Failure analysis on circulating water pump of duplex stainless steel in 1000 MW ultra-supercritical thermal power unit

Yue-Yue Ma, Shi Yan, Zhen-Guo Yang, Guo-Shui Qi, Xin-You He

Abstract

With a large number of properties such as good mechanical properties and excellent corrosion resistance, 2205 duplex stainless steel (DSS) has been extensively used in many industries for the last decades. However, improper welding procedures will induce embrittlement of the weld joint, seriously decreasing the safety reliability of the weld joint. In this study, lots of unexpected fractures occurred on 2205 DSS which was used as the material for making circulating water pump (CWP) in an ultra-supercritical thermal power plant of China for the first time. By means of diverse characterization methods, comprehensive investigation was carried out on the failed CWP. Analysis results reveal that many lack of penetrations (LOPs) in the weld joint and unbalance ferrite/austenite ratio induced by improper welding procedures should be responsible for the fracture of the CWP. And effective countermeasures and suggestions were also proposed. So the analysis results have instructive significance for the fracture prevention of the CWP, even for ensuring safety operation of other equipment under similar seawater environment.

1. Introduction

As one of the largest thermal power plants in the eastern part of China, Jiaxing power plant phase III has two 1000 MW ultra-supercritical thermal power generating units, which are named by 7# and 8#, respectively. These two units were put into commercial operation on June 23, 2011 and October 20, 2011, respectively, contributing a lot to the development of local economic development.

Circulating water system is an important facility in a thermal power generating unit, which is used to pump seawater and then to feed seawater into a condenser to cool exhaust steam by heat exchange. Hereby, each of the two units of Jiaxing power plant phase III was equipped with three CWPs, named 7A, 7B, 7C and 8A, 8B, 8C, respectively, all of which have same structure, designed and manufactured by Hitachi Pump Manufacture (Wuxi) Co., Ltd. Fig. 1(a) and Fig. 1(b) show the external appearance and the structure of 8A CWP respectively.

Since the surrounding of the CWP's shell is natural seawater which usually contains high contents of salts, chloride ions and sediment particles, it requires a high performances such as excellent corrosion resistance and good mechanical properties for the material used in the CWPs, so DSS is one of the best choices in this condition. In China, 2205 DSS was the first time used as the material of CWPs in thermal power plants.
However, in this event, after only ten months’ operation, substantially less than the design lifetime of 30 years, a number of severe fractures occurred on the CWP of thermal power unit 8, as shown in Fig. 2, causing substantial economic losses as well as potential safety problems. By means of visual inspection, it was easy to find that most of the fractures occurred on the weld joints rather than the base materials, just as Fig. 2(a)–(c) show. Material property, manufacturing technology, equipment operation, service environment, routine maintenance or other factors, which were the main causes for inducing these abnormal fractures, were urgently investigated. Consequently, a comprehensive failure analysis including a variety of characterization methods was conducted to identify the root cause based on our previous failure analysis experiences [1–9].
The mechanism of these fractures on the DSS used in CWP was carefully discussed. Finally, effective countermeasures and suggestions were proposed as well.

Actually, many researchers have focused on the properties of DSS, such as its fatigue behavior, welding property, corrosion resistance [10–17], but such an engineering practical study of mechanical degradation on DSS applied in CWP of 1000 MW ultra-supercritical thermal power unit has been rarely reported. What’s more, the phenomenon that large numbers of fractures occurred on the flanges of the CWP is even less reported. Therefore, the analyses and results given in this study have not only important engineering values in failure prevention of the CWP’s used under seawater environment, but also practical significance in ensuring safety operation of other equipment under similar condition.

2. Experimental

2.1. Visual observation

The 8A CWP is located in the Number 3 CWP house of Jiaxing power plant phase III, with a vertical structure and the length of the underground part is 17.1 m. As shown in Fig. 1(b), 8A CWP is mainly composed with two parts, i.e. the pump shell that weighs 42 tons and the shaft that weighs 26 tons. The pump shell mainly consists of an inlet bellmouth, a bell pipe, four connecting pipes and a bent outlet from bottom to top. Each connecting pipe is constituted of two round flanges and a cylindrical body by means of welding. Hereby, the two flanges are located on both ends of the connecting pipe, and each flange is made up with four same flange arcs with a thickness of 46 mm by means of welding technology. The cylindrical body was manufactured by a process of rolling and welding, with an outer diameter of 2200 mm and a thickness of 14 mm.

In this event, more than twenty severe cracks were discovered on the surface of 8A CWP. Among the damaged pipes, the severest one is the second connecting pipe counted from bottom to top, whose macroscopic appearance is showed in Fig. 3(a). Two target pairs of cracking samples analyzed in this study were both from the flange of this damaged pipe. One pair’s crack occurred on the weld joint of the flange, noted by cracking A and the other occurred on base material of the flange, noted by cracking B. The location of the two samples and the appearances are displayed in Fig. 3(a)–(c)

2.2. Characterization methods

In order to figure out the failure causes and mechanisms, a variety of characterization methods were successively conducted. Oxygen nitrogen hydrogen (ONH) analyzer, carbon sulfur analyzer (CSA), and inductively coupled plasma atomic emission spectroscopy (ICP-AES) were used to inspect their chemical compositions. Optical microscopy (OM) was utilized to observe their metallographic structures and the austenite/ferrite ratio of the butt weld was obtained by electron backscatter diffraction (EBSD) and dyeing calculation method under metalloscope, respectively. The impact toughness of the DSS used in the CWP was also measured by Charpy impact test. And the constituents of the seawater were detected by ion chromatography (IC) and ICP-AES. Meanwhile, besides further observation of the macroscopic morphologies of the ruptures on the two samples, three-dimensional stereomicroscopy (3D-SM), scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS) were adopted to analyze their microscopic morphologies along with micro-area compositions.

3. Results and discussion

3.1. Matrix materials

3.1.1. Chemical compositions

The chemical compositions of the cylindrical body, the flange and the weld joint of the CWP are listed in Table 1 respectively. It can be concluded that the materials used in the cylindrical body and the flange are the same, both of which are in accordance with the requirements of the UNS31803 grade DSS [18] (equals to the 2205 DSS in GB/T 21833-2008 [19]). Flux cored duplex stainless steel welding wire and gas shielded welding were used according to the manufactory. However, as seen in the third row of Table 1 , the carbon content at the weld is much higher than that at the cylindrical body and the flange. It meant that the quality of the weld joint was unqualified and it would induce the embrittlement of the weld joint.

3.1.2. Metallographic structure

The metallographic structures of the matrix are displayed in Fig. 4. Fig. 4(a) and (b) present the metallographic structures of the material used in the flange and cylindrical body, both of which show a typical 2205 DSS structure. It is obviously that the materials used in making the cylindrical body and flange are the same kind of DSS, which consists of ferrite and austenite, distributing very evenly. The ferrite acts as the matrix, whose color is grey, while the austenite in white color distributes in the ferrite matrix. The grain of the two phases is quite clearly, so is the boundary. Fig. 4(c) presents the metallographic structure of the weld joint, which is also consisted of ferrite and austenite, but quite different with those of the cylindrical body and flange. It is obviously that the amount of ferrite is much more than that of the austenite with a dendritic grain shape. By means of EBSD, the ratio of the two phases in the microscopic field can be calculated. Just as the Fig. 5 shows, the amount of
Fig. 2. Fractures on the CWP’s flange: (a) welding joint 1#, (b) welding joint 2#, (c) welding joint 3# and (d) base material.
Table 1
Chemical composition of the base material and weld joint of the CWP (wt%).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSS of the flange</td>
<td>0.015</td>
<td>22.26</td>
<td>5.20</td>
<td>3.22</td>
<td>0.17</td>
</tr>
<tr>
<td>DSS of the cylindrical body</td>
<td>0.019</td>
<td>22.52</td>
<td>5.47</td>
<td>3.02</td>
<td>0.17</td>
</tr>
<tr>
<td>Weld joint</td>
<td>0.35</td>
<td>22.22</td>
<td>8.18</td>
<td>2.90</td>
<td>0.11</td>
</tr>
<tr>
<td>ASTM-A790/A790M-09</td>
<td>&lt;0.03</td>
<td>21.0–23.0</td>
<td>4.5–6.5</td>
<td>2.5–3.5</td>
<td>0.08–0.20</td>
</tr>
<tr>
<td>GB/T 21833</td>
<td>&lt;0.03</td>
<td>21.0–23.0</td>
<td>4.5–6.5</td>
<td>2.5–3.5</td>
<td>0.08–0.20</td>
</tr>
</tbody>
</table>

Fig. 3. Macroscopic appearance of the failed CWP pipe and samples: (a) appearance of the failed connecting pipe, (b) crack A and (c) crack B.
austenite in the weld joint is only about 23.0%, far below the standard of qualified 2205 DSS, indicating an unbalanced austenite/ferrite ratio in the weld joint. By means of determined metallographically point count method, the same conclusion was drew out that the amount of austenite in the weld joint is less than 25%. By the same method, the amount of the austenite in the cylindrical body and flange are nearly 48.13% and 49.38% respectively, both of which are in accordance with the standard of 2205 DSS.

Fig. 4. Metallographic structures of the DSS: (a) flange (b) cylindrical body and (c) butt weld.
3.1.3. Mechanical test

In order to identify whether the DSS used in the water circulating pump is qualified, the impact toughness of samples from the flange and the cylindrical body were tested respectively by the method of Charpy impact test. It revealed that the Charpy impact value of the flange and the cylindrical body is both greater than 300 J, exhibiting a superior toughness quality. To further investigate into the toughness of the base material, SEM morphology analysis was applied. As seen in Fig. 6, a number of dimples were found on the Charpy impact fractography under magnification of 500, confirming the excellent ductility of the DSS used in CWP.

Based on the analysis above, it was concluded that the 2205 DSS used in the CWP was fully qualified and the root cause of the failure did not ascribe to the selection of materials. Thus, the scope of the root cause for the failure was narrowed down to the quality of the weld.

3.2. Environmental media

By means of ICP-AES and IC, the main element constituents of the seawater are revealed in Table 2, which conformed to the normal compositions of natural seawater – a high content of chloride ions. Judging from the appearance of the CWP, there is no severe corrosion, thus selecting 2205 DSS as the base material of the CWP is right and essential because of the strict demand for corrosion resistance.

3.3. Rupture of the sample A

3.3.1. Macroscopic morphologies

Fig. 7 shows the macro morphologies of sample A. Just as Fig. 7(a) shows, besides the butt weld in the flange, there is also a weld joint that joins the flange and the cylindrical body, and these two weld joints are converged in a point. It also shows that the crack propagated along the weld joint of the flange, noted by the arrow in Fig. 7(a). Further studies were conducted on the cross-sections of this fracture. Fig. 7(b) shows sample A's two corresponding cross sections (marked by Sections 1 and 2), on each lie a long and deep ditch respectively. This kind of ditch throughout the weld joint of the flange is a serious defect in welding, which is so called lack of penetration (LOP). Besides the LOP inside the butt joint (marked by LOP1), an obvious crevice, which is also a LOP, can be found in the weld joint connecting the cylindrical body and the flange (marked by LOP2), just as Fig. 7(b) represents. As known, there is more residual stress in the weld joint, especially for those without a well heat treatment after welding [20]. As Fig. 7(b) shows, the two serious defects mentioned above are linked to an area, greatly increasing the stress concentration and residual stress, and the intersection becomes the weakest area of this weld joint. According to the characteristics of the fracture surface, it can be learnt that the crack initiated from the intersection of the two weld joints, and propagated along the weld joint of the flange, as showed in Fig. 7(b).

With the help of 3D-SM, morphologies of the section surface can be observed more clearly. As Fig. 7(c) shows, the welding flux did not fill the gap between the cylindrical body and the flange, leaving a serious defect that the cylindrical body and the flange were jointed only by two small areas. Judging by the morphologies of cross section, crack origin site can be located, as illustrated in Fig. 7(d), which is the weakest area of the weld joint.
3.3.2. SEM and EDS
In order to find the root cause of the fracture, Section 2 of sample A that was cleaned thoroughly by ultrasonic cleaning, was studied further by SEM and EDS. The total morphology of the origin site showed in Fig. 8(a) was selected to be observed thoroughly. Fig. 8(b) shows the overall morphology of the origin site, where an uneven surface can be observed. More definite cracking origin site can be located in a further magnified scheme in Fig. 8(c), besides, some impurities near the cracking origin site can also be found, displayed by Fig. 8(d).
Additionally, chemical compositions near the cracking origin site (sites 001, 002, 003 in Fig. 9) were detected by EDS. Based on the results in Table 3, very high carbon elements were detected in all the three sites, demonstrating the fracture surface of the weld joint was contaminated by organic substances under the seawater environment.

Further experiments were conducted on the fillet weld. Fig. 10 shows the overall appearance of the fillet weld connecting the flange and the cylindrical body. With a high magnification, multiple microcracks were observed by SEM, which strongly enhanced the conclusion about the embrittlement of the weld joint.

3.4. Rupture analysis of sample B
Fig. 11 shows the appearances of sample B, which does not locate on the weld joint. Fig. 11(a) shows the overall morphology of this crack on the sealing surface and Fig. 11(b) exhibits the two corresponding cross sections. As Fig. 11(c) and (d)
show, fatigue cracks could be clearly observed, propagating along the arrows marked in the figures. According to the surface morphologies, the crack seemed to be torn by external force, exhibiting a kind of secondary fracture rather than the first fracture.

So it can be sure that the fracture appeared in this location happened after the fracture in the weld joint of sample A. The fracture in the weld joint of the flange led to an unbalanced of the CWP and large force was applied suddenly on the location of sample B, which cause it to be finally fractured. As a result, further studies are not needed to conduct for the sample B.

4. Failure analysis

4.1. Lack of penetration

Based on the analysis results presented above, it is clear that lack of penetrations (LOPs) existing in the weld joints induced by improper welding procedures should be blamed for the serious fracture of the circulating water pump (CWP). Just as Fig. 7(b) illustrates, LOP not only lies in the weld joint that connects the flanges, but also in the weld joint that connects the flange and the cylindrical body, decreasing the strength of the weld joint. LOP1 locating in the weld joint of the flange even runs through the weld joint. These LOPs would result in high stress concentration on the crack tip, and reduce the strength and fatigue life of the joints significantly.

It has been proved by many researchers that LOP, as a kind of common defect in the weld joint, would markedly decrease the strength of the weld joint and reduced greatly the fatigue life, leading to a severe fracture. Kim [21] studied the effect of LOP on the fatigue strength of butt weld by a number of fatigue tests of high steel containing partial and full penetration butt welds, revealing that fatigue strength of partial penetration butt weld was lower remarkably than that with full penetration, and the fatigue cracks initiated at the LOP section. Wahab [22] pointed out that the weld imperfections such as LOP, porosity, lack of fusion, undercut effectively reduced the fatigue crack propagation life and fatigue strength of welded joints by
studying a variety of weld imperfections. Kim [23] pointed out that the LOPs significantly reduced the fatigue lives of 9 mm thick transverse butt welded specimens without weld reinforcements, showing shorter fatigue life than JSSC-B. Sanders and Lawrence [24] studied the effects of lack of penetration (LOP) and lack of fusion (LOF) on the fatigue behavior of butt welds. He concluded that LOP defects can seriously reduce the fatigue life, while inclined LOF defects were generally less serious than LOP defects.

Former studies [25–27] also proved that LOP had much to do with welding procedure, including welding method, groove, welding speed, welding heat input and so on. In this event, the welding method used here was multi-layer and multi-pass welding and no sufficient heat treatment was conducted after the welding according to the manufacturer.

The weld groove is one of the most important facts to affect the quality of welding. Here, the Double-V preparation with proper parameters is recommended, listed in Table 4.

As for LOP2 shows in Fig. 7 (c), the weld groove is improper because the depth of preparation is too short and the groove angle is quite small according to the standard of ISO9692-1:2003 [28]. So, it is difficult for the weld flux to fill the gap even though other operations are correct. Here, the K preparation with proper parameters is recommended, also listed in Table 4.

4.2. Unbalanced microstructure with excessive ferrite

As the EBSD analysis result shows, there was a much higher ferrite to austenite ratio in the weld joint, also proved by means of determined metalllographically point count method. As known, the toughness of DSS weld joint with higher content of ferrite phase decreases remarkably. According former researches [29–31], this phenomenon had much to do with the welding procedure, especially the cooling rate or heat input. As Table 1 shows, the content of nitrogen in weld metal is in requirement with the standard, which indicates that the low austenite contend of the weld metal is rather due to the low heat input or high cooling rate employed in the welding than to nitrogen loss. Fig. 12 shows the vertical section of Fe–Cr–Ni ternary diagram based on Chromium-Equivalent, clearly presenting the phase transformation of 2205 DSS during the welding procedure. Based on the Fig. 12, austenite will start to precipitate at about 1330 °C, above which all the phase in the weld joint is ferrite. However, during continuous cooling there is not enough time for austenite to precipitate until the temperature has decreased to about 1200 °C, when a sufficiently amount of nuclei has been formed [32], thus a high cooling
Fig. 9. EDS results of the three sites near the crack’s origin: (a) site 001, (b) site 002 and (c) site 003.

Table 3
EDS results of the three sites near the crack’s origin (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>O</th>
<th>Al</th>
<th>Si</th>
<th>Mo</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 001</td>
<td>1.02</td>
<td>1.33</td>
<td>0.53</td>
<td>4.99</td>
<td>0.59</td>
<td>21.58</td>
<td>0.88</td>
<td>61.28</td>
<td>7.8</td>
</tr>
<tr>
<td>Site 002</td>
<td>0.58</td>
<td>0.67</td>
<td>0.37</td>
<td>1.73</td>
<td>0.51</td>
<td>21.95</td>
<td>0.63</td>
<td>65.34</td>
<td>8.22</td>
</tr>
<tr>
<td>Site 003</td>
<td>45.61</td>
<td>18.93</td>
<td>-</td>
<td>0.83</td>
<td>0.43</td>
<td>8.19</td>
<td>0.40</td>
<td>22.02</td>
<td>3.59</td>
</tr>
</tbody>
</table>
The cooling rate would prevent the forming of austenite. According to Adams [33], cooling rate in weld joints could be expressed as follows:

\[ V_c = 2\pi K p C f^2 \left( \frac{f}{HI} \right)^2 (T - T_0)^3 \]

\[ \int_{800}^{1200} \frac{dT}{V_c} = \frac{(HI)^2}{4\pi K p C f^2} \left[ \frac{1}{(800 - T_0)^2} - \frac{1}{(1200 - T_0)^2} \right] \]

where \( V_c \) = cooling rate (°C/s), \( \Delta t_{12/8} \) = cooling time between 1200 °C and 800 °C (s), \( K \) = thermal conductivity (W m/°C), \( \rho \) = density (g/cm³), \( C \) = heat capacity (J/kg°C), \( HI \) = heat input (J/mm), \( f \) = thickness (mm), \( T_0 \) = pre-heating temperature (°C).

According to Eqs. (1) and (2), the use of pre-heating can help to an increase of \( \Delta t_{12/8} \), which contributes to the forming of austenite in the weld joint. Badji [34] pointed out that throughout the weld regions of 2205 DSS, the optimal mechanical properties and an acceptable ferrite/austenite ratio corresponds to annealing at 1050 °C. Just mentioned above, there was no heat treatment after each welding, thus, an post weld heat treatment (PWHT) at 1050 °C is recommended to solve this problem.

4.3. Fracture process and crack propagation analysis

As mentioned before, the pump shell of the CWP weights 42 tons and locates vertically to the ground. When it was on operation, there was always accompanied with a vibration. So a cycle load was applied on the whole pump including the weld joint during its operation.

With so many serious defects like LOPs and unbalanced ferrite/austenite ration discussed above, the weld joint was too weak to withstanding the cycle load, thus a premature fatigue fracture occurred. Due to the fracture of the flange, an unevenly load was distributed on the whole CWP thus an unbalance of the CWP occurred, causing other severe fractures. So the crack occurred on the base material belongs to a secondary fracture. The process of the fractures is illustrated in Fig. 13.
As for the process of fatigue crack on the weld joint includes two important stages, i.e. crack initiation and crack propagation. So the total life ($N_t$) of weld joint consists of the crack initiation life ($N_i$) and the crack propagation life ($N_p$), which can be expressed as:

$$N_t = N_i + N_p$$  \hspace{1cm} (3)

However, in this event, there are two obvious LOPs in the weld joint, which act as the pre-existing crack-like imperfections in the weld joint, so it is normally considered to eliminate the so-called crack initiation stage of fatigue life. Therefore, the emphasis of the fatigue assessment could be focused on the crack growth stage of the fatigue life in some conditions.

Fatigue crack growth rate is usually analyzed in terms of fracture mechanics by using relations involving stress intensity factor. The most accepted approach to the analysis of fatigue crack propagation by linear-elastic fracture mechanics using a semi-empirical power law was Paris’ formula [35]:

$$\frac{da}{dN} = C(\Delta K)^m$$ \hspace{1cm} (4)

![Figure 11](image1.png)

**Table 4**

Recommended preparations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of preparation</th>
<th>Cross section</th>
<th>Angle $\alpha$, $\beta$</th>
<th>Gap $b$ (mm)</th>
<th>Thickness of root face $c$ (mm)</th>
<th>Depth of preparation $h$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange to flange</td>
<td>Double-V preparation</td>
<td></td>
<td>$40^\circ \leq \alpha \leq 60^\circ$</td>
<td>$1 \leq b \leq 3$</td>
<td>$\leq 2$</td>
<td>$=t/2$</td>
</tr>
<tr>
<td>Flange to cylindrical body</td>
<td>K-preparation</td>
<td></td>
<td>$35^\circ \leq \beta \leq 60^\circ$</td>
<td>$1 \leq b \leq 4$</td>
<td>$\leq 2$</td>
<td>$=t/2$ or $t/3$</td>
</tr>
</tbody>
</table>

![Table 4](image2.png)
where \( \frac{da}{dN} \) means the cyclic rate of crack growth, \( C \) and \( m \) are material constants defined by experiment, \( \Delta K \) donates the range of stress intensity factor.

It should be noted that Paris's law only represents the linear phase of crack growth curve. As the stress intensity factor range increases approaching its critical value of fracture toughness, \( K_c \), the fatigue cracks growth becomes much faster than that predicted by Paris, and Forman et al. [36] proposed the following relationship for describing the whole region of crack growth curve

\[
\frac{da}{dN} = C (\Delta K)^m / \left[ (1 - R) K_c - \Delta K \right]
\]

where \( R \) is the stress ratio, equal to \( S_{\text{min}}/S_{\text{max}} \), \( K_c \) the critical stress intensity factor describes material toughness (a measure of resistance to crack propagation).

Thus the number of cycles required to propagate a crack from an initial crack size \( a_0 \) to a final crack \( a_f \) can be calculated by using the following equation:

\[
N_p = \int_{a_0}^{a_f} \frac{(1 - R) K_c - \Delta K}{C (\Delta K)^m}
\]

And an equation of \( \Delta K \) is usually assumed to relate the range of stress intensity factor as below:

\[
\Delta K = \alpha \Delta \sigma \sqrt{\pi a}
\]
where $\varepsilon$ is a factor related to the specific geometry in question, $\Delta \sigma$ the nominal stress range, a the crack length.

Based on former research [31], the two approaches that have mostly been used for assessing stress intensity factors for crack in weldments are numerical method and finite element method (FEM). It was proved [37] that the propagation lives of joints had much to do with the existence and the size of the LOP. The propagation live of joints with shorter size showed larger propagation lives, which was due to the fact that the crack had to propagate a longer distance in the weld metal. It showed that the intercept 'C' varies with respect to LOP sizes. This provides a reasonable explanation to the pre-mature failure of the CWP.

5. Conclusions and recommendations

5.1. Conclusions

1. The LOPs in the weld induced by improper groove design decreased remarkably the strength and fatigue resistance performance of the weld joint, which was the most important cause to the fracture of the CWP.
2. Excessive content of ferrite in the weld joint, which should be induced by improper welding procedure, decreased the impact toughness and fatigue resistance performance, acting as another important cause to the failure.
3. The base materials used in the flanges and cylindrical bodies of the CWP were qualified, indicating the failures cannot be ascribed to the base material.
4. With an unavoidable cycle load caused by operation of the pump, the crack was originated on the intersection of the LOPs in the weld joints, propagating along the weld joint of the flange and eventually, the final fracture of the flanges happened when it reached a certain length.
5. After the fracture of the flange, an unbalanced occurred on the whole shell, resulting in the other severe fractures. Thus the crack occurred on the base material belongs to a secondary fracture.

5.2. Recommendations

1. Proper and strict procedure must be applied during the welding in order to obtain a full penetration joint and prevent the LOP. K preparation and Double-V preparation with proper parameters are recommended.
2. Proper way such as enough cooling time, postweld heat treatment at 1050 °C should be applied to obtain a balanced austenite/ferrite ratio.
3. Non-destructive method must be applied thoroughly after welding to ensure there is no fatal defect or flaw inside the weld joint.

References


