Residual life evaluation of 12Cr1MoVG steel for main steam pipeline

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Abstract: 12Cr1MoVG steel is a commonly used steel for boiler main steam pipes. With the increase of service time, the material's endurance performance is deteriorating. In this paper, the performance analysis of the 12Cr1MoVG steel main steam pipe which has spheroidized and deteriorated after 70,000 hours of service in a power plant was carried out, and the residual life of this pipeline was evaluated. According to the evaluation, the residual life of the pipeline is more than 100,000 hours.

1. Introduction
The main steam pipeline is one of the main pressure-bearing components in the pressure-bearing system of the boiler in thermal power plants. Long-term service in a high temperature environment, the performance of its material directly affects the safe operation of the boiler [1-4]. The chemical compositions of 12Cr1MoVG is shown in Table 1. 12Cr1MoVG steel is a commonly used steel for the main steam pipeline of boilers. Under the long-term action of high temperature and pressure, pearlite will be spheroidized. These structural transformation processes reduce the durable strength of the material and the residual life. When a power plant conducted a safeguard inspection of pipelines within a boiler that had been in service for more than 70,000 hours, it was found that the base metal of a weld of a main steam pipeline had been severely spheroidized after metallographic analysis, with a spheroidization rating of 4.5-5, and life assessment is required according to regulations. The pipe was cut on the base material at the weld on site. Through the material performance test of the sampling samples of the on-site cutting pipe, the life state assessment of the pipe section was carried out based on the data of the field inspection and the related material performance test results.

Table 1. Chemical compositions of 12Cr1MoV.

| Material  | C(%) | S(%)  | Mn(%) | Mo(%) | Cr(%) | V(%) |
|-----------|------|-------|-------|-------|-------|------|
| 12Cr1MoV  | 0.08-0.15 | 0.17-0.37 | 0.4-0.7 | 0.25-0.35 | 0.9-1.2 | 0.15-0.30 |

2. Materials and experimental procedure
Material performance tests include metallography, room temperature tensile, high temperature tensile, and hardness.
2.1. Metallographic test results on site

The test process of metallographic inspection is as follows: cut the welded joint part of 20mm×8mm×8mm from the steel body by wire cutting. For metallography, scanning electron microscope experiments need to first polish the sample with 180-1500WC sandpaper in turn. When the scratches of the previous level of grinding are not visible, rotate the sample by 90° and change to the next level of sandpaper to polish; until the scratches are not visible to the naked eye, use 1μm diamond to polish the sample. Then use 4% nitric acid alcohol to corrode the surface of the observed sample for 10-15s, then wash it with absolute ethanol, dry it and observe its metallographic structure under a metallographic microscope.

![Metallography of base material (500x).](image)

![Metallography of welded seam (500x).](image)

![Metallography of the heat affected zone (500x).](image)

The metallographic inspection results of the main steam pipeline weld are shown in Figure 1, Figure 2, and Figure 3. According to the DL/T 773-2016 standard [5], the spheroidization rating of the
The base metal of the weld is 4.5-5, the spheroidization rating of the weld is 2.5, and the spheroidization rating of the heat-affected zone is 3.5. According to DL/T 940-2005 “Technical Guidelines for Life Assessment of Steam Pipes in Thermal Power Plants” [6], when the pearlite spheroidization in the metallographic structure of the parent material of the 12Cr1MoVG steel steam pipeline reaches level 5, the life assessment should be carried out.

2.2. Tensile performance test at room temperature

This test is carried out in accordance with Method B in GB/T 228.1-2010 “Metallic Materials Tensile Test Part 1 Room Temperature Test Method” [7]. Take a sample of the cut pipe section. The size of the sample is as follows: the diameter of the tensile parallel section is 6mm, the length is 60mm, both ends of the thread are M8, the transition arc is about R15mm, and the tensile test is carried out at room temperature 25℃. And the size is shown in Figure 4. The test results are shown in Table 2.

| Serial number | Elongation after fracture A (%) | Specified non-proportional extension strength Rp0.2 (MPa) | Tensile strength Rm (MPa) |
|---------------|---------------------------------|--------------------------------------------------------|----------------------------|
| 1#            | 24.5                            | 331                                                    | 483                        |
| 2#            | 25.5                            | 347                                                    | 494                        |

The material properties meet the mechanical property requirements of 12Cr1MoVG in GB / T 5310-2017” seamless steel tubes for high pressure boilers” [5].

2.3. Tensile performance test at high temperature

This test is based on GB/T 228.2-2015 “Metallic Material Tensile Test Part 2 High Temperature Test Method” [8]. Take a sample of the cut pipe section. The size of the sample is as follows: the diameter of the tensile parallel section is 6mm, the length is 60mm, both ends of the thread are M8, the transition arc is about R15mm, and the tensile test is carried out at room temperature 25℃. And the size is shown in Figure 4. The test results are shown in Table 3.

| Serial number | Elongation after fracture A (%) | Specified non-proportional extension strength Rp0.2 (MPa) | Tensile strength Rm (MPa) |
|---------------|---------------------------------|--------------------------------------------------------|----------------------------|
| 1#            | 53.0                            | 251                                                    | 330                        |
| 2#            | 34.5                            | 252                                                    | 320                        |
| 3#            | 30.0                            | 308                                                    | 345                        |

The material properties meet the mechanical property requirements of 12Cr1MoVG in GB / T 5310-2017” seamless steel tubes for high pressure boilers” [9].

2.4. Hardness test

The hardness test adopts the direct verification method, the material of the indenter is tungsten carbide, the diameter of the indenter is D=10000mm, and the applied load is F=29.42KN. The hardness of the cut pipe section tested in the laboratory is shown in Table 4.

| Serial number | Section                  | Brinell hardness HBW (kgf/mm2) |
|---------------|--------------------------|-------------------------------|
| 1#            | Base metal at weld       | 151                           |
| 2#            | Base metal at weld       | 152                           |
| 3#            | Base metal at weld       | 152                           |
The material properties meet the mechanical property requirements of 12Cr1MoVG in GB/T 5310-2017 “seamless steel tubes for high pressure boilers” [9].

3. Life assessment

3.1. Wall thickness strength check

The main operating parameters of the pipeline are shown in Table 5.

According to DL/T 5054-2016 “Code for Design of Steam and Water Piping in Thermal Power Plants” [10], the allowable stress of steel should be the minimum of the following three items based on the strength characteristics of the steel.

### Table 5. The main operating parameters of the pipeline.

| Section                  | Diameter (mm) | Wall thickness (mm) | Material   | Design pressure (MPa) | Design temperature (℃) | Working pressure (MPa) | Working temperature (℃) | Running time (h) |
|--------------------------|---------------|---------------------|------------|-----------------------|-------------------------|------------------------|------------------------|-------------------|
| 3# Boiler main steam pipe| 219           | 9                   | 12Cr1MoVG  | 5.3                   | 495                     | 5.3                    | 485                    | 72546             |

\[ \sigma_f = \frac{R_{t0}^0}{3}, R_{m0}^0 \] - Minimum tensile strength of steel at 20℃ (MPa);

\[ \sigma_f = \frac{R_{t0.2}^0}{1.5}, R_{p0.2}^0 \] - The minimum value of non-proportional elongation strength specified by 0.2% of the steel at the design temperature (MPa);

\[ \sigma_f = \frac{R_{t0}^0}{1.5}, R_{D}^t \] - Average value of 10^5-hour endurance strength of steel at design temperature (MPa);

According to the requirements of sampling test in GB/T 16507.4-2013 “Water Tube Boiler Part 4: Calculation of Compression Element Strength” [11], the minimum value of \( R_{m0}^0 \) and \( R_{p0.2}^0 \) obtained from the test And the average value of \( R_{D}^t \) multiplied by 0.9 as the calculated value.

According to the laboratory test results of the pipe cutting section, the minimum tensile strength at room temperature is 483 MPa; the non-proportional elongation strength specified by 0.2% at 495℃ design temperature is the minimum 320 MPa; \( R_{D}^t \) refers to GB/T 5310-2017 the value of Appendix B in “Seamless Steel Pipe for High Pressure Boiler” [9] is 184MPa. Since the material has been running for 72,546 hours, and according to the high temperature tensile properties of the material, it is assumed that the material has been damaged to a certain extent, and the damage degree is taken as 10%, namely Conservatively take 0.8 times the value in the standard.

After calculation and comparison, take the minimum of the three, \( \sigma_f = 88 \) MPa.

### Table 6. Comparison of minimum wall thickness and measured wall thickness.

| Section                  | Diameter (mm) | Wall thickness (mm) | Pressure (MPa) | Temperature (℃) | Allowable stress minimum wall thickness (MPa) | Measured minimum wall thickness (mm) | Minimum allowable wall thickness (mm) | Whether to meet the wall thickness strength check |
|--------------------------|---------------|---------------------|----------------|-----------------|-----------------------------------------------|-------------------------------------|----------------------------------------|---------------------------------------------|
| 3# Boiler main steam pipe| 219           | 9                   | 5.3            | 495             | 88                                            | 9.4                                 | 6.4                                    | Satisfy                                      |

For steam and water pipelines with \( \frac{D_1}{D_0} \leq 1.7 \) bearing internal pressure stress, the minimum wall thickness \( S_m \) of straight pipes is:

\[ S_m = \frac{P D_0}{2\sigma_f Y_p + 2Y_p} + C = 6.4 \text{mm} \] (1)

Where: \( S_m \) - Minimum wall thickness of straight pipe, mm;

\( D_0 \) - The nominal outer diameter of the pipe, the largest outer diameter including the positive deviation of the pipe diameter, mm;
Y - The correction coefficient of temperature to the formula for calculating pipe wall thickness, for ferritic steel, 0.5 at 510°C and above;

P - The pressure of the pipeline under normal operation, Mpa;

η - The pressure factor of allowable stress is 1.0 for seamless steel pipes;

C - Consider the additional thickness required for corrosion, wear and mechanical strength, and for general steam pipes, the effects of corrosion and wear may not be considered;

[σ] - Allowable stress of steel at design temperature, MPa;

The calculated minimum wall thickness of the pipe is less than the measured minimum wall thickness, and the pipe wall thickness strength is qualified, and the comparison results are shown in Table 6.

3.2. Calculation of working stress

According to DL/T 940-2005 “Technical Guidelines for Life Assessment of Steam Pipeline in Thermal Power Plants” [6], the commonly used calculation formula for the internal pressure converted stress of the straight section of the steam pipeline is:

\[
\sigma_{eq} = \frac{P[D_0 - \gamma'(S - \alpha)]}{S - \alpha} = 65.6 \text{ MPa}
\]

\(\sigma_{eq}\) - Internal pressure converted stress, MPa;

P - The pressure of the pipeline under normal operation, MPa; taking into account the fluctuation of the load during operation, the operating pressure of 1.05 times is taken.

D₀ - Outside diameter of steam pipe, mm;

S - Steam pipe wall thickness, mm, take the minimum of the nominal wall thickness and the measured wall thickness of 9 mm;

α - Consider the additional thickness of corrosion, abrasion and mechanical strength, generally 0;

Y - Temperature correction coefficient for the calculation of pipe wall thickness formula (for carbon steel, low alloy pipe and high chromium steel, Y = 0.4 at 480°C and below, Y = 0.5 at 510°C, Y = 0.7 at 538°C and above, intermediate temperature the Y value can be calculated by interpolation).

3.3. Assessment of residual life

According to DL/T 654-2009 “Technical Guidelines for Life Evaluation of Thermal Power Units” [8], life evaluation can be carried out by using isotherm extrapolation method for components with creeping into the main failure mode.

The endurance strength curve of the material \( \sigma = K(t_r)^m \) and its specific parameters are based on DL/T 654-2009 “Technical Guidelines for Life Assessment of Thermal Power Units” [12] Appendix A, calculate with reference to the data of the 12Cr1MoV main steam pipe supervision section that has been running for 90,000 hours, where \( k = 238.5 \) and \( m = -0.06918 \).

According to the durable strength curve of the material, the residual life of the main steam pipe is calculated by the following formula.

\[
\log t = \frac{\log (\sigma_{10^4} \sigma_{10^5})}{\log (\sigma_{10^4} \sigma_{10^5})} \cdot \frac{\log (\sigma_{10^4} \sigma_{10^5})}{\log (\sigma_{10^4} \sigma_{10^5})} 
\]

\(\sigma_{10^4}, \sigma_{10^5}\) - The lasting strength of 10⁴h and 10⁵h at a certain temperature;

n - Stress coefficient, when the value life line is selected, take 1.5, when the lower limit line is selected, take 1.2.

Table 7. Evaluation results of residual life of main steam pipe section of No. 3 boiler.

| Section                        | Diameter (mm) | Wall thickness (mm) | Internal converted pressure (MPa) | \(\sigma_{10^5}\) (MPa) | \(\sigma_{10^4}\) (MPa) | Residual life (10k hours) |
|-------------------------------|--------------|---------------------|----------------------------------|---------------------------|---------------------------|--------------------------|
| 3# Boiler main steam pipe     | 219          | 9                   | 65.6                             | 108                       | 126                       | >10                      |
The calculation result of the life evaluation of the main steam pipe of the 3# boiler in Table 7 shows that when the safety factor of the main steam pipe of the 3# boiler is taken as 1.5, its residual life is greater than 100,000 hours.

4. Conclusions and suggestions
Carry out life assessment based on on-site inspection results, test data of sampling materials and data recommended in relevant standards. The evaluation result based on the above data shows that when the safety factor of the main steam pipe base material is 1.5, its residual life is greater than 100,000 hours.

   Based on the evaluation results, the following suggestions are made:
   (1) During operation, the operation parameters should be strictly controlled to avoid pipeline failure caused by excessive steam superheat temperature or fluctuation.
   (2) Attention should be paid to the main steam pipeline in the next examine and repair, and the maintenance times should be increased if necessary.

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