linear defects are clearly visible, as shown in Figure 10. Using the Bruker energy spectrometer xflash detector 510 to carry out the energy spectrum analysis on the oxide, the results show that the main components are Fe and O elements, that is, the high-temperature oxidation products, rather than inclusions, as shown in Figure 11, which shows that the defects on the inner wall of the tube are formed during the hot processing in the manufacturing stage.

**Table 2. Statistics of linear defect depth of inner wall of 27 sampling pipes**

| Linear defect depth L/mm | $L=0$ | $L<0.01$ | $0.01 \leq L < 0.02$ | $L \geq 0.02$ |
|--------------------------|--------|-----------|----------------------|----------------|
| Number of sampling tubes | 3      | 8         | 12                   | 4              |

FIG.7 Linear and pit defect of inner wall of pipe  
FIG.8 Linear defects in the inner wall of #10  
FIG.9 Linear defects in the inner wall of #11
3. Analysis of test results
The A213-t91 pipe used in the infrastructure project is a cold drawn steel pipe manufactured by a domestic steel plant. Based on the above test results of 27 sampling pipes,

(1) There are longitudinal linear defects on the inner wall of T91 steel tube of the final superheater of two boilers, some of which are small, some of which are round, blunt and wide. The defect is formed in the manufacturing process of hot rolling and cold drawing, which is the original defect. The forming process is as follows: the working environment of the plug for hot rolling piercing of steel tube is poor, and the fatigue cracking of the hot rolling plug is caused after many times of piercing, and the surface forms pits and bulges, as shown in Figure 12. The plug with rough surface causes round and blunt pits with different depths or sharp pits on the inner wall of hot-rolled tube blank. After cold drawing deformation with mandrel and empty drawing sizing for many times, the pits are continuously elongated and evolved into grooves. The grooves are continuously deepened along the direction of wall thickness and become thin and closed, forming linear defects on the inner wall [1-4].

(2) In the flattening test of four samples, the longitudinal cracks are clearly visible, and the results are analyzed as follows: (a) the metallographic observation and comparison of the specimens before and after the flattening test show that the cracks of the flattened specimens all expand along the linear defects of the inner wall. It shows that the defect has stress concentration, and under the action of tensile stress in the process of flattening, it is prior to cracking in other parts. (b) According to the requirements of GB/T 5310 or ASTM A1016, when S/D > 0.1, the cracks or cracks on the inner surface of the sample at 6 o'clock and 12 o'clock positions shall not be used as the basis for determining the nonconformity. Flattening test is used to test the technological performance of circular section metal pipe, including the ability to resist axial cracking (caused by tensile stress) and axial cracking (caused by shear stress), and to show its internal and surface defects. In this test, the outer diameter ratio of the flattened sample wall thickness is S/D = 0.18, which can not accurately reflect the technological performance of the steel pipe, but can accurately detect the linear defects, which is another significance of the flattening test in the detection.
According to the requirements of GB/T 242 and ASTM A1016, the test results shall be judged as unqualified without the use of magnifier. The metallographic observation and comparison of the samples before and after the flaring test show that the cracks of the flaring samples all expand along the linear defects of the inner wall, which shows that the flaring test has a positive effect on the detection of the linearity of the inner wall.

In 2010, China began to pay attention to the linear defects of the straight section and the inner wall of the bend of the heating surface pipes (water wall, superheater, reheater, etc.) of the boiler components (20G, 15CrMoG, 12Cr1MoVG, T91, etc.) of the thermal power unit, caused by the scratch of the mandrel[5]-[6]. Therefore, GB/T 5310-2017 has added a new requirement for the surface quality of the inner wall of steel pipe scratched by "non sharp mandrel". According to this requirement, the maximum allowable depth of linear defects on the inner wall of Φ38×7mm cold drawn pipe is 0.2mm. Among the 27 sampling tubes, the linear defect depth of the inner wall of 4 tubes was more than 0.2mm, accounting for 14.8%. The unqualified rate of flattening and expanding test is 100%.

4. conclusion
The main reason for cracking and leakage of T91 tube water pressure test for last stage superheater of #1 boiler is that the inner wall of the steel pipe produces a longitudinal linear defect in the process of hot rolling and cold drawing, and the stress concentration is formed at the tip of the defect. During the hydraulic test, the crack tip opens to form cracks and expand cracks, leading to leakage of the last stage superheater.

In the manufacturing process of seamless cold drawn steel tube, the longitudinal distribution linear defects on the inner wall have certain damage to the life of boiler, which has the potential risk of causing tube explosion failure on the heating surface. At present, there is not an effective and feasible short-term test or theoretical simulation method to evaluate its harmfulness accurately.

Visual inspection and penetrant inspection can not find the linear defects of this type of inner wall effectively. Metallographic inspection, flattening test, flaring test and other methods should be used for detection. For the installed tube banks, due to the structural limitations, it is impossible to use a-pulse ultrasonic, ultrasonic phased array, eddy current and other conventional nondestructive testing methods to conduct 100% inspection on the tubes, so it is necessary to strengthen the nondestructive testing in the manufacturing stage.

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