

Cause Analysis of Type IV Cracking of Main Steam Pipe of Ultra Supercritical Unit

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Abstract. In order to explore the cause of cracking of the main steam pipe of an ultra-supercritical unit, A series of corresponding physical and chemical tests for crack failure pipelines. Including chemical composition analysis, room temperature tensile test, high temperature tensile test, impact test, bending test of HAZ(Heat Affected Zone)and base metal, it's also including metallographic observation and section scanning electron microscopy analysis of crack tip, overall force analysis of pipeline, etc. The results show: Failure crack has obvious characteristics of crack type IV. for example, a large number of creep holes appear in the fine-grained region of the HAZ, Creep holes accumulate, grow up, and form microcracks. In addition, the stress analysis shows that the outer arc side of the pipe is subjected to large tensile stress. In conclusion, the pipe cracking failure is caused by the combination of tensile stress and type IV crack.

1. Introduction

At present, ferritic heat-resistant steel with a mass fraction of Cr of 9%~12% is widely used in supercritical and ultra-supercritical thermal power generating units in China. Such as T/P91, T/P92, etc. The steels have high temperature strength, low thermal expansion coefficient, good thermal conductivity and low stress corrosion sensitivity, so they have been widely used [1]. This kind of steel is widely used in the process of installation and repair. Due to the influence of the welding thermal cycle, the weld heat affected zone with uneven microstructure including the coarse grain zone, the fine grain zone and the incomplete phase transition zone is formed. After the unit is operated for a period of time, the welded joint of this type of steel is prone to type IV crack defects. Tabuchi et al. [2] believe that early type IV crack failure is prone to occur in fine grain regions where the heating peak temperature is close to the Ac3 temperature. Type IV creep rupture is related to the microstructure change and performance of the base metal during welding and heat treatment. Albert et al. [3] found that the type IV crack occurred in the fine-grained heat-affected zone of the welded joint when the creep fracture of the welded joint of P122 steel was found, and the deformation of the welded joint was small when fractured, and a large number of creeping pores were observed at the fracture.

July 24, 2015, In a power plant #2 boiler, the butt welds of the straight pipe section and the elbow section of main steam pipe are cracked. Pipe design temperature 600 ° C, design pressure 25 MPa, pipe material SA335-P92, Straight pipe section specification $\Phi 559 \times 102$ mm, and elbow specification is $\Phi 559 \times 95$ mm. In order to find out the cause of the crack failure of the main steam pipeline, the author conducted a series of related tests and analysis.



2. Macroscopic Observation of Crack

The macroscopic morphology of the crack shows: The outer wall crack is parallel to the straight pipe side weld fusion line and extends in the circumferential direction, the crack is about 2mm from the fusion line. From 12 o'clock to 6 o'clock (Observing along the flow direction of the medium) in the clockwise direction, the crack length is 1000 mm or more. The surface of the crack was straight and no tearing was found. The maximum opening was at 3 o'clock. The maximum opening width of the crack is about 2mm. The crack in the inner wall extends in the circumferential direction parallel to the weld line of the root of the straight pipe. From 2 o'clock to 4 o'clock, the total length is 340 mm, and the surface of the crack is relatively straight. No opening is found.

3. Sampling and Analysis

3.1. Test Sampling

The high temperature (590 ° C) longitudinal stretching and the room temperature longitudinal tensile test specimens are respectively taken along the axial direction of the base material and the heat affected zone. The sampling positions are respectively in the vicinity of the inner wall, the middle part and the near outer wall of the main steam pipe, and a total of 24 samples. The curved specimens were taken in the near outer wall and the near inner wall respectively, including 4 in the base material area and 4 in the heat affected zone. At 3 o'clock and 9 o'clock three transverse impact samples from each parent metal area. Three longitudinal impact samples were taken in the heat affected zone and the parent metal zone of the near inner wall, middle section and near outer wall of the pipeline, A total of 18 longitudinal impact specimens.

The metallographic sample is taken from the crack tip of the outer wall of the pipe and the entire pipe section. Cut the crack tip sample and observe the microstructure of the different sections of the sample. The different observation surfaces are numbered as #A, #B, #C, as shown in Figure 1a. The metallographic sample number of the pipe section is #D, as shown in Figure 1b.



Figure 1. Metallographic sample; a crack tip; b pipe cross section

3.2. Chemical Composition Analysis

3.2.1. Chemical composition test results

The chemical composition analysis results are as follows:

Table 1. Chemical composition and standard reference value of P92 sample

Steel grade	Composition (%)												
	C	Si	Mn	P	S	Ni	Cr	Mo	W	V	Nb	Al	N
P92	0.09	0.27	0.45	0.012	< 0.010	0.20	8.62	0.48	1.63	0.21	0.083	/	/
HAZ	6												
Base material area	0.09	0.33	0.44	0.015	< 0.010	0.28	8.59	0.39	1.8	0.21	0.079	/	/
standard value	0.07~0.13	≤0.50	0.30~0.60	≤0.02	≤0.01	≤0.4	8.5~9.5	0.3~0.6	1.5~2.0	0.15~0.25	0.04~0.09	0.04	0.03~0.07

The results of chemical composition analysis showed that the content of each element was within the normal allowable range, and no abnormalities were found in the chemical composition analysis.

3.3. Analysis of Mechanical Test Results

3.3.1. Stretching test

Performing room temperature and high temperature tensile tests on the sample taken, The test results show that the room temperature longitudinal yield strength(427.5MPa) of the sample taken only in the heat affected zone of the outer wall is slightly lower than the standard value(≥ 440 MPa). The tensile strength of the sample is 630Mpa (standard requirement ≥ 620 MPa), and the yield ratio is 0.68. The room temperature and high temperature longitudinal tensile test results of the base metal and heat affected zone in the remaining positions are higher than the standard requirements. In addition, the high temperature tensile strength, yield strength, area shrinkage and elongation of the base metal are superior to the heat affected zone. It can be seen that the weld heat affected zone has poor plasticity.

3.3.2. Bending test

The bending test results are as follows: There are 2(sampling position is on the outer wall of the pipe) complete fractures of 4 samples in the heat affected zone at the indenter position. In the other two, one crack occurred and the crack length was 10 mm. The other one showed no visible cracks. There were no visible cracks in the four specimens of the base material at the indenter position. It can be seen that the plasticity of the heat-affected zone is significantly degraded compared with the parent metal, and the plasticity of the outer wall of the pipeline is the worst, indicating that its resistance to external impact loads is poor.

3.3.3. Impact test

The average value of the impact absorption of the lateral impact sample of the base metal is 34J, which is higher than the standard value required by 27J. The average longitudinal impact result of the heat affected zone of the outer wall of the pipeline is 13.7J, which is much lower than the standard requirement of 40J. The average longitudinal impact result of the heat affected zone in the middle of the pipeline is 33.5J, which is slightly lower than the standard value. The longitudinal impact of the heat affected zone on the inner wall of the pipe is 43J, which is slightly higher than the standard value. The test results show that the toughness of the heat-affected zone of the welded joint of the pipe is getting worse from the inside to the outside, and the outer wall of the pipe is the worst and the brittleness is the highest. The longitudinal impact results of the outer wall and inner wall of the pipe are slightly lower than the standard requirements. The impact of the base material in the middle of the pipe is higher than the standard requirement, indicating that the toughness of the base metal is better than that of the heat affected zone.

From overall view, the impact value of the base metal is close to the standard requirement, and the toughness is good. The impact value of the heat affected zone of the outer wall pipe is far lower than the standard requirement, and the toughness is insufficient. The analysis may be due to the long-term operation of the pipeline, P92 steel aging in the high temperature creep process, resulting in

deterioration of material properties, and the weld heat affected zone is further deteriorated due to the influence of welding thermal cycle and post-weld heat treatment.

3.4. Crack Metallographic and Fracture

3.4.1. Microscopic metallographic analysis

Take the crack tip sample #C of the outer wall of the pipe, polish the crack tip position of the #C sample, and then etch it with ferric chloride hydrochloric acid solution. After etching, washing and air drying, observe the metallographic microscope under the optical metallographic microscope. The results are as follows:

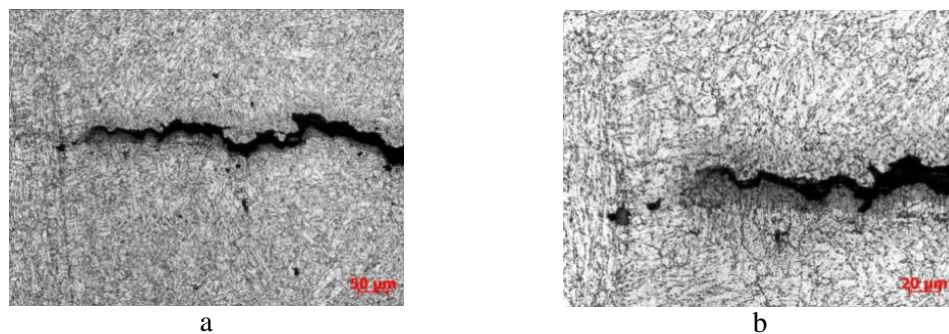


Figure 2. #C surface crack tip metallographic structure - a-200X,b-500X

From the metallographic photograph of the crack tip in Fig. 2, the position is organized as tempered lath martensite, micro-cavities exist around the main crack, and micro-holes are also formed in the front of the crack tip. The crack does not expand flatly, mainly along the crystal cracking characteristics. The crack occurrence region is the recrystallization region of the heat affected zone.

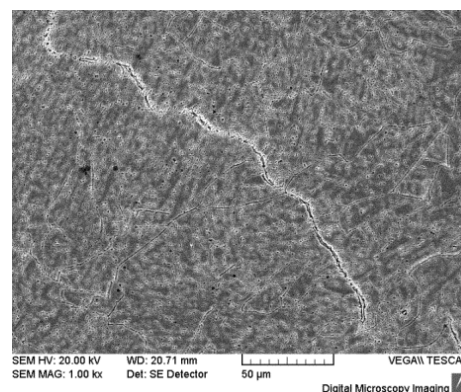


Figure 3. Scanning electron microscopy morphology of microcracks near the crack tip

In addition, during the observation of the crack tip microstructure, microcracks were found in the vicinity of the main crack, and microscopic cracks were observed by 1000X scanning electron microscopy are shown in Fig. 3.

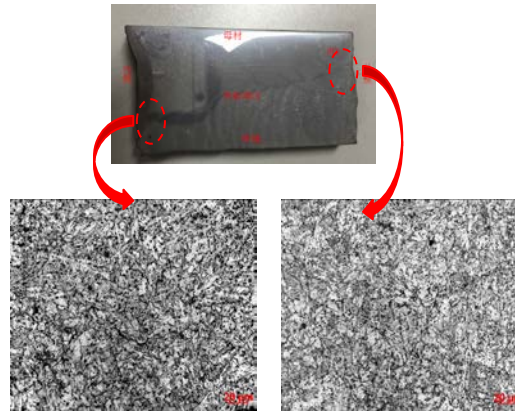


Figure 4. #D inner wall (left side), outer wall (right side) metallographic structure (500X)

It can be seen that the inner wall and the outer wall of the sample #D are organized into tempered lath martensite, and a small amount of creep pores exist in the structure, and the creep pores are distributed along the grain boundary.

3.4.2. Observation of crack fracture morphology

In order to determine the crack initiation site, the crack needs to be opened, and the crack fracture is observed by scanning electron microscopy. Scanning electron microscopy was performed on the 3 mm outer wall fracture with the largest crack crack width. The results of scanning electron microscopy are shown in Fig. 5.

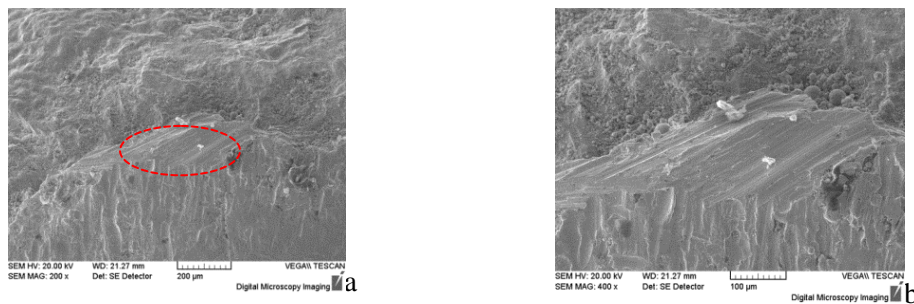


Figure 5. The outer wall crack fracture 3 o'clock-a-200X,b-400X

Looking at the scanning electron micrograph of Fig. 5, it is found that the fracture has been oxidized in a high temperature environment, and the thickness of the oxide film is thick, which masks the true shape of the fresh crack surface to some extent. In Fig. 5a, it can be seen that there is a similar river pattern through a large angle to reverse the grain boundary morphology (in the red circle), which is a distinct brittle transgranular fracture morphology^[4], and the crack cracking direction is extended from the bottom to the top, here It should be the crack initiation point. And the crack cracking direction is extended from the bottom to the top, where it should be the crack initiation. In addition, the high-magnification picture in Fig. 5b shows that the oxide film is mostly composed of oxide particles, and the fracture of the spherical particles is not flat expansion, which is characterized by the fracture along the crystal. Therefore, it can be shown that the crack is cracked by the outer wall in the long-term. During the operation, the crack gradually expands along the grain boundary and together, eventually forms a through crack.

3.4.3. #B crack tip electron microscope observation

Scanning electron microscopy observation of the #B crack tip is shown in Figure 6:

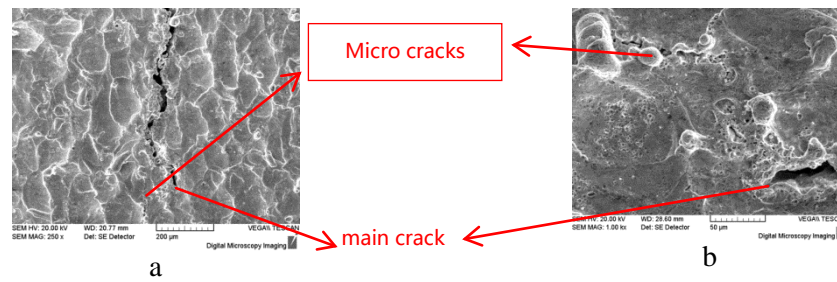


Figure 6. #B side crack tip scanning electron micrograph- a-250X, b-1000X

Observing the cracked tip of the #B sample, it is found that the main crack propagates along the grain boundary, there are new microcracks in the front of the crack tip, and there are many micro creep holes between the microcrack and the main crack tip, and the holes are connected. The tendency of microcracking, the morphology has obvious IV cracking characteristics.

3.4.4. Mechanical properties test fracture scanning electron microscopy

Scanning electron microscopy observations of some samples with lower than standard values in bending test, tensile test and impact test were carried out. The results are as follows:

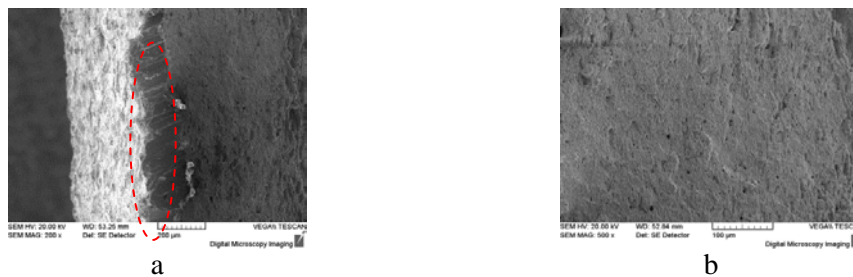


Figure 7. Scanning electron microscopy of fracture section of fractured specimen of curved specimen—a-200X, b-500X

Observing the fracture of the curved specimen, Figure 7a, it can be seen that the river pattern in this area also has a large angle to reverse the grain boundary morphology. The crack propagation direction is from left to right, and the middle intersection line is grain boundary. Due to the large twist angle, a large step is generated in the right crystal grain, so that the crack can continue to expand, which is obvious brittle cracking. The fracture morphology of the crack initiation zone is similar to that of the fracture zone of the outer wall of the pipeline, which indicates that the load subjected to the crack initiation failure is a bending load. Observe the fracture morphology of Figure 7b. There are more diffuse creep holes in the fracture zone, and the fracture surface is flush and brittle fracture.

For the impact sample, the sample with the lower impact value was selected for scanning electron microscopy of the cracking zone. The results are as follows:



Figure 8. Scanning electron microscopic observation of the cracking zone of impact specimen ZCJ3—a-500X, b-1000X

Figure 8 is a scanning electron microscope observation of the cracking zone of the longitudinal impact specimen, in which the crack propagation direction is from left to right. The crack initiation zone begins with a small amount of dimple-like morphology, followed by a river pattern, and then a distinct cleavage fracture. This is consistent with a small impact test value. In addition, there are many micro-creep holes scattered in the cracking position, and no hole connection tendency is found. Combined with the impact fracture of the sample, it is found that the fracture has no obvious macroscopic plastic deformation, and the fracture is relatively flush, which is a distinct brittle fracture.



Figure 9. Room temperature tensile fracture scanning electron microscope - a-1000X, b-2000X

Figure 9 is a scanning electron microscope observation picture of the room temperature tensile test fracture. There are many dimples in the figure, and the tearing ridge is obvious. In combination with the macroscopic necking phenomenon, the fracture mode is ductile fracture.

In summary, the fractures formed by different load types are observed. It is found that the fracture morphology of the fracture surface of the main steam pipe is similar to that of the main steam pipe at 3 o'clock. The fracture morphology of the cracking zone is similar. The cracking failure was caused by the bending load of the pipeline.

4. Analysis and Discussion

Judging by the location of the crack, the direction, and the area where the creep hole is concentrated, the failure is the fracture failure caused by the type IV crack [5]. Looking for the maintenance records before the location, it was found that the pipeline was replaced at the A-level inspection in October 2012, and the welding repair was carried out at the C-level inspection in September 2014. Two welding heat treatment processes were carried out in less than two years, and the location of the organization was greatly affected. Due to the multiple thermal cycles of welding, the grain size of the fine-grained zone in the heat affected zone is reduced. The grain of the precipitated phase is coarsened, and the strengthening effect of the M23C6 carbide on the grain boundary and the subgrain boundary is weakened, and the large M23C6 carbide and there is a large stress concentration around the Laves phase particles, and the creep holes are easy to nucleate at this position first. The MX carbonitride is needle-like roughened into a spherical shape, and the dispersion strengthening effect is weakened. the original lath martensite structure becomes a sub-cell, and the dislocation density is remarkably lowered.

Due to the above changes in microstructure, the creep strength of the incomplete phase change zone of the welded heat affected zone is significantly reduced. The fine-grained zone of the weld heat-affected zone is lower in the process of welding thermal cycle due to the lower temperature, shorter time, the original carbide can not be completely dissolved, and coarsened in the subsequent cooling process, resulting in solid solution strengthening of the alloying element and second The phase strengthening effect is reduced, so it is easy to form type IV cracks [6].

In addition, there is a large residual stress in the welding process, and the stress is not completely eliminated during the heat treatment, and finally a large residual stress exists in the pipe. The relevant literature points out [7] that the residual stress of the weld is in the tensile stress state in the heat-affected zone, and the maximum value is concentrated in the fine-grained heat-affected zone of the welded joint, so more creep is likely to occur in the fine-grained zone. Holes and eventually lead to the appearance of type IV cracks.

Dispersed micro-creep holes appear in the fine-grained areas of the inner wall and outer wall heat-affected zone of sample #D. It shows that during the long-term operation of the pipeline under high temperature and low stress environment, creeping pores appear in P92 steel, and the overall performance deteriorates. In addition, during the operation of the unit, the vibration of the pipeline caused by the start and stop of the unit and the operation process may cause the support and hanger to be inclined, resulting in the outer wall of the pipeline being subjected to the bending and tensile stress load. The joint action of the two causes the crack to first open on the outer wall of the pipeline. crack. Therefore, the cracking failure is mainly caused by the bending load on the outer arc side of the pipeline, and the IV creep crack is the auxiliary interaction result.

5. Conclusion

(1) Creep holes mainly appear in the fine-grained area of P92 steel welded joints. Under high temperature and low stress environment, creep pores grow and gradually aggregate and connect, and finally form type IV micro-cracks in fine-grained areas.

(2) For the main steam pipeline, it is necessary to pay attention to the reasonable setting of the support and hanger. Control the number of weld repairs, reduce the stress applied to the pipeline and the residual stress of the weld.

(3) The main cause of crack cracking is that the outer wall of the pipeline is subjected to the bending load, and the outer arc side of the pipeline is subjected to tensile stress. The secondary cause is the long-term high temperature and low stress operation of the pipeline, which leads to the creep hole of P92 steel, and the overall performance deteriorates. Type IV microcracks appear.

6. References

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