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

Yu Feng[1, a], He Feng [2,b] and Qin Kai [2,c,*]

[1] Wuhan Transportation Engineering Construction Investing Group Co. Ltd, Wuhan Hubei China

[2] Wuhan University of Technology, Wuhan Hubei China

[a]277158056@qq.com, [b]410901969@qq.com,

[c]happybrid1234@163.com, *Corresponding author

Keywords: butt-welded joints, welding deformation, fatigue-initiation-life, stress concentration factor, fatigue notch factor

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

Δe	Local strain amplitude	e_f'	Fatigue plastic coefficient
s_f'	Fatigue strength coefficient(MPa)	N_f	Crack initiation life
s_m	Mean stress	K'	Cyclic strength factor(MPa)
s_R	Residual stress	n'	Cyclic strain hardening exponent
s_{max}	Maximum nominal stress	E	Young's modulus
Δs	Local stress amplitude	R	Stress ratio
ΔS	Nominal stress amplitude	K_f	Fatigue notch factor
b	Fatigue strength exponent	K_t	Stress concentration factor
c	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.

$$q = \frac{K_{\mathrm{f}} - 1}{K_{\mathrm{t}} - 1}. \tag{1}$$

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

$$q = \frac{1}{1 + \sqrt{\frac{A}{r}}}. \tag{2}$$

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 $K_{\mathrm{t}} \le 3$. Eq. 3 and Eq. 4 are fitted curves under different stress ratios.

R=0.06 $$K_{\mathrm{f}} = 0.0497K_{\mathrm{t}}^2 + 0.3676K_{\mathrm{t}} + 0.6075. \tag{3}$$

R=0.5 $$K_{\mathrm{f}} = 0.5627K_{\mathrm{t}} + 0.4249. \tag{4}$$

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 Δe and local stress amplitude Δs corresponding to fatigue notch factor can be calculated by Eq. 5 [12].

$$\Delta s \cdot \Delta e = \frac{\left(K_{\mathrm{f}} \cdot \Delta S\right)^2}{E}. \tag{5}$$

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

$$\frac{\Delta e}{2} = \frac{\Delta s}{2E} + \left(\frac{\Delta s}{2K'}\right)^{\frac{1}{n'}}. \tag{6}$$

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.

$$\frac{\Delta e}{2}=\frac{s_{\mathrm{f}}^{'}}{E}\left(2N_{\mathrm{f}}\right)^{b}+e_{\mathrm{f}}^{'}\left(2N_{\mathrm{f}}\right)^{c}\ . \tag{7}$$

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.

$$\frac{\Delta e}{2}=\frac{s_{\mathrm{f}}^{'}-s_{\mathrm{m}}}{E}\left(2N_{\mathrm{f}}\right)^{b}+e_{\mathrm{f}}^{'}\left(2N_{\mathrm{f}}\right)^{c}\ . \tag{8}$$

$$s_{\mathrm{m}}=\frac{1+R}{2}s_{\max}+s_{\mathrm{R}}\ . \tag{9}$$

where is the mean stress considering the residual stress. $s_{\mathrm{f}}^{'}, e_{\mathrm{f}}^{'}, n^{'}$, b and c are the uniaxial fatigue material constants of HTS-A steel shown in Tab. 1.

Table 1 Fatigue characteristic parameters of HTS-A steel [12]

$s_{\mathrm{f}}^{'}/E$	b	$e_{\mathrm{f}}^{'}$	c	$s_{\mathrm{f}}^{'}$	$n^{'}$
0.0098554	-0.1048704	64.5226	-1.244646	1193	0.0629158

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).

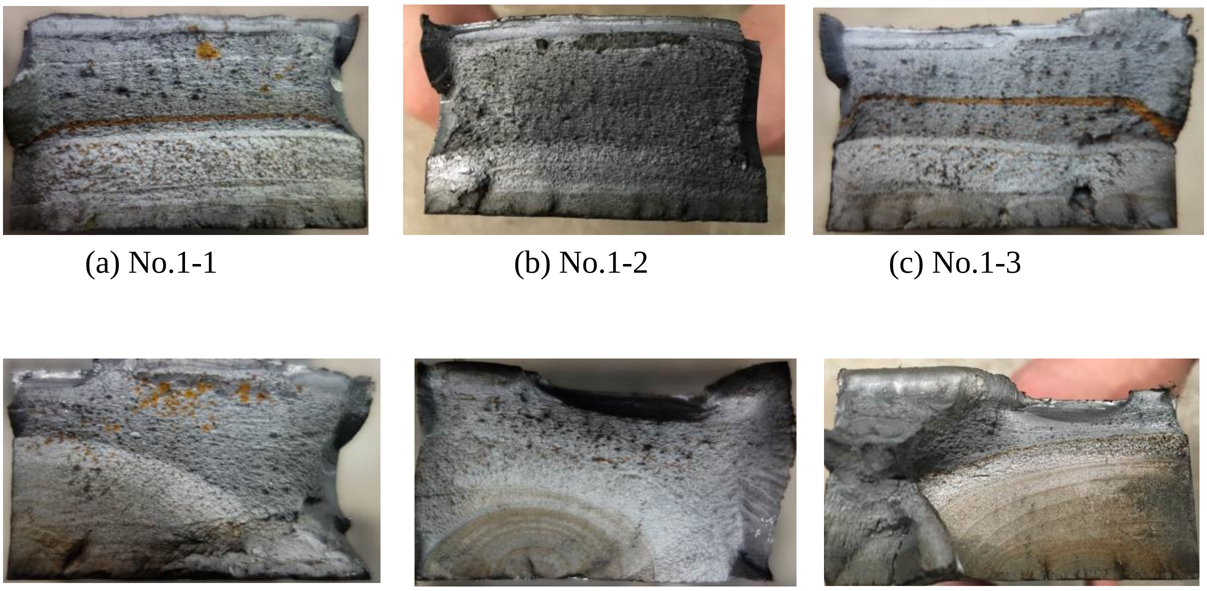
In this research work, nondestructive testing and residual stress testing of the specimens were carried out before the fatigue test, and the test instrument is an X-ray stress analyzer X-350AL.

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)).



(a) No.1-1 (b) No.1-2 (c) No.1-3

(d) No.1-4 (e) No.1-5 (f) No.1-6

Fig. 1 Fatigue fracture of specimens

Fatigue life analysis.

Table 2 Fatigue life statistics

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

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 ($10^{-9} \sim 10^{-5}\, m/C$) 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.

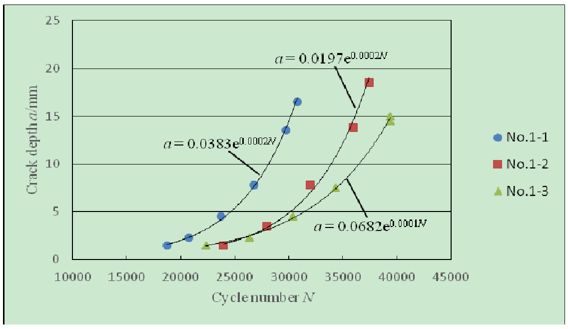


Fig. 2 crack depth a and cycle number N

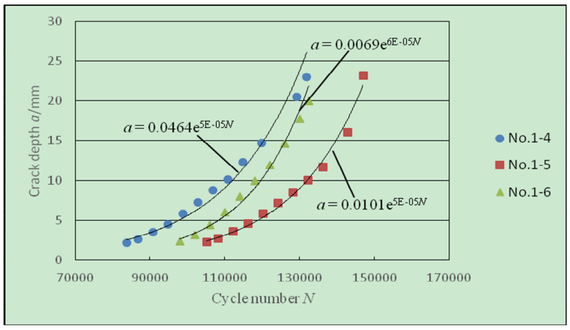


Fig. 3 crack depth a and cycle number N

Numerical analysis

Fatigue notch factor K_f .

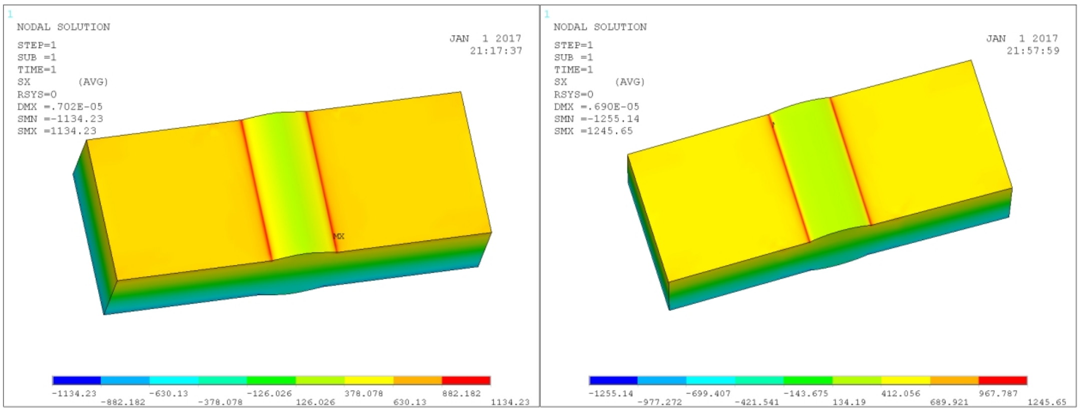
In order to obtain the fatigue notch factor K_f , stress concentration factor should be determined first. The stress concentration factor K_t can be calculated by the FEA method. In this paper, FEA was carried out by using the FEA software Ansys. According to Fig. 1, it can be concluded that fatigue notch factor K_f 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_f 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=1.96×10^{5}N/mm^2, and Poisson's ratio μ=0.3 [18].

To determine the most suitable mesh size, four different minimum mesh sizes(10^{-3}m、10^{-4}m、0.5×10^{-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_f in different minimum mesh sizes.

Table 3 Stress concentration factor K_t and fatigue notch factor K_f of different minimum mesh sizes.

Minimum mesh size（m）	Maximum stress(MPa)	Stress concentration factor K_t	Fatigue notch factor K_f
10^{-3}	1070.32	1.49	1.27
10^{-4}	1128.71	1.57	1.31
0.5×10^{-4}	1133.83	1.57	1.31
10^{-5}	1134.23	1.58	1.31

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^{-5}m for all joints.



(a) Bending stress of straight joint (b) Bending stress of joint with deformation

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}

Joint type	Stress concentration factor K_t	Fatigue notch factor K_f
Straight butt welded joint	1.58	1.31
Butt joint with angular deformation	1.73	1.39

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 $0.2s_{\mathrm{S}}$, and China Pressure Vessel Code recommended the range of the residual stress for $0.2s_{\mathrm{S}} \sim 0.6s_{\mathrm{S}}$ [4], s_{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

Joint type	Straight butt welded joint	Butt joint with angular deformation
Mean residual stress	144.75MPa	262.73MPa

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

Specimen number	Test results	Predicted results
No.1-1	12845	
No.1-2	16170	18052
No.1-3	19921	
No.1-4	47546	
No.1-5	78041	50904
No.1-6	71384	

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

[1] A.F. Hobbacher in: Recommendations for fatigue design of welded joints and components, edtied by IIW Doc IIW-2259-15, Int Inst Welding (2016), p.80-81

[2] Sung-Wook Kang, Yong-Man Park, Beom-Seon Jang, Yu-Chul Jeon and Seong-Min Kim in: Study on fatigue experiment for transverse butt welds under 2G and 3G weld positions, edtied by International Journal of Naval Architecture and Ocean Engineering, 07 (2015), p. 833-847

[3] Y. Garbatov, C. Guedes SoaresK and Masubuchi: Residual Stresses and Distortion in Welds, Reference Module in Materials Science and Materials Engineering (2016)

[4] L. Xu and R. Yan: Three dimensional numerical simulations of welding T – joint residual stress and distortion, edtied by Jangsu Ship, 01 (2007), p.5-8+45

[5] C. M. Sonsino: Multiaxial fatigue of welded joints under in-phase and out-of-phase local strains and stresses, edtied by International Journal of Fatigue, 17(1) (1995), p. 55-70

[6] T. Nyk€anen and T. Bj€ork: Assessment of fatigue strength of steel butt welded joints in as-welded condition-Alternative approaches for curve fitting and mean stress effect analysis, edtied by Marine Structures, 44 (2015), p. 288-310

[7] W. Shen, R. Yan, L. Xu, X. Zhang and L. Geng: Study on Multi-Axial Fatigue Damage of Weld Joints Considering Residual Stress, edtied by Shipbuilding of China, 55(2) (2014), p. 67-76

[8] H. Neuber: Kerbspannungslehre (Berlin, Springer 1937), English translation: J. W. Edwards: Theory of Notch Stress (Ann Arbor, Michigan 1946).

[9] X. Huang, W. Cui and D. Shi: Prediction of fatigue initiation life of cracks at weld toe subjected to compressive and bending loads, edtied by Marine Engineering, 24(3) (2002), p.413–416

[10] S. Zhao and Z. Wang: Fatigue resistance design - method and data (China Machine Press, Beijing, 1997), p. 41-63 and pp. 90-107

[11] H. Neuber: Kerbspannungslehre (Springer Verlag, 1958).

[12] B. Hu, J. Liu and J. Chen: Relationship between fatigue notch factor and stress concentration factor, edtied by Material Engineering, 07 (2007), p. 70-73

[13] S. S. Manson: Behavior of materials under conditions of thermal stress, edtied by NACA TN-2933, National Advisory Committee for Aeronautics, (1954).

[14] J. Coffin and L. F: A study of the effects of cyclic thermal stresses on ductile metal, edtied by Transaction of American Society of Mechanical Engineers 76 (1954) p. 931-950

[15] H. Zhou: Study on low-cycle biaxial fatigue at butt joint of HTS-A steel (Wuhan University of Technology, Wuhan, 2011).