Fatigue crack growth analysis of surge line under thermal stratification conditions

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Abstract. As the connection between the pressurizer and the main pipeline of nuclear reactor, thermal stratification occurs in the pressurizer surge line during the operation. The thermal stratification through the pipe wall increases the possibility of plastic deformation and fatigue failure in the nozzle, tee, elbow and weld. So it is of great significance to carry out research on the fracture mechanics of surge line under thermal stratification conditions. Therefore, in this paper, based on the results of finite element analysis and ASME specifications, and with the results of pipeline stress analysis under temperature and pressure transient loads, the fatigue crack growth analysis of the surge line under thermal stratification conditions is carried out, and the technical means of suppressing crack propagation is explored, which provides a reference for the safe operation of the surge line of the nuclear power plant.

1. Introduction

In the primary loop system of nuclear power plant, the pipeline system, as the transportation artery of the coolant, plays an important role in the safe operation of the reactor equipment. The pressurizer surge line is an important link for connecting the pressurizer and the primary pipe. Inside the surge line, the fluid from the hot section of the primary pipeline has a low temperature and a high density, occupying the lower part of the pipeline section; while the fluid from the pressurizer has a high temperature and low density, and occupies the upper part of the pipe section, thus forming a thermal stratification phenomenon. The corresponding temperature gradient results in local stresses, and the pipe support constraints lead to global stress, making global bending inconsistent with the design and reducing pipe fatigue life [1,2]. During the long-term service of the surge line, cracks or defects may occur at the inner surface of the pipe. Affected by the thermal stratification conditions for a long time, the crack may continue to expand and eventually penetrate through the wall thickness, causing the pipeline to rupture and the leakage of coolant, which seriously affect the safe operation of the surge line and other primary loop equipment. Therefore, in order to ensure the safe operation of the nuclear power plant, it is of great engineering value to carry out the analysis of the fatigue crack propagation of the surge line, understand the crack propagation mechanism and explore the crack arrest technology.

Since the large value of stress intensity and fatigue usage factor of the surge line always occur at the joint of the straight pipe and the elbow, it is meaningful to carry out the research on the fatigue crack propagation of the weld structure. Zheng [3] discussed the crack initiation mechanism and early crack propagation behavior of TC21 titanium alloy electron beam welded joints. Ihara [4] estimated the residual stress distribution generated by butt welding and surface machining, and performed thermal elastoplastic analysis on the welding model. The surface machining simulation was performed on the thermo-mechanical coupling analysis based on the Johnson-Cook material model. The calculated crack
propagation analysis based on the stress intensity factor (SIF) was performed using the calculated residual stress distribution generated by welding and surface machining. Gotoh [5] investigated the fatigue crack propagation behavior of the out-of-plane welded joint under biaxial loading and two different phase conditions. The phase difference effect of the fatigue crack shape evolution under biaxial loading was confirmed by measurement. Arora [6] studied the fatigue crack propagation (FCG) behavior of austenitic stainless steel pipe welds. Compact tension (CT) specimens have been tested from actual narrow gap pipe welds. The slit is located in the weld centerline (WCL), heat affected zone (HAZ), HAZ-Fusion line (FL) interface and base metal. The FCG rates at different locations of the crack were compared. Testing was performed using the standard procedure of ASTM E647. The FCG efficiency of narrow gap welds (HAZ, WCL, HAZ-FL interface and parent metal) was compared to conventional VW weld seam welds (SMAW).

In order to reduce the crack propagation and slow down the crack further expansion, the surfacing technology is often used in the engineering. By welding the dissimilar metal on the surface of the pipeline, the crack surface is in the state of compressive stress, which resists the crack propagation. Huang [7] conducted a structural integrity analysis of the pilot weld overlay on different metal welds (DMW) of pressurized nozzles in pressurized water reactors (PWR). Based on MRP-169 and ASME code case N-504-2, the analysis of fatigue crack growth and fatigue usage was performed. Figure 1 shows the axial stress after application of the overlay welding procedure. Surfacing provides further compressive residual stress in the DMW, with more than 75% of the original weld thickness being compressed. According to the analysis, the weld overlay layer has the effect of significantly improving the compressive residual stress field of the DMW region.

Based on the above method, Wei [8,9] constructed the failure assessment curve of the structure after surfacing repair by ABAQUS finite element analysis and fracture mechanics analysis method. The effects of weld overlay thickness, crack depth and crack location on the failure assessment curve and LBB safety margin were analyzed. Jiang [10] proposed a new method of laminating welding on the inner surface of the nozzle to reduce the residual stress of the through joint. The finite element method was used to study the residual stress of the weld before and after surfacing. Based on the size of the spray tube nozzle of the Qinshan I nuclear power plant, Zhang [11] established the axisymmetric finite element model, and made use of the life-and-death element to simulate the transient heat input of the welding process, and investigated the temperature field of the structure during the surfacing repair process. According to the variation distribution characteristics, the calculated structural heat distribution history is taken as the thermal load, and then the variation characteristics of the structural residual stress during the surfacing repair process are obtained. The results show that after the surfacing repair is completed, the residual stress on the inner wall of the DMW weld zone can play the role of controlling the stress corrosion cracking (PWSCC). Liu [12] analyzed the welding residual stress of dissimilar metal welds in the water supply nozzle of boiling water reactor in Taiwan. In order to reduce the degradation of the nozzle weld, weld coverage repair was implemented to ensure its structural integrity. An axisymmetric model of the feedwater nozzle was established, taking into account the on-site welding procedure and detailed weld simulation to predict the weld residual stress during weld coverage repair.

![Figure 1. Axial stress after overlay procedure.](image-url)
Yusa [13] evaluated the applicability of eddy current testing for fatigue crack detection and size in embedded Inconel weld overlays. Jun [14] performed a series of failure analysis and crack propagation analysis on fractured weld repair rails to determine the cause of rail failure and the effect of residual stress on crack growth rate.

Antunes [15] developed a numerical model to predict plasticity induced crack closure (PICC), and isolated basic micromechanisms of crack closure and developed qualitative and quantitative relations between individual plastic wedges and PICC. García [16] conducted a numerical analysis of PICC based on a cohesive zone model (CZM) with irreversible damage that employs a crack growth method coupled with cyclic plasticity at crack tip and phenomenological fracture. The results show the ability of the proposed CZM to capture the influence of crack tip plasticity in the evaluation of crack closure phenomenon. Funari [17,18] introduced a numerical model to predict crack propagation phenomena in sandwich structures, and proposed numerical approaches which are able to compute the fracture variables (i.e. J integral approach). And the research results mentioned above are essentially meaningful and inspirational for the research of this paper.

According to the overlay analysis method, this paper carried out the analysis of the fatigue crack propagation of the surge line and explored the pipe arrest technology, which provides the method and technical basis for the operation and maintenance of the surge line.

2. Method description

2.1. Overlay stress analysis method for surge line

By depositing a layer of metal on the outer wall of the pipeline, the distribution of the stress field of the pipeline with and without overlay welding was compared. By selecting the relevant path on the pipe section, the stress variation from the inner wall to the outer wall was obtained under different paths.

### Table 1. Material property for surge line.

| Temperature T(°C) | Elastic modulus E(GPa) | Density ρ(kg/m³) | Poisson ratio υ | Heat expansion coefficient α(10^-6/°C) | Specific heat C(J/kg.°C) | Heat conductivity λ(W/(m.°C)) | Allowable stress intensity S_m(MPa) | Yield stress S_y(MPa) | Tensile strength S_u(MPa) |
|-------------------|------------------------|-----------------|----------------|----------------------------------------|--------------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| 20                | 197.0                  | 7910            | 0.3            | 15.54                                  | 455.0                    | 14.0                          | 358                          | 199               | 517               |
| 50                | 195.0                  |                 |                | 16.00                                  | 468.0                    | 14.4                          | 358                          | 199               | 517               |
| 100               | 191.5                  |                 |                | 16.49                                  | 494.0                    | 15.2                          | 358                          | 199               | 517               |
| 150               | 187.5                  |                 |                | 16.98                                  | 507.0                    | 15.8                          | 358                          | 199               | 517               |
| 200               | 184.0                  |                 |                | 17.47                                  | 526.0                    | 16.6                          | 358                          | 199               | 517               |
| 250               | 180.0                  |                 |                | 17.97                                  | 538.7                    | 17.3                          | 358                          | 199               | 517               |
| 300               | 176.5                  |                 |                | 18.46                                  | 542.7                    | 17.9                          | 358                          | 199               | 517               |
| 350               | 172.0                  |                 |                | 18.95                                  | 552.0                    | 18.6                          | 358                          | 199               | 517               |

### Table 2. Material property for weld.

| Temperature T(°C) | Elastic modulus E(GPa) | Density ρ(kg/m³) | Poisson ratio υ | Heat expansion coefficient α(10^-6/°C) | Specific heat C(J/kg.°C) | Heat conductivity λ(W/(m.°C)) | Allowable stress intensity S_m(MPa) | Yield stress S_y(MPa) | Tensile strength S_u(MPa) |
|-------------------|------------------------|-----------------|----------------|----------------------------------------|--------------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| 20                | 209                    | 7810            | 0.3            | 11.1                                   | 465.0                    | 31.2                          | 358                          | 178               | 569               |
| 50                | 208                    |                 |                | 11.4                                   | 469.0                    | 32.1                          | 358                          | 178               | 569               |
| 100               | 207                    |                 |                | 11.7                                   | 475.0                    | 34.8                          | 358                          | 178               | 569               |
| 150               | 204                    |                 |                | 12.0                                   | 481.0                    | 36.5                          | 358                          | 178               | 569               |
| 200               | 202                    |                 |                | 12.4                                   | 490.0                    | 38.2                          | 358                          | 178               | 569               |
| 250               | 199                    |                 |                | 12.8                                   | 502.0                    | 39.9                          | 358                          | 178               | 569               |
| 300               | 196                    |                 |                | 13.1                                   | 512.0                    | 41.6                          | 358                          | 178               | 569               |
| 350               | 191                    |                 |                | 13.4                                   |                         |                               |                               |                   |                   |

The material properties of the surge line and the weld are shown in tables 1 and 2. The load cases, transient load of temperature and pressure for fatigue crack propagation analysis are shown in table 3.
Table 3. Load cases for fatigue crack propagation analysis.

| Load Case | Number     | Pressure (MPa) | Low T (°C) | High T (°C) |
|-----------|------------|----------------|------------|-------------|
| 1         | 7000000    | 0.1            | 30         | 35          |
| 2         | 10700000   | 15.6           | 285        | 345         |
| 3         | 12200000   | 15.6           | 290        | 345         |
| 4         | 4200000    | 3.4            | 130        | 240         |
| 5         | 3000000    | 15.6           | 295        | 345         |
| 6         | 4000000    | 16.6           | 240        | 350         |
| 7         | 4000000    | 12.9           | 220        | 330         |
| 8         | 3000000    | 16.6           | 290        | 350         |
| 9         | 12000000   | 15.6           | 320        | 345         |
| 10        | 10000000   | 15.6           | 315        | 315         |

Figure 2. Transient load of temperature and pressure.

The two-dimensional section models with and without a weld overlay layer for surge line were established, as shown in figure 3. According to the 16-division temperature assumption, the inner wall surface of the pipe is divided into 16 equal parts, and different temperature loads are applied to different parts, as shown in figure 4. Transient thermal load was applied to the inner wall surface of the pipeline, and thermal transient analysis was carried out to obtain the temperature distribution of the pipeline section.
Figure 3. Finite element model of pipe section for the surge line with (a) and without weld overlay (b).

Figure 4. Temperature distribution of pipe section for the surge line. (a) 16 equal temperature distribution assumption, (b) with overlay and (c) without overlay.

Combined with the temperature distribution results, transient pressure load was applied to the inner wall surface of the pipeline, and thermal stress analysis was carried out to obtain the displacement field and stress field distribution with and without overlay weld. Select the nodes on the top (TOP), middle (MIDDLE) and bottom (BOTTOM) paths as shown in figure 5 to extract the path joint stress results with or without the overlay layer as the input conditions for the fatigue crack propagation analysis of the surge line.
2.2. Fatigue crack growth analysis method for surge line

Combined with the stress analysis results of the surge line with or without the overlay layer obtained above, the fatigue crack propagation analysis of the wave tube can be carried out. In this paper, the fatigue crack growth calculation under the thermal stratification condition of the surge line is mainly based on the relevant specifications. The relevant methods are as follows:

Refer to the ASME XI volume IW3-3640 requirements for crack propagation analysis of the overlay design. Due to the subcritical expansion analysis of cracks, a lot of numerical calculations are needed. In order to complete the crack propagation analysis effectively, accurately and quickly, the crack subcritical expansion calculation program was compiled by Matlab software according to the crack propagation analysis method in ASME Code XI volume. With the program, the fatigue crack propagation of the crack for the pressurizer surge line can be calculated. Combined with the transient load of the surge tube operation, the crack propagation amount at the end of the analysis period was obtained.

The surface crack stress intensity factor is calculated according to ASME XI Volume Appendix A-3320 formula:

$$K_I = \left[ \left( A_0 + A_p \right) G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3 \right] \sqrt{\pi a Q}$$  \hspace{1cm} (1)

Where, \(a\) is crack depth; \(A_0, A_1, A_2, A_3\) are coefficients of equation A-3200(b). \(G_0, G_1, G_2, G_3\), as the free surface correction factors of Point 1 and Point 2, were determined according to Tables A-3320-1 and A-3320-2 (Detailed table can be seen in ASME code). The locations of Point 1 and Point 2 are shown in figure 6.
Q is the crack shape parameters calculated in equation A-3310, equation A-3310(3) is as follows:

\[ Q = 1 + 4.593 \left( \frac{a}{l} \right)^{1.65} - q_y \]  

(2)

Where, l is crack length; \( q_y \) is the plastic zone correction factor, which is calculated by Equation A-3320(6):

\[ q_y = \left[ \left( A \sigma_y \right) + A \sigma_y \right] / \sigma_y \]  

(3)

Where, \( \sigma_y \) is yield strength.

For surface cracks, the relationship between the normal stress and the crack depth of the crack surface at the crack location is determined by the following ASME XI Appendix A Equation A-3200(b)(1)

\[ \sigma = A_0 + A_1 \left( \frac{x}{a} \right) + A_2 \left( \frac{x}{a} \right)^2 + A_3 \left( \frac{x}{a} \right)^3 \]  

(4)

Where, \( \sigma \) is circumferential or longitude stress; \( x \) is the distance between the inner surface and crack front; \( A_i \) is coefficient, and \( i = 0, 1, 2, 4 \).

The fatigue crack growth rate CGR(\( da/dN \)) is determined by the applied stress intensity factor range \( \Delta K_I \) and related materials and environmental constants. In ASME XI Vol. Appendix C-3210(1), the formula for calculating the fatigue crack growth rate is as follows:

\[ \frac{da}{dN} = C_0 \left( \Delta K_I \right)^n \]  

(5)

Where, \( n \) is the slope of \( \log(da/dN) \) and \( \log(\Delta K_I) \); \( C_0 \) is the proportional constant of the environment and material; \( \Delta K_I \) is the range of applied stress intensity factors; \( n = 3.3 \); and

\[ C_0 = CS \]  

(6)

Where \( A \) is the proportional parameter considering temperature:

\[ C = 10^{[-8.714 + \frac{1.341 \times 10^{-8}T - 3.341 \times 10^{-8}T^2 + 5.951 \times 10^{-9}T^3}{}]} \]  

(7)

Where \( T \) is the metal temperature (°C), \( S \) is a proportional parameter considering the R ratio(\( K_{imin}/K_{imax} \)) and

\[ S = \begin{cases} 1.0 & R \leq 0 \\ 1.0 + 1.8R & 0 < R \leq 0.79 \\ -43.35 + 57.97R & 0.79 < R < 1.0 \end{cases} \]  

(8)

3. Results and discussion

3.1. Stress distribution analysis results of overlay weld

The transient temperature load was applied to the inner surface of the surge line section with and without the overlay layer, and the temperature field distribution of the surge line section under different transient loads was obtained. Then, considering the temperature distribution result as an input condition, a transient pressure load was applied to the inner surface of the pipe to carry out thermal stress analysis of the surge line. The stress and displacement field distribution results for the cross section of the surge line with and without the overlay layer were obtained.

Figure 7 shows the maximum displacement values for surge line with and without weld overlay under different operating conditions. It can be seen that under all operating conditions, the maximum displacement value of the surge line containing the weld overlay is less than that associated with the
surge line without overlay, which indicates that the displacement level of the surge line is reduced under the condition of the overlay layer.

Figure 7. Maximum displacement of surge line with and without weld overlay.

Figure 8. Maximum stress intensity of surge line with and without weld overlay.

Figure 8 shows the maximum stress intensity values for surge line with and without weld overlay under different operating conditions. It can be seen that under most working conditions, the maximum stress intensity value of the surge line containing the weld overlay is smaller than that of the surge line without weld overlay, thus indicating that in the presence of the weld overlay, the stress level of the surge line is reduced.

For the stress distribution of the pipe section, taking the results of 70000s in figure 8 as an example, the stress distribution of the surge line with or without the overlay layer are shown in figure 9. It can be seen that under the condition of no-overlay layer, the stress distribution of the section of the pipeline is: the top is the largest, the middle is the smallest, and the stress is gradually increased from the middle to the both ends. Under the condition of surfacing layer, the maximum stress intensity appears on the top and bottom inner wall surface, the middle stress intensity is relatively small, and the stress gradually decreases from the top to the bottom.

Figure 9. Stress distribution of the surge line section with (a) or without overlay layer (b) at 70000s.

3.2. Analysis result of fatigue crack expansion

According to the analysis results of the overlay stress, the stress value in the thickness direction of the
relevant path is extracted, and the fatigue crack propagation analysis under the transient cyclic load of the surge line is carried out by using the fatigue crack propagation calculation method introduced in Section 2.2.

Assume an initial longitude semi-elliptical surface with a depth of 17.85 mm and a length of 53.55 mm. According to the stress results at the BOTTOM path, MIDDLE path and TOP path of the section, fatigue crack propagation under transient loading were calculated.

The calculated crack propagation profile is shown in figure 10. For the case without overlay layer, the crack at the location of BOTTOM-PATH, MIDDLE-PATH and TOP-PATH were expanded by 3.82 mm, 4.07 mm and 7.15 mm, respectively; for the case with overlay layer, the corresponding results of BOTTOM-PATH, MIDDLE-PATH and TOP-PATH are 3.52 mm, 1.15 mm and 0.87 mm, respectively.

![Figure 10](image)

**Figure 10.** Crack profile of crack growth. (a) Without overlay-BOTTOM-PATH, (b) with overlay-BOTTOM-PATH, (c) without overlay-MIDDLE-PATH, (d) with overlay-MIDDLE-PATH, (e) without overlay-TOP-PATH, (f) with overlay-TOP-PATH.

3.3. **Crack arrest evaluation result**

The amount of crack propagation obtained with and without the weld overlay were compared, as shown in figure 11. For the cracks at BOTTOM-PATH, MIDDLE-PATH and TOP-PATH, the crack depth extension results under the conditions of the surfacing layer are 0.3 mm, 2.92 mm and 6.28 mm smaller than those without overlay layer, respectively. For the result of the crack length increasement, the former
is 0.1 mm, 1.6 mm and 2.2 mm smaller than the latter. It can be seen that the results for the crack located in BOTTOM-PATH is similar. Difference get bigger for the crack located in MIDDLE-PATH, and the crack located at TOP-PATH has the largest difference. Therefore, the crack arresting ability is gradually increased as crack moves from the bottom to the top.

![Graphs](a) (b) (c)

**Figure 11.** Comparison of crack depth and length growth with or without overlay layer. (a) BOTTOM-PATH, (b) MIDDLE-PATH and (c) TOP-PATH.

The above results can be explained by figure 12: For the surge line containing the weld overlay, the X-Y direction stress distribution of the pipe section when weld overlay was completed and cooled down to nearly room temperature was examined. It can be found that there is a X-direction compressive stress 1.75 MPa at the left and right ends of the pipe section, and a 1.15 MPa Y-direction compressive stress at the upper and lower ends of the pipe section, thus making the two regions under compressive stress. Therefore, the crack growth ratio at the middle and the top part of pipe section are significantly suppressed. While for the crack at the bottom, despite the compressive stress, the crack arrest effect is weaker due to the relatively lower temperature (See figure 4(a)).
4. Conclusion

In this paper, the analysis of fatigue crack propagation and crack arrest of the pressurizer surge line were carried out. The main conclusions are as follows:

- Apply transient temperature load to the inner wall surface of the pipe section for the surge line with and without the overlay layer, the temperature field distribution of pipe section under different transient loads were obtained, and then considering the temperature distribution results as the input condition. The transient pressure load was applied to the wall surface, and the thermal stress analysis of the surge line was carried out to obtain the stress and displacement field distribution results of the cross-section of the surge line under two conditions.
  ➢ Under the condition of overlay layer, the displacement level of the surge line is reduced;
  ➢ Under the condition of surfacing layer, the stress level of the wave tube is reduced;
  ➢ Under the condition without overlay layer, the stress distribution of the pipeline section is: the largest value occurs in the top, the smallest appears in the middle, and the stress is gradually increased from the middle to the both ends. Under the condition of overlay layer, the maximum stress intensity appears on the top and bottom inner wall surfaces, the stress intensity in the middle is relatively small, and the stress gradually decreases from top to bottom.

- With the results of surfacing stress analysis, the stress values in the wall thickness direction of the bottom, middle and top paths were extracted, and the fatigue crack propagation analysis under the transient cyclic load of the surge line was carried out.
  ➢ Obtaining crack propagation profile results on three paths under two conditions;
  ➢ Comparing the crack propagation of cracks at different locations with or without overlay layer, it can be found that the crack propagation amount for the crack at the top has the largest difference, and the bottom crack propagation amount is similar;
  ➢ Because of the compressive stress in the top and middle of the pipeline, the crack arresting effect for the cracks at these location are better, and cracking arrest effect for the bottom is the weakest due to the lower temperature. In general, the addition of overlay weld layer to the surge line can effectively decrease the rate of fatigue crack growth, thereby achieving the purpose of crack arrest.

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