Analysis of Cracking Causes of P91 Welding Seam of High Pressure Steam Guide Pipe of Supercritical Unit

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Abstract. A 600MW supercritical unit in a thermal power plant has been in operation for 63,000 hours, and a P91 weld leak occurred between the high-pressure steam guide pipe and the high-pressure governor valve. After macroscopic morphology analysis, alloy composition analysis, metallographic structure observation, and microhardness test analysis, it is found that the cracking of the base metal and weld on the high-pressure speed control valve is caused by structural stress and welding stress, which leads to cracking due to creep. The crack originated in the fine-grained area of the heat-affected zone, and it has been operating in a high-temperature operating environment for a long time. The P91 weld on the high-pressure steam guide tube produces creep holes in the fine-grained heat-affected zone, which gradually grow to form creep cracks, and eventually lead to cracks and leakage. Therefore, the failure of pipeline cracking is caused by the joint action of tensile stress and type IV crack.

1. Introduction

Because w(Cr)9%-12% ferritic heat-resistant steel has strong high temperature performance, good thermal conductivity, low thermal expansion coefficient, low stress corrosion sensitivity and other characteristics, it is widely used in supercritical and ultra-supercritical thermal power generating units, such as P/T91 steel, P/T92 steel, etc. This ferritic heat-resistant steel is mainly used in high-temperature superheaters, high-temperature reheaters, main steam pipes and valves in power plants. Its normal structure is tempered martensite, which includes a high density of dislocations \cite{1} and dispersion strengthening (precipitates include carbides and nitrides). However, in the process of on-site installation and repair, due to the limitation of the on-site environment, the welding interface of w(Cr) 9%-12% ferritic heat-resistant steel will generally form a coarse-grain zone, a fine-grain zone and an incomplete phase zone. Three different regional organization forms. This type of weld is prone to form type IV crack defects during long-term operation \cite{2-5}.

2. Research object

In order to facilitate the analysis and observation, the middle position of the P91 weld crack is sampled...
as sample 1#, and the crack tip position is sampled as sample 2#. The macroscopic morphology analysis, alloy composition analysis, metallographic structure observation, and microhardness test were carried out on the two groups of samples. Among them, the metallographic observation samples are inlaid, ground, polished, and corroded with hydrochloric acid and picric acid solutions. Metallographic observation and photographing are carried out under an optical metallographic microscope.

3. Experimental research

3.1 Macro analysis

Figure 1 shows the weld of the high-pressure steam guide pipe where cracks have occurred. It can be seen that the cracking location is in the heat-affected zone of the reduced diameter base metal on the side of the door body, cracking along the ring direction, and the entire length of the crack accounts for about 3/4 of a week. There is no surfacing transition between the welding seam and the variable diameter in this part, and it is in a concave state, forming a stress concentration.

Figure 1. Cracked high pressure steam pipe weld

Figure 2 is a macro photograph of a sample taken near the crack tip. When sampling, a sample was cut from the middle of the crack. Since the complete crack could not be obtained, the crack was divided into upper and lower parts as shown in Figure 2(a)(b). The crack morphology of these two parts can meet the analysis needs. The cross-sectional morphology of the sample is shown in Figure 2(c), which shows the tendency of cracks to expand from the inside to the outside. Figure 2(d) shows the fracture surface morphology of the submitted sample after the crack opens. It can be seen that the fracture has no metallic luster and is rough and granular. The surface of the fracture is covered with black oxide layer or corrosive formed after high temperature oxidation. According to the oxide color and the thickness of the oxide layer, the length of the crack cracking time can be judged. The figure shows that the crack formation time is longer.

Figure 2. Macro photo of the crack tip of the submitted sample
In the sample taken in the middle of the crack, the fracture area is almost completely destroyed, and only a small amount of area can be analyzed by metallography. After taking samples from the middle and apex of the crack, hot mounting can be initiated at the temperature of about 120°C. Then polish and etch the samples. Figure 3 shows the macro morphology of the mosaic sample after polishing and corrosion. The sample 1# in the figure is the structure near the middle of the crack. The macro corrosion picture shows that the main crack is cracked along the fine-grained area on the side of the base material. Sample 2# is the structure at the crack tip. It can be seen that the crack at the crack tip also extends along the fine-grained region on the side of the base material.

Figure 3. Macro morphology of the sample after polishing and corrosion

### 3.2 Alloy composition analysis

A handheld spectrometer was used to analyze the alloy composition of the sample base material and the weld. The measurement data are shown in Table 1.

| Sample serial number | Chemical elements (mass fraction) (%) |
|----------------------|--------------------------------------|
|                      | Cr  | Mo  | V   | Nb  |
| Base material        | 9.24| 1.01| 0.24| 0.064|
| Weld                 | 8.53| 0.97| 0.25| 0.085|
| SA335-P91            | 8.0-9.5| 0.85-1.05| 0.18-0.25| 0.06-0.10|

### 3.3 Microhardness test

The MHVS-30V microhardness tester was used to measure the hardness values of the weld near the crack tip, the heat-affected zone, and the microstructure of the base metal. The test parameters are: load 200g, load time 10s, indenter type is square pyramid diamond. The measurement data is shown in Table 2, where the hardness value in Table 2 has been converted to Brinell Hardness (HB). The position of the crack tip position of the microhardness test is shown in Figure 4. The data in Table 2 shows that whether it is the base metal side or the weld side, the closer to the crack position, the smaller the hardness value. The hardness value of the base metal side is already lower than the minimum value required in DL/T 438-2016 "Metal Technical Supervision Regulations for Thermal Power Plants".
Figure 4. The position of the crack tip position of the microhardness test

### TABLE 2. CRACK TIP MICROHARDNESS TEST RESULTS

| Sample position | Base material area | Heat affected zone | Weld zone |
|-----------------|--------------------|--------------------|-----------|
|                 | 4                  | 3                  | 2         | 1         | crack     | 1         | 2         | 3         | 4         | 5         | 6         |
| Hardness value (HB) | 184               | 179                | 176       | 169       | crack     | 180       | 206       | 223       | 227       | 231       | 235       |

3.4 Metallographic inspection

A laser confocal microscope was used to sample the crack tip position and the crack middle position for metallographic observation. Figure 5 is the matrix metallographic structure. Figure 6 shows the metallographic structure near the crack tip. Figure 7 shows the metallographic structure near the main crack.

Figure 5 shows that the base material of the submitted sample (far away from the weld) and the metallographic structure of the weld are tempered martensite, and there is no abnormality in the structure. Figure 5 (a) is the metallographic structure of the base metal of the high-pressure governor valve. Figure 5 (b) is the metallographic structure of the weld. With reference to the aging assessment of martensite structure in the DL/T884-2019 standard, the aging level of welds and base materials can be rated as level 2, mild aging.

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![Metallographic structure of the matrix](image)

(a) The metallographic structure of the base material is 500 times

(b) The metallographic structure of the base weld is 500 times

Figure 5. Metallographic structure of the matrix

Figure 6 is the metallographic structure of the sample in the middle of the crack. Figure 6(a) is the morphology near the main crack at 50 times. The figure includes the weld zone and the heat-affected zone. The base metal zone is not found. It shows that the main crack is extended along the fine-grained area of the heat-affected zone. Figure 6(b) is the morphology near the main crack at 1000 times. There
is no obvious martensite phase in the metallographic structure. The structure is composed of ferrite and precipitates, and there are more creep microcracks near the main crack. As indicated by the arrow in the picture.

Figure 7 shows the metallographic structure near the crack tip. Figure 7(a) is the morphology near the crack tip at 50 times, including the weld zone, heat-affected zone and base metal zone. The cracked crack is located in the fine-grained zone of the heat-affected zone, and the crack extends along the heat-affected zone. Figure 7(b) is the morphology of the crack tip under 500 times. There are obvious corrosion products in the crack. The crack tip is relatively round. The metallographic structure around the crack is composed of tempered martensite and a small amount of precipitates. There are also creep microcracks nearby.

4. Crack formation mechanism

(a) The alloy composition analysis shows that the alloy composition of the weld and the base metal meets the standard requirements, and the metallographic structure of the base metal and the weld are tempered martensite, with no abnormalities.

Macroscopic observation and metallographic structure show that cracks develop along the fine-grained zone of the welded heat-affected zone on the nozzle side of the governor valve. There are a large number of creep holes around the main crack [5], and these creep holes are gradually connected together to form micro cracks. The crack propagates along the creep hole into a macroscopic crack, which is a typical type IV crack.

(b) The change of creep strength in the heat-affected zone has a certain relationship with the
dissolution, precipitation, aggregation growth of the precipitate phase and the density of the fine precipitate phase. When the hardness difference between the precipitate and the matrix is large, it will be the weakest point of the material at the boundary. When the precipitate is a hard spot, its brittleness is greater than that of the matrix, the plastic deformation performance is poor, and there is inconsistency with the matrix plastic deformation performance. The existence of hard spots hinders the plastic deformation of the matrix, so grain boundary sliding or slip bands will block the “action” of the precipitates and form holes. The holes grow and connect together, forming the original crack. Under the long-term action of stress, crack propagation will occur at the boundary.

(c) According to the microhardness test, the hardness value of the fine-grained zone in the heat-affected zone on the side of the high-pressure speed control valve is significantly reduced, which is lower than the DL/T 438-2016 [7] standard requirement.

At this time, the hardness value of the fine-grained region decreases significantly faster than other regions, resulting in a "weakened zone" of creep strength in the fine-grained region. Because the expansion displacement of the cylinder and the combined main valve are not synchronized during the operation of the unit, there is a large thermal stress. Moreover, the transition between the weld and the variable diameter of the valve nozzle is not overlaid to form a concave angle, which causes stress concentration. In this way, under the action of structural stress and internal stress [7], creep pores are preferentially generated at the fine-grained area of the heat-affected zone at the weakest point, and they grow to form cracks and eventually cause cracks.

(d) Since neither the metallographic structure of the base material nor the metallographic structure of the weld has obvious aging, it can be considered that the operating temperature is not the main reason for the large precipitation of precipitates in the heat affected zone. Therefore, the period of large amounts of precipitates occurs during the welding process, which is related to the excessive heat input and the excessively high welding temperature during welding.

5. Conclusions
(1) The alloy composition of the base material and weld of the high-pressure speed control valve meets the standard requirements. The metallographic structure of the base metal of the high-pressure speed control valve body is normal, and the metallographic structure of the weld is normal.

(2) The cracks between the base metal and the weld of the high-pressure speed control valve are in the fine-grained zone of the heat-affected zone, and the cracks extend along the heat-affected zone.

(3) The main cause of cracking is that the stress concentration zone formed by poor welding forming overlaps with the heat-affected zone with weakened performance. As a result, the structural stress is relatively large, and creep holes are generated in the heat-affected zone under high-temperature operating environment. Creep cracks are formed, which eventually lead to cracking and leakage.

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References
[1] Wang Guomei, Wan Farong. Material Physics. 2nd Edition [M]. Wuhan University of Technology Press, 2015.
[2] Tabuchi M, Watanabe T, Kubo K, et al. Creep crack growth behavior in the HAZ of weldments of W containing high Cr steel[J]. International Journal of Pressure Vessels & Piping, 2001, 78(11-12):779-784.
[3] Smith D J, Walker N S, Kimmins S T. Type IV creep cavity accumulation and failure in steel welds[J]. International Journal of Pressure Vessels and Piping, 2003, 80(9): 617.
[4] Laha K, Chandravathi K S, Parameswaran P, et al. Type IV cracking susceptibility in weld joints of different grades of CrMo steel[J]. Metallurgical and Materials Transaction, 2009, 40A: 386.
[5] Tang Chunpo, Yin Shaohua, Xu Yao, et al. Cause analysis of type IV cracking in main steam pipe of ultra-supercritical unit[J]. Welding Technology, 2019, v.48;No.324(12):99-103.

[6] Fu Hua, Zhang Guanglei. Material Properties [M]. Peking University Press, 2010: 69-70.

[7] National Energy Administration. DL/T 438-2016 Metal Technology Supervision Regulations for Thermal Power Plants [S].

[8] Zhang Jianqiang, Luo Chuanhong, Zhang Yinglin. Finite element simulation of mechanical control parameters of mode IV cracks in P91 steel welded joints[J]. Transactions of the China Welding Institution, 2012, 33(3): 57-60.