Fatigue Crack Initiation Life Analysis of Butt-Welded joints Considering Welding Deformation

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Abstract. In this paper, fatigue tests of butt-welded joints, under four-point bending cyclic load, were conducted to investigate the influence of welding deformation on fatigue crack initiation life. It is found that the distribution of residual stress around the weld toe is changed depending on the welding deformation. Meanwhile, welding deformation has an effect on stress concentration factor in the corner. So FEM was used to obtain the stress concentration factor of butt joints considering the welding deformation. A modified Neuber method was adapted to predict fatigue crack initiation life. Moreover, the fatigue notch factor was defined and on which the influence of mean stress and residual stress were considered. Finally, the evaluated results with the modified formula and the test results were compared. It is showed that welding deformation in the corner has an important influence on fatigue crack initiation life. The effect of welding deformation cannot be neglected in the life estimation.

Nomenclature
Δε Local strain amplitude εᵢ Fatigue plastic coefficient
σᵢ Fatigue strength coefficient(MPa) Nᵢ Crack initiation life
σᵣ Mean stress K Cyclic strength factor(MPa)
σₘ Residual stress n Cyclic strain hardening exponent
σₘ₉ Maximum nominal stress E Young’s modulus
Δσ Local stress amplitude R Stress ratio
ΔS Nominal stress amplitude Kᵢ Fatigue notch factor
b Fatigue strength exponent Kᵩ Stress concentration factor
σ Fatigue plastic exponent q Sensitivity factor of notch
μ Poisson’s ratio r Radius of the notch

Introduction
In butt welded joints, it is usually difficult to avoid misalignment, especially angular deformation. According to the IIW recommendations [1], welding deformation in axially loaded joints leads to the increase of stress due to the secondary bending stress, which may reduce the fatigue resistance. Fatigue tests of series of butt welded joints were investigated in literature [2], and the effect of angular deformation was analyzed.

Additionally, Residual stress and welding deformation usually exist in the welded structures at the same time [3, 4], and both of them need to be considered. In order not to interfere with residual stresses, Sonsino [5] conducts fatigue tests in which the specimens are stress-relieved by heat
treatment. However, when taking the residual stress into account, the residual stress can be included in the stress ratio [6, 7].

This paper investigates the fatigue life of butt welded joints subjected to cyclic four-point bending load. In order to consider the effect of welding deformation, the fatigue test of butt welded joints containing angle deformation are also conducted. In the end, the test results and evaluated results in two kinds of joints are compared and analyzed.

**Prediction of crack initiation life**

The modified Manson-Coffin formula [8] was chosen to evaluate the crack initiation life. In this method, local strain is an important parameter. Neuber [9] proposed a method to estimate the local stress and strain. According to this method, elastic-plastic notch stress and strain analysis method should be considered for the reason that stress at the weld toe often exceeds the yield limit of the material. In this paper, the modified Neuber method has been used to estimate the local strain, and the modified Manson-Coffin method has been used to predict the crack initiation life.

**Fatigue notch factor.**

The fatigue notch factor \( K_f \) is an important parameter when using the modified Neuber method to estimate the local stress and strain [10]. Among all the factors that affect the fatigue notch factor, the theoretical stress concentration factor \( K_t \) is the most important one. Eq. 1 is a formula about the relationship between fatigue notch factor and stress concentration factor.

\[
q = \frac{K_t - 1}{K - 1},
\]

where \( q \) is notch sensitivity factor, which can be calculated as follow [11]:

\[
q = \frac{1}{1 + \frac{A}{r}},
\]

where \( A \) is a material related parameter.

According to Eq. 2 radius of the notch should be determined first. However, the actual notch radius can hardly be measured in actual structures.

In order to solve this problem, the relationship between fatigue notch factor and stress concentration factor has been summarized by a series of tests [11]. The result showed that, for steel, there was a good linear relationship between fatigue notch factor and stress concentration factor when \( K_t \leq 3 \). Eq. 3 and Eq. 4 are fitted curves under different stress ratios.

\[
R=0.06 \quad K_f = 0.0497 K_t^2 + 0.3676 K_t + 0.6075,
\]

\[
R=0.5 \quad K_f = 0.5627 K_t + 0.4249.
\]

**Local stress and strain.**

Local stress and strain of the weld toes can be calculated by the modified Neuber method. In this method, local strain amplitude \( \Delta \varepsilon \) and local stress amplitude \( \Delta \sigma \) corresponding to fatigue notch factor can be calculated by Eq. 5 [12].

\[
\Delta \sigma \cdot \Delta \varepsilon = \frac{(K_t \cdot \Delta S)^2}{E}.
\]

The magnitude of cyclic stress-strain curve of the material can be expressed as Eq. 6.

\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left( \frac{\Delta \sigma}{2K} \right)^{\frac{1}{2}}.
\]
Relationship between strain and life.
Manson and Coffin analyzed a number of strain fatigue tests and proposed an equation to evaluate crack initiation life with local strain.

\[
\frac{\Delta \varepsilon}{2} = \frac{\sigma_i}{E} (2N_i)^b + \varepsilon_i'(2N_i)^c.
\] (7)

The mean stress and residual stress have great importance on the evaluation of crack initiation life. Therefore, the modified Manson-Coffin equation considering the mean stress and residual stress can be proposed.

\[
\frac{\Delta \varepsilon}{2} = \frac{\sigma_i - \sigma_m}{E} (2N_i)^b + \varepsilon_i'(2N_i)^c.
\] (8)

\[
\sigma_m = \frac{1+R}{2} \sigma_{\max} + \sigma_R.
\] (9)

where \( \sigma_m \) is the mean stress considering the residual stress. \( \sigma_i, \varepsilon_i, n, b \) and \( c \) are the uniaxial fatigue material constants of HTS-A steel shown in Tab. 1.

<table>
<thead>
<tr>
<th>( \sigma_i / E )</th>
<th>( b )</th>
<th>( \varepsilon_i )</th>
<th>( c )</th>
<th>( \sigma_i )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0098554</td>
<td>-0.1048704</td>
<td>64.5226</td>
<td>-1.244646</td>
<td>1193</td>
<td>0.0629158</td>
</tr>
</tbody>
</table>

Fatigue test and results.
MTS loading test analysis system was used in the experiment. Four-point bending was used to simulate the case of pure bending. In this experiment, transverse load was proportional sinusoidal with the frequency of 2.30Hz. The maximum load was 95kN, and the stress ratio was \( R=0.1 \). 34mm thick butt-welded joints of HTS-A steel were adopted to carry on fatigue test after ultrasonic flaw detection. To reduce the external damping, an inverted cone briquette supported by a base was used in the experiment. Meanwhile, a row of rollers was set between the briquette and base.

In order to make the observation of the fatigue fracture much easier, rust hook method which uses the detergent reagent to brush onto the surface of weld toe [18] is used, this method is based on the drop hook method. When crack appears, the detergent reagent will cause a series of white bubbles, which can be easily spotted. Specimens in this test were divided into two groups: butt weld joints with angular deformation (No.1-1, No.1-2 and No.1-3); and straight butt weld joints (No.1-4, No.1-5 and No.1-6).

In this research work, nondestructive testing and residual stress testing of the specimens were carried out before the fatigue test, and the test instrument is an X-ray stress analyzer X-350AL.

Fatigue fracture analysis.
The crack propagation can be observed easily after the specimen is broken (see Fig. 7(a) ~ (f)).

The test results had indicated that the crack initiates from one point and grows to a considerable length for specimens with deformation (see Fig. 7(a) ~ (c)).

As for straight specimens, surface cracks formed a multi-point initiation group near the weld toe line in the beginning. When the small cracks propagated to a certain extent, small cracks would converge into a single long crack (see Fig. 7(d) ~ (f)).
Fatigue life analysis.

Table 2 Fatigue life statistics

<table>
<thead>
<tr>
<th>Number</th>
<th>Total life</th>
<th>Propagation life</th>
<th>Percentage of propagation life</th>
<th>Initiation life</th>
<th>Percentage of initiation life</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1-1</td>
<td>26709</td>
<td>13863</td>
<td>51.90%</td>
<td>12846</td>
<td>48.10%</td>
</tr>
<tr>
<td>No.1-2</td>
<td>30033</td>
<td>13863</td>
<td>46.16%</td>
<td>16170</td>
<td>53.84%</td>
</tr>
<tr>
<td>No.1-3</td>
<td>47647</td>
<td>27726</td>
<td>58.19%</td>
<td>19921</td>
<td>41.81%</td>
</tr>
<tr>
<td>No.1-4</td>
<td>115570</td>
<td>68024</td>
<td>58.86%</td>
<td>47546</td>
<td>41.14%</td>
</tr>
<tr>
<td>No.1-5</td>
<td>146065</td>
<td>68024</td>
<td>46.57%</td>
<td>78041</td>
<td>53.43%</td>
</tr>
<tr>
<td>No.1-6</td>
<td>128071</td>
<td>56687</td>
<td>44.26%</td>
<td>71384</td>
<td>55.74%</td>
</tr>
</tbody>
</table>

From the perspective of engineering applications, the crack initiation depth is entirely artificial, and it depends on the detection technology accuracy and resolution used by researchers. In engineering, the crack initiation depth is often set to 0.5mm, and the fatigue life corresponding to this depth is then termed as the crack initiation life. When the crack propagates to the critical crack depth, the crack growth rate increases rapidly, the specimen can be considered fatigue fracture. In this paper, fatigue life from the initiation depth to the critical depth is termed as the crack propagation life. For the sake of simplicity, the present paper defines the life of the crack depth less than 0.5mm as the initiation life, and the life of crack depth from 0.5mm to fracture is called crack propagation life.

The corresponding relationship curves between crack depth (a) and cycle number (N) are shown in Fig.8 and Fig. 9.

In accordance with the definition of medium rate crack propagation region \(10^{-9} - 10^{-5} \text{ m/C}\) and crack propagation rate in the test record, the critical crack size \(a_c\) of specimen No.1-1, No.1-2, and No.1-3 is taken as 8mm; the critical crack size \(a_c\) of specimen No.1-4, No.1-5, and No.1-6 are taken as 15mm. Then, crack initiation life and propagation life correspond to each joint was calculated by the formulation of the fitting curve.

Tab. 2 shows crack initiation life, crack propagation life, and the total life of every specimen.

According to Tab. 2 it can be concluded that the ratio of initiation life to the total life is between 40% and 55% which means the initiation life cannot be ignored in the whole fatigue life.
Numerical analysis

Fatigue notch factor $K_t$.

In order to obtain the fatigue notch factor $K_t$, stress concentration factor should be determined first. The stress concentration factor $K_t$ can be calculated by the FEA method. In this paper, FEA was carried out by using the FEA software Ansys. According to Fig. 1, it can be concluded that fatigue notch factor $K_t$ is approximately the same under different stress ratios when the range of the stress concentration factor $K_t$ is between 1.5 and 2.0. In this paper, fatigue notch factor $K_t$ was calculated by Eq. 4, Fig. 10, shows two FE models of straight joint and angular deformation joint, respectively. The solid model mesh element used for the analysis was solid 95, and the mesh size around the weld toe required extremely refined element mesh, while the far region could use a relatively coarse mesh. Meanwhile, multi-linear kinematic hardening (KINH) model was used to simulate the elastic-plastic process. As for HTS-A steel in this test, Young’s modulus $E=1.96 \times 10^5$ N/mm$^2$, and Poisson’s ratio $\mu=0.3$ [18].

To determine the most suitable mesh size, four different minimum mesh sizes ($10^{-3}$ m, $10^{-4}$ m, $0.5 \times 10^{-4}$ m and $10^{-5}$ m) were compared in FEA. Take the straight butt welded joint as an example. Firstly, the stress concentration factors under different minimum mesh sizes were calculated, then, fatigue notch factor could be calculated by Eq. 4, Tab. 3, shows the stress concentration factor and fatigue notch factor $K_t$ in different minimum mesh sizes.

<table>
<thead>
<tr>
<th>Minimum mesh size (m)</th>
<th>Maximum stress (MPa)</th>
<th>Stress concentration factor $K_t$</th>
<th>Fatigue notch factor $K_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>1070.32</td>
<td>1.49</td>
<td>1.27</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>1128.71</td>
<td>1.57</td>
<td>1.31</td>
</tr>
<tr>
<td>$0.5 \times 10^{-4}$</td>
<td>1133.83</td>
<td>1.57</td>
<td>1.31</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>1134.23</td>
<td>1.58</td>
<td>1.31</td>
</tr>
</tbody>
</table>

It is concluded from Tab. 3 that fatigue notch factor remain constant ($K_f = 1.31$) as the minimum mesh size is $10^{-5}$ m. For the sake of simplicity, the minimum mesh size in this paper was chosen to be $10^{-3}$ m for all joints.
Fig. 4, Bending stress of joints

The simulated bending stresses are analyzed in Fig. 11. It is easy to calculate the nominal stress value, then the stress concentration factors can be calculated according to the stress nephogram, and the fatigue notch factor can be calculated by Eq. 4. Tab. 4 presents the final results of stress concentration factors and fatigue notch factors.

Table 4 Stress concentration factor $K_t$ and fatigue notch factor $K_f$

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Stress concentration factor $K_t$</th>
<th>Fatigue notch factor $K_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight butt welded joint</td>
<td>1.58</td>
<td>1.31</td>
</tr>
<tr>
<td>Butt joint with angular deformation</td>
<td>1.73</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Crack initiation life.

As for evaluation of the crack initiation life, mean stress and residual stress should be taken into account when using the modified Neuber method. The distribution of residual stress is complicated, and it is difficult to obtain the actual value of residual stress. The reference value from Japan Welding Association was $0.2\sigma_s$, and China Pressure Vessel Code recommended the range of the residual stress for $0.2\sigma_s$ ~ $0.6\sigma_s$ [4], $\sigma_s$ is the yield strength. As for HTS-A steel, the yield strength is 900MPa. Tab. 5 shows the results of mean residual stress measured by X-ray stress analyzer X-350AL.

Table 5 Mean residual stress of two different specimens

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Straight butt welded joint</th>
<th>Butt joint with angular deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean residual stress</td>
<td>144.75MPa</td>
<td>262.73MPa</td>
</tr>
</tbody>
</table>

It can be concluded that mean residual stresses of joints are close to the recommended values. Then, crack initiation life can be evaluated by Eq. 5 ~ Eq. 9. Tab. 6 represents the test results and the predicted results.

Table 6 Test results and predicted results

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Test results</th>
<th>Predicted results</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1-1</td>
<td>12845</td>
<td></td>
</tr>
<tr>
<td>No.1-2</td>
<td>16170</td>
<td>18052</td>
</tr>
<tr>
<td>No.1-3</td>
<td>19921</td>
<td></td>
</tr>
<tr>
<td>No.1-4</td>
<td>47546</td>
<td></td>
</tr>
<tr>
<td>No.1-5</td>
<td>78041</td>
<td>50904</td>
</tr>
<tr>
<td>No.1-6</td>
<td>71384</td>
<td></td>
</tr>
</tbody>
</table>
Based on the comparative analysis between the predicted results and the test results, the following conclusions are drawn:

(1) From Tab. 6, it can be seen that the crack initiation lives are between 12000 cycles to 20000 cycles for the joints with angular deformation. While the crack initiation lives are between 47000 cycles to 72000 cycles for straight specimens. The initiation life of joints with angular deformation is about a quarter of that of the straight butt joints. Angular deformation reduces the fatigue initiation life apparently.

(2) Compared with the test results, the predicted results are reasonable, confirming the validity of approach formalized and validated in the present paper.

Conclusions

In the present investigation, numerical and experimental methods are used to investigate the effect of welding deformation on fatigue life. Moreover, the modified Neuber method and modified Manson-Coffin equation are used to predict the crack initiation life. The results can be concluded as follows:

(1) The crack initiation life accounted approximately for 40%–50% of the total fatigue life in this paper, so the crack initiation life of HTS-A steel cannot be neglected. The initiation life of joints with angular deformation is about a quarter of that of the straight butt joints. Angular deformation reduces the fatigue initiation life apparently.

(2) Considering the effect of welding deformation, the modified Neuber method was adapted to predict fatigue crack initiation life. From the comparison between test results and predicted results, the predicted results are within the range of the test results.

References


