Stress Relief Cracking on the Weld of T/P 23 Steel

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Abstract

T/P 23 weld failures occurred in coal fired supercritical power plants were investigated and possible causes were considered. Susceptibility of stress relief cracking was tested through mechanical properties varying heat treatment conditions in weld and intrinsic stress level in the pipe system was calculated by FEM analysis using displacement data. We also investigated what elements in the filler composition affected stress relief cracking examined. The results showed any serious susceptibility of stress relief cracking in T/P 23 steel. Post weld heat treatment (PWHT) about 740°C, 1hr specified in welding procedure produced good tensile and ductility, and cause reasonable reduction of hardness. Finite element analysis for the system has shown that the stress ranges of inlet header, link pipe and outlet header were 83~96Mpa, 95~104Mpa, 40~41Mpa, respectively. The ratio of maximum stress for the design allowable stress was only 0.565 in link pipe. In the microstructural examination of T/P 23 weld, an interesting result was found that Mo content in the filler composition was significantly involved in the boundary behavior which affected stress relief cracking. Mo content close to the high level of ASME range has shown good microstructural stability and low susceptibility to stress relief cracking.

Keywords : T/P 23; stress relief cracking.; weld; grain boundary behavior; hardness

1. Introduction

T/P 23 was reported that improved weldability from compositional modifications may permit elimination of costly preheat and/or PWHT requirement in the early stage of development because ASME Committee classified this alloy as P.No.5 and could be followed the same welding parameters as T22 steel. But this alloy may be susceptible to stress relief cracking from a compositional standpoint because it contains many strong carbide forming elements and elements known to embrittle grain boundaries [1,2]. As a result of welding and PWHT on this alloy, the finely dispersed carbides within the grains are segregated on the prior austenitic grain boundaries, leading to internal stress. This internal stress is aggravated by the unavoidable residual stress caused by welding. This lead to cracking after welding made between the grain and grain boundaries, which known as stress relief cracking (SRC) and can be seen in a number of Mo-V and Cr-MoV steels. This type of cracking occurs as a result of residual stress (which is similar to parent material) produced after welding. The mechanism of PWHT cracking is explained by (1) precipitation strengthening of matrix and formation of soft denuded zone adjacent to grain boundary (2) tramp elements segregation (P, S, Sb, Sn, As, Al) at prior austenite grain boundary [3-6]. In the former mechanism, the carbide precipitation, such as M23C6 and M7C3, along the prior austenite grain boundary forms C- or Cr- denuded zone and thus the matrix adjacent to the grain boundary becomes softer as comparing to the grain boundary. In addition, the austenite grain interior can be strengthened by the precipitation of fine carbide like MC, typically. Hence most of the strain, which result from stress relaxation during post weld heat treatment could be concentrated in the soft denuded zone, causing

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intergranular cracking. In the latter mechanism, segregation of impurities is also known to cause the PWHT cracking by lowering cohesive strength along grain boundaries. According to J. G. Nawrocki, T23 has higher PWHT cracking susceptibility than that of T22 due to fine, dispersive and stable (V, Nb)C carbide in matrix.

In this paper, the failure of T/P 23 weld was investigated through replica method of welds in super critical coal fired fossil power plant which design steam pressure and temperature are 240 bar and 560 °C and just had about 30,000hrs operating time. FEM analysis of pipe system was performed to know intrinsic stress and deviation from the design stress using PipePlus 7.02 software because grain boundary segregation was aggregated by residual stress level concentrated on the weld. Reheat cracking test, mechanical properties such as elongation and reduction of area, and macro- and micro-structure for the specimens followed by test were examined to understand the failure causes T/P 23 weld that manufactured according to approved welding procedure and materials subjected to various heat treatment conditions.

2. Experimental Procedure

The examination of microstructures for the weld of T/P 23 pipe of super critical coal fired fossil power plant in service was performed using standard replica method specified in ASTM E1361-01. Base metal for preparation T23 mock-up weld was used in the normalized and tempered condition. The chemical composition of base metal and T/P 23 filler metals are shown in Table 1. Gas tungsten arc welding process was employed with heat input of 8~10kJ/cm using two different T/P 23 filler metals and the welding parameters are given in Table 2. T23 steel was classified as P-No. 5A and considered same as 2.25Cr-1Mo steel (SA-213 T22), such as welding condition of pre-heat and post welding heat treatment at the time of first enrolled in ASME Code in 1995, but the welding condition was remanded, especially in post welding heat treatment as Code case 2199-3 at ASME Code 2006 Edition. So we performed welding procedure according to heat treatment condition specified in the new version. T/P 23 base metal and two T/P 23 filler metals used in mock-up weld specimen have similar Cr, W, V and Nb content but differ in other alloying elements such as Mo, Al, which HCM2S(Sumikin Co.) contains more than Union P23(Thysyen Co.).

Table 1. Chemical compositions of base material and filler (wt%).

|       | C    | Mn  | P    | S    | Si   | Cr | Mo | W    | V    | Nb   | B    | Al |
|-------|------|-----|------|------|------|----|----|------|------|------|------|----|
| Parent| 0.878| 0.54 | 0.005| 0.004| 0.28 | 2.08| 0.08| 0.22 | 1.65 | 0.026| 0.002| -  |
| P23   | 0.668| 0.55 | 0.011| 0.001| 0.38 | 2.10| 0.02| 0.22 | 1.42 | 0.009| 0.007| 0.02|
| HCM2S | 0.663| 0.53 | 0.01 | 0.004| 0.39 | 2.35| 0.51 | 0.30 | 1.35 | 0.012| 0.005| 0.007|

Table 2. Parameter and picture of resultant of mock-up weld.

| Issue | Process | Filler metal | Welding Condition | Heat treatment Condition |
|-------|---------|--------------|-------------------|-------------------------|
| Rev. 6 | GTAW | 5A 0.2 4 | 90-180 8-20 8-20 | 5.40 10.00 |
| Rev. 1 | GTAW | 5A 0.2 4 | 90-200 10-15 8-15 | 6.75 11.00 |

Fig. 1. Dimension of specimen for re-heat cracking test.

Finite element analysis was performed to evaluate the intrinsic stress level and displacement change imposed on Superheater Division Link Pipe system that has P23 welds with proven cracks detected by Nondestructive testing method. The software used in the analysis was general purpose Pipeplus ver. 7.02 that was analytical tool for pipe system analysis. Modeling was made using construction drawings and design stresses were calculated based on the data offered from manufacturer. Mechanical properties were measured for specimens by using Vickers hardness Tester (MATAUZAWA, MMT-7) and INSTRON 8801 machine. Fig. 1 shows test specimen dimension for reheat cracking test. Fracture surfaces were examined by SEM (JEOL6360). Both thin foil and replicas were used for transmission electron microscopy studies. Thin carbon film was deposited on samples and extracted in the same etchant at 2V. Collected carbon replica was observed by TEM (JEOL2010) and precipitates were identified by EDS analysis and SAED pattern. Thin foils were prepared by mechanical polishing followed by jet electro polishing using an electrolyte consisting of a mixture of 95% methanol and 5% perchlolic acid, which was held at a temperature of -40 °C. The examinations of grain boundary segregation were carried out using electron probe microanalyser (JEOL JXA-8200).
3. Results and Discussion

3.1. Failure experiences in T/P 23 Weld

The number of 566°C class supercritical coal fired fossil power plants in domestic is 16 plants and weld cracks and leakages were detected all the plants in T/P 23 weld of pipe, stub and tube. The cases of forced outage were 32 times and crack detected places in interim inspection periods were totally 333 places for 5 years. The shape of crack showed micro cracks that number of micro voids connected with adjacent voids and located along with prior austenite grain boundaries in tempered bainite matrix. Figure 2 shows crack origin was weld metal and propagation direction of cracks was going to base material in pipe weld vertically and radial of weld metal only located on the centerline in tube weld, respectively. Judging from the shape of front edge of cracks, the growth rate of these cracks was considered very fast. Generally typical cracks in weld used HCM 2S filler were found in field welded places, but newly constructed plant showed in field and shop welded places that used Union P23 filler.

3.2. Microstructure of base material and weld

The microstructure of base materials was tempered bainite after normalizing and tempering (750°C, 2h) as shown in Fig. 3. Fig. 4 shows typical TEM microstructure composed of coarse M23C6 carbide aligned along austenite grain boundary and fine V-Carbide located in interior of grains. Fig. 5 shows optical microstructure of as-weld tube cut with 3 positions of crater, 30° and 300° directions that can distinguish typical weld, HAZ, soft zone and base material. Any weld crack and void was found and surface showed no cracks by non-destructive testing. The size of HAZ regions area was different with shape of weld and asymmetric in left and right size. SEM microstructure after PWHT 740°C for 1hr. shown in Fig. 6 showed precipitation behaviour of tube weld compared with as-weld condition (without PWHT). Carbides found in without PWHT was ε-carbide formed by auto tempering occurred during cooling process after welding and after PWHT ε-carbide was disappeared by dissolution into matrix. During this dissolution process, main carbide such as M23C6 was precipitated on prior austenite grain boundary, and fine MX carbide on lath boundary and interior of grain, respectively.

3.3. Hardness Examination of T-23 weld with various heat treatments

Vickers hardness test was performed on the stub welds after cutting from serviced facility (LP superheater inlet) that classified as crack detected and sound weld by non-destructive test method. According to the result in Fig. 7, the hardness of base materials in cracked weld had range of 187–215 Hv indicating PWHT performed during construction. HAZ showed 210–227 Hv that a little higher than base material. Crack occurred area in weld metal that shown as Fig. 2 (a) showed about 275 Hv in close surface positions which higher than other results, but internal area of weld metal was 225 Hv that similar to HAZ. Hardness of weld without crack showed 211 Hv in base material, 203–217 Hv in HAZ, and 236–237 Hv in weld metal, respectively, that indicating normal range compared with V&M technical book [7,8] for mechanical properties of weld. To understand the hardness variations with filler and heat treatment condition, mock-up weld using two fillers (Union P23, HCM2S) and three PWHT conditions (None, 710°C, 740°C) were selected. Hardness variation was shown in Fig. 8. Hardness of weld using Union P23 filler in as-weld condition without PWHT showed no more than 300 Hv within normal range. After PWHT at 740°C, hardness was reduced about 40–50 Hv due to stress relieving. Weld using HCM2S showed maximum 330 Hv in weld metal of as-weld state without PWHT, and the hardness was 310–320 Hv of almost same level as without PWHT condition, that had a little effect on the reduction of hardness after PWHT at 710°C. The result suggests that PWHT condition of 710°C was improper because this temperature was useless in hardness reduction inevitable in residual stress relieving. In the standpoint of maximum hardness, Union P23 filler showed more good result than HCM2S filler that was contrast with field experiences. Microstructures of all the samples showed no defect, void and other weld defect except hardness between two fillers. Elevated mechanical properties were evaluated to understand the suitable temperature range of
T/P 23 weld as shown in Fig. 9. Reduction of area was minimum 10% in the range of 650–700°C in spite of reduction of tensile strength. Reduction of area in case of PWHT at 720°C reduced around 25% and in PWHT over 740°C it recovered about 50%. Fig. 9 suggests that PWHT had to perform around 600°C in low temperature range and 740°C in high temperature range. But the former case the effect of stress relieving is reduced and the cost was increased by prolonged heat treatment to meet hardness requirement.

![Fig. 3. Optical microstructure of base material of T-23.](image)

![Fig. 4. TEM and EDS results of Carbide. (a), (b) M23C6, (c), (d) MC Carbide.](image)

![Fig. 5. Optical photographs of as-weld microstructure according to direction.](image)

![Fig. 6. SEM microstructures (a), (c) before and (b), (d) after PWHT.](image)

![Figure 7. Vicker’s hardness results for the field welded tube using Union P23 filler.](image)

![Figure 8. Hardness results for the weld with heat treatment conditions and filler.](image)

![Figure 9. Mechanical properties of the T/P 23 weld using Union P23 filler.](image)
Fig. 10 showed SEM microstructural pictures of fractured surfaces of different filler during tensile test at elevated temperature of 650°C and 700°C. Fracture mode was intergranular showing cleavage mode in Union P23 weld and intragranular mode showing dimples on fractured surface. The cause of this difference was examined by microstructural investigation as shown in Fig. 11 and Fig. 12. Fig. 11 showed morphology of grain boundary carbide and EDS analysis result formed in weld using Union P23 and HCM2S filler by TEM. According to the result of EDS analysis in Fig. 12, there is no discernable difference in size of the denuded zone and carbides type (Fe-rich M₃C). However, in a case of Union P23 filler metal depletion of Cr and W were detected along prior austenite grain boundary. For HCM2S filler metal which has high Mo contents, W depletion was not observed due to partitioning of Mo which diffusion rate is definitely higher than that of W [9,10]. Therefore, HCM2S filler metal has low susceptibility to PWHT cracking by effectively inhibiting depletion of W having higher solution strengthening effect and thus low stress concentration at grain boundary.

3.5. Stress analysis of pipe system

Finite element analysis on superheater division outlet header, superheater platen inlet header and the link pipe that routed between the headers was performed to estimate transient stress level and displacement variation of pipe system because the weld of above pipes was main source of weld cracks. Dimensions and operating conditions used in modelling were based on the construction drawing, and the result was shown in Fig. 13. Displacement of link pipe was subjected on the movement of inlet header in X-, and Y-direction and of outlet header in Z-direction as in Fig. 14. The result of stress analysis based on displacement of pipe showed superheater platen inlet header was 83–96Mpa which ratio (calculated stress/allowable stress) was 26–30%, link pipe was 95–140Mpa which ratio was 30–44%, and superheater division outlet header was 40–41MPa, which ratio was 10–12%. Fig. 15 showed maximum stress region was link pipe and the stress ratio was only 44% that was far below from the allowable stress level. According to the calculated stress level, we can reach the conclusion that stress on the pipe was not cause the crack of the weld.
4. Conclusion

The serious defects were detected at T/P 23 welded parts in the newly constructed domestic power plants. The voids formed at the grain boundary and the residual stress from welding process may effect to the crack growth. Even though there are some differences of the hardness value between the damaged and sound welding part, it is in the acceptable range of the manufacturer’s standard, but the microstructures of the damaged and sound welding part have no difference. According to the analysis of the welding specimen mocked for 2 fillers and undergone various heat treatment, there are no difference of mechanical properties and microstructures after treating PWHT of 740°C, 1hr, in spite of initial hardness difference. The result of microstructure investigation of fractured surface might show that the Mo element effect to the character of the grain boundary. This fact can be proven that the welding part using Union P23 filler have higher generation rate of the defects than the welding part using HCM2S filler by the experience of the site. In the case of HCM2S filler, the relatively higher Mo contents inhibit depletion of W and softening of denuded zone which relieves the stress concentration around the grain boundary and provides resistance against PWHT cracking in the present work. In addition, the result of the outside stress analysis showed that the stress from outside manages maximum 44% of the designed stress. Finally, to reduce the welding crack, it is recommended that the contents of the Mo element should be controlled to close to the upper range of the ASME standard of T/P 23.

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