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Fatigue Life Assessment of Cruciform Welded Joints Based on Interval Dissipation Energy Method

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1. Introduction

Metal plates are often connected by welding, while the cruciform welded joints are widely used in engineering structure. However, fatigue cracks always appear at the root of welded toe [1]. Therefore, in order to improve the fatigue reliability of welded joints, the accurate fatigue life prediction is one of important factors to conduct on the fatigue resistance design.

In general, engineers are likely to estimate the fatigue life of welded joints based on the S-N curve, while the nominal stress is considered as the damage parameter [2-3]. If the section of geometrical structure is complex, the hot spot stress is suggested to instead of the nominal stress [4-5]. The hot spot stress is quantized to characterize the mechanical responses related with the local geometric features. When the welded joints have some defects like pores or micro-cracks, the notch stress method is prone to accurately calculate the fatigue life of weld seam [6-7]. However, the defects are difficult to know in advance. Therefore, if there are obvious pre-cracks, the fracture mechanics method based on crack propagation analysis is suggested to estimate the remaining lifetime of welded joints [8]. But, the methods mentioned above depend on the fatigue tests of welded joints, which takes a long time to obtain the needed experimental data.

Some researchers have turned to using infrared thermal imaging technology for rapid assessment of fatigue life [9-10]. The temperature evolution process of welded joints under cyclic loading could be recorded, and then the dissipated energy is determined. The energy-based approach can directly reflect the mechanism of internal friction and crystal slip between micro-structures, and build the mathematical relationship of energy conversion caused by the external loads. The quantitative thermal imaging method can rapidly estimate the fatigue damage accumulation behavior through the gradual change of surface temperature [11]. Qiang Guo [12] proposed a mathematical model that takes into account the heat exchange and energy dissipation inside the material, and further constructed mathematical equations for the stress amplitude, life, and cumulative dissipated energy. Xiao gang Wang [13] proposed to use the energy dissipation rate of fatigue behavior to characterize the fatigue resistance of materials, and attempted to establish its mathematical relationship with the evolution of microstructural damage. Shun peng Zhu [14] determined the affiliation functions of fuzzy variables under different loads and established a fuzzy fatigue damage model based on fuzzy set analysis theory, and predicted the fatigue life of structures under different loads. Zhengqi Gu [15] proposed an interval boundary method to estimate strain fatigue life parameters based on a small sample of measurement data. However, it is difficult to accurately evaluate fatigue life using temperature increments because the heat exchange is easy to happen, unless the environment is insulated. Therefore, the dissipated energy-based method is suggested to predict the lifetime of welded joints, and the inherent dissipation of welded joints is utilized to quickly evaluate the fatigue performance [12]. However, the fatigue parameters in the damage model is dependent on the welding quality of the weld seam, and therefore the uncertain factors of welding process also need be concerned as well.

In this paper, the fatigue tests of butt-welded joints and cruciform welded joints are performed by the infrared thermal imaging technology. Then, considering the uncertainty factors existing in the fatigue test process, the uncertainty of fatigue parameters in the fatigue life prediction model is represented by an interval mathematical model, the interval energy dissipation method is constructed to determine the fatigue parameters and interval bounds, as well as interval curves. A fatigue life prediction model based on interval energy dissipation of cruciform welded joints is constructed, the fatigue life estimation of cruciform welded joints is compared with the experimental data, so as to evaluate the fatigue life of the specimen in a more comprehensive way.

2. Experimental work

2.1. Fatigue test of butt welded joint

To determine the asymptotic dissipated energy of welded joints, the infrared thermography fatigue test is conducted on the specimens, as shown in Fig. 1 [16]. The base material is ASTM A6 low-alloy steel, while the connecting process is arc welding. The current is within 250-270 A, and the voltage is within 28-30 V. The wire feeding speed is within 38-45 cm/min. The thickness of plates is 6 mm, and the dimension of specimen is shown in Fig. 1.

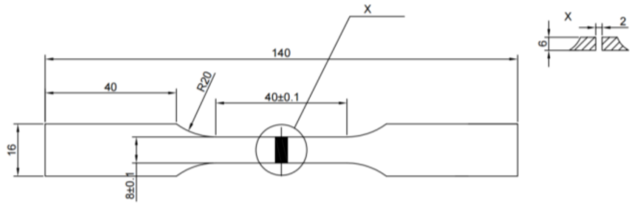

Fig. 1 Welded joint specimen size

Based on the infrared thermal imaging technology, the infrared thermography fatigue test bench is built, as shown in Fig. 2. The surface of welded joint specimen attaches the black matte paint. The black strip covers the actuator to avoid the reflection. Then, an infrared thermal imager (American FLIR-A655sc model) stands in front of the specimen, while its measurement accuracy reaches 20 mK at room temperature. The electro hydraulic servo control testing machine (Chinese PLD-100 model) is used to offer the cyclic loading.

Fig. 2 Installation schematic of fatigue test and thermal measurement

Then, 20 specimens were prepared and 18 specimens were used in the experimental study. the constant amplitude fatigue tests are conducted on the specimens of butt welded joint at four stress ratios, R = -1, R = 0.1, R = 0.3 and R = 0.5, respectively. The loading frequency is 2 Hz, and all tests are under displacement control. The loading speed is 0.01 mm/s. If the fatigue failure of welded joints does not happen within 1×10^7 cycles, the test will be suspended. While the applied load reduces by seventy percent of the maximum forces, the testing will be stopped and the data will not be recorded. In order to accurately obtain fatigue parameters of welded joints, different stress amplitudes are conducted on the specimens. The experimental results are listed in Table 1 [16]. The cracks appear at the root of weld toe, as shown in Fig. 3. The thermal variation of specimen at stress amplitude of 260 MPa is displayed in Fig. 4.

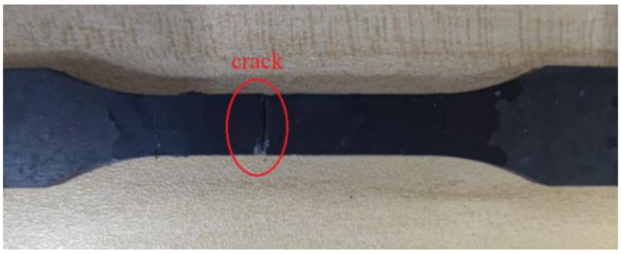

Fig. 3 Crack at the toe of weld.

Table 1

Experimental data of fatigue tests for butt welded joints

Specimen number	Stress ratio	Stress amplitude, MPa	Number of cycles
F07	-1	300	6562
F08	-1	260	16804
F09	-1	220	71404
F10	0.1	180	83894
F11	0.3	150	142021
F12	0.3	140	94450
F13	0.3	95	165346

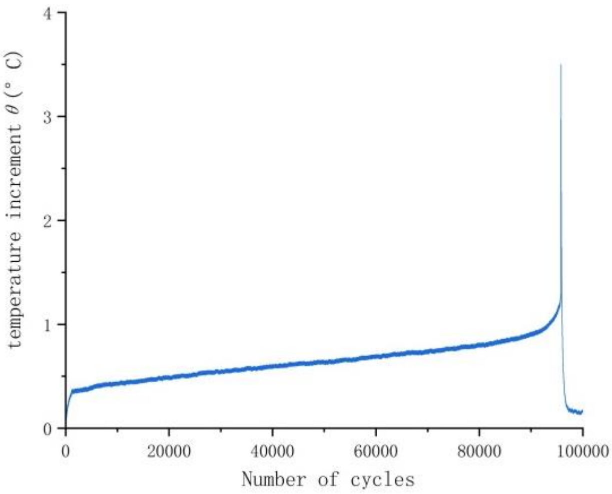

Fig. 4 Thermal change of welded joint at stress amplitude 140 MPa

2.2. Fatigue test of cruciform welded joint

According to the experimental data mentioned above, the interval dissipated energy-based model can be established. Then, based on the presented model, the fatigue life prediction of cruciform welded joints could be performed. However, in order to testify the accuracy of the suggested model, the fatigue test of cruciform welded joint is conducted. The dimension of cruciform welded joint is shown in Fig. 5 and Fig. 6. The cruciform welded joint is

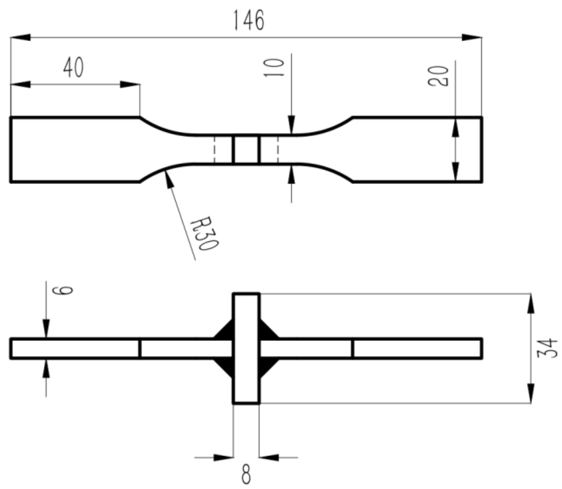

Fig. 5 Dimension of cruciform welded joint specimen

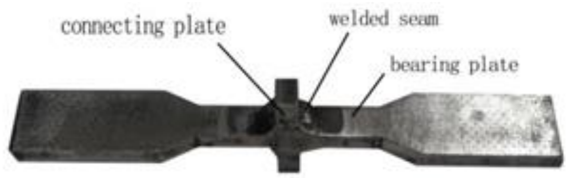

Fig. 6 Physical cruciform welded joint specimen

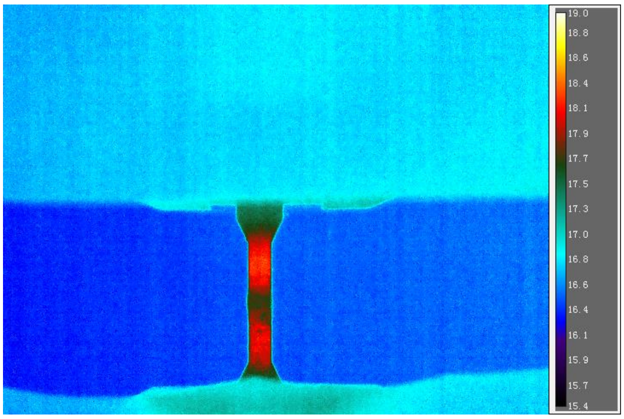

Fig. 7 Infrared thermal image of cruciform welded joint

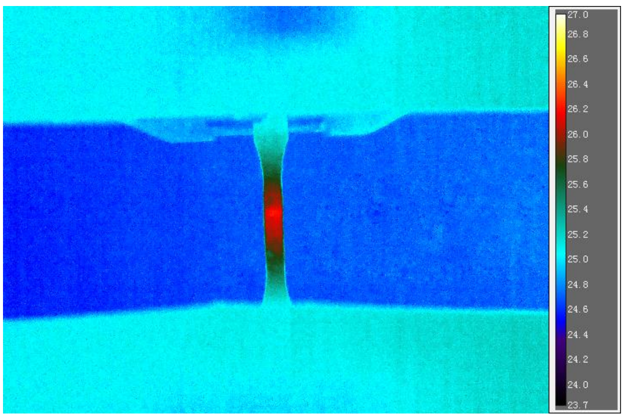

Fig. 8 Infrared thermal image of butt welded joint

load-bearing type. The thickness of bearing plate is 6 mm, and the thickness of connecting plate is 8 mm. The width of weld seam is 5 mm. Similarly, the constant amplitude fatigue tests are conducted on the specimens of cruciform welded joint at four stress ratios, R = -1, R = 0.1, R = 0.3 and R=0.5, respectively. All testing parameters are the same as the fatigue test of butt welded joint. The infrared thermal image of cruciform welded joint at stress amplitude of 150 MPa is shown in Fig. 7 and the infrared thermal image of the butt joint is shown in Fig. 8. It can be seen from the figure that the temperature shows a distribution characteristic of high at the middle and low at the ends in the axial direction of the specimen, and this distribution trend gradually becomes more obvious as the loading proceeds. Finally, the fatigue testing results are listed in Table 2.

Table 2

Experimental data of fatigue tests for cruciform welded joints

Specimen number	Stress ratio	Stress amplitude, MPa	Number of cycles
F1	-1	300	5788
F2	0.1	180	76701
F3	0.3	150	112117
F4	0.5	95	237471

3. Interval dissipation energy method

In general, the thermal increment of welded joint under cyclic loading could be described into three parts, as shown in Fig. 9 [16]. In the stage I, the temperature would rapidly increase within short time. Then, most of the lifespan will stay in the second stage, and the temperature rising rate is not too high. The temperature increment at the inflection point between stage I and stage II is defined as the asymptotic temperature θ_{AS}. After that, stage III the temperature increment will again produce rise increase until the specimen appears fatigue fracture.

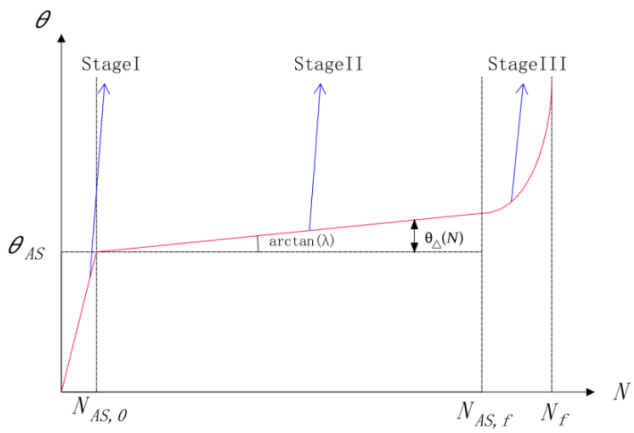

Fig. 9 Evolution of temperature increment

As like what mentioned above, the inherent dissipated energy d_1 is more suitable to characterize the fatigue damage evolution than the temperature increment θ. Based on the laws of thermodynamics and the principle of energy conservation, the inherent dissipated energy d_1 could be expressed as [17-19]:

$$d_1=\rho C\left(\frac{\partial\theta}{\partial t}+\frac{\theta}{\tau}\right), \quad (1)$$

where ρ is density, C is specific heat capacity, the temperature increment θ is equal to the difference between real-time surface temperature and initial temperature, t is time, and τ is a time constant of heat loss.

The thermal diffusion along the thickness of the specimen is assumed to be constant, and the thermal increment during the second stage is stable. Then, the asymptotic dissipated energy $d_{1,AS}$ can stand for the average dissipated energy intensity, and could be calculated as [17-19]:

$$d_{1,AS} = \rho C \frac{\theta_{AS}}{\tau} . \tag{2}$$

If the asymptotic dissipated energy $d_{1,AS}$ in each cycle during the second stage is accumulated, then fatigue failure energy tolerance E_C could be described as [17-19]:

$$E_C = \int_0^{N_f} \frac{d_{1,AS}}{f} dN , \tag{3}$$

where f is number of cycles per unit time. In fact, for the same material, the fatigue failure energy tolerance E_C tends to be a constant.

Then, based on nonlinear fatigue mechanical relationships, the asymptotic dissipated energy $d_{1,AS}$ could be rewritten as:

$$d_{1,AS} = c\left(N_f\right)^d , \tag{4}$$

where c is a coefficient of asymptotic dissipation energy and d is an exponent of asymptotic dissipation energy.

In fact, the deterministic fatigue parameters may produce the calculation deviation because of the limited fatigue test data and welding process inconsistency. In order to take uncertain factors of welding process into account, based on the interval analysis method, the asymptotic dissipated energy $d_{1,AS}$ can be transformed as:

$$log_{10}\left(d_{1,AS}\right) = d\, log_{10}\left(N_f\right) + log_{10}\left(c\right) . \tag{5}$$

Based on the least square method, Eq. (5) could be described as [17]:

$$y_i = \beta_{1i} x + \beta_{2i} ,\ \left(i = 1,\ 2,\ 3,\ ...N\right) . \tag{6}$$

The scalar equation mentioned above could be vectorized as [21]:

$$X\beta = y . \tag{7}$$

Furtherly, it can be determined as [19]:

$$X = \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{bmatrix} = \begin{bmatrix} log_{10}\left(N_{f1}\right) & 1 \\ log_{10}\left(N_{f2}\right) & 1 \\ log_{10}\left(N_{f3}\right) & 1 \\ \vdots & \vdots \\ log_{10}\left(N_{f4}\right) & 1 \end{bmatrix},$$

$$\beta = \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix},\ y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} log_{10}\left(d_{1,AS\,1}\right) \\ log_{10}\left(d_{1,AS\,2}\right) \\ log_{10}\left(d_{1,AS\,3}\right) \\ \vdots \\ log_{10}\left(d_{1,AS\,N}\right) \end{bmatrix} . \tag{8}$$

The regression coefficient could be expressed as [19]:

$$\hat{\beta}_1 = \frac{\overline{xy} - \overline{x} \times \overline{y}}{\overline{x^2} - \overline{x}^2} , \tag{9}$$

$$\hat{\beta}_2 = \overline{y} - \hat{\beta}_1 \overline{x} , \tag{10}$$

$$\overline{x} = \sum x / n,\ \overline{y} = \sum y / n . \tag{11}$$

Then, the limited original experimental data could be rearranged and expanded to produce more sample data. Based on the new data set, Eq. (5) could be rewritten as:

$$log_{10}\left(d_{1,AS_k^{i,j}}\right) = \hat{\beta}_1^{\,i,j}\ log_{10}\left(N_{f_k}\right) + \hat{\beta}_2^{\,i,j} , \tag{12}$$

where $i \in 1,\ 2,\ 3 \cdots m;\ j \in 1,\ 2,\ 3 \cdots n;\ k \in 1,\ 2,\ 3 \cdots N$.

The minimum and maximum dependent variable could be determined as:

$$log_{10}\left(d_{1,AS^i_{k_{min}}}\right) = min\Big(log_{10}\left(d_{1,AS_k^{i,1}}\right), log_{10}\left(d_{1,AS_k^{i,2}}\right), \dots\ log_{10}\left(d_{1,AS_k^{i,n}}\right)\Big), \tag{13}$$

$$log_{10}\left(d_{1,AS^i_{k_{max}}}\right) = \Big(max\, log_{10}\left(d_{1,AS_k^{i,1}}\right), log_{10}\left(d_{1,AS_k^{i,2}}\right), \dots\ log_{10}\left(d_{1,AS_k^{i,n}}\right)\Big). \tag{14}$$

Then, the minimum and maximum independent variable could be calculated as:

$$y_{i_{min}} = \begin{bmatrix} log_{10}\left(d_{1,AS^i_{1_{min}}}\right) \\ log_{10}\left(d_{1,AS^i_{2_{min}}}\right) \\ \vdots \\ log_{10}\left(d_{1,AS^i_{N_{min}}}\right) \end{bmatrix} , \tag{15}$$

$$y_{i_{max}} = \begin{bmatrix} log_{10}\left(d_{1,AS^i_{1_{max}}}\right) \\ log_{10}\left(d_{1,AS^i_{2_{max}}}\right) \\ \vdots \\ log_{10}\left(d_{1,AS^i_{N_{max}}}\right) \end{bmatrix} . \tag{16}$$

Based on the obtained data set, the new coefficients $\hat{\beta}_{i1}$ and $\hat{\beta}_{i2}$ could be characterized the uncertainties of fatigue parameters, and is described as:

$$\hat{\beta}_{i1} = \left(X^T X\right)^{-1} X^T y_{i_{min}},$$
$$\hat{\beta}_{i2} = \left(X^T X\right)^{-1} X^T y_{i_{max}} \ . \qquad (17)$$

The minimum and maximum coefficient $\hat{\beta}_{i1}$ could be expressed as:

$$\beta_1^l = min\left(\hat{\beta}_{i1_1}, \hat{\beta}_{i2_1}\right),$$
$$\beta_1^u = max\left(\hat{\beta}_{i1_1}, \hat{\beta}_{i2_1}\right), \qquad (18)$$

where β_1^l is lower bound of coefficients $\hat{\beta}_{i1}$, β_1^u is upper bound of coefficients $\hat{\beta}_{i1}$.

The minimum and maximum coefficient $\hat{\beta}_{i2}$ could be expressed as:

$$\beta_2^l = min\left(\hat{\beta}_{i1_2}, \hat{\beta}_{i2_2}\right),$$
$$\beta_2^u = max\left(\hat{\beta}_{i1_2}, \hat{\beta}_{i2_2}\right), \qquad (19)$$

where β_2^l is lower bound of coefficients $\hat{\beta}_{i2}$, β_2^u is upper bound of coefficients $\hat{\beta}_{i2}$.

Then, the upper and lower bound of coefficients $\hat{\beta}_{i1}$ and $\hat{\beta}_{i2}$ could be determined as:

$$\beta_{i1} = \left[\beta_1^l, \beta_1^u\right],$$
$$\beta_{i2} = \left[\beta_2^l, \beta_2^u\right] \ . \qquad (20)$$

Finally, the interval asymptotic dissipated energy can be described as:

$$d_{1,AS}^I = C^I \left(N_f^I\right)^{d^I}, \qquad (21)$$

where $d_{1,AS}^I$ is interval asymptotic dissipated energy, C^I is interval coefficient of asymptotic dissipation energy, d^I is interval exponent of asymptotic dissipation energy. N_f^I is interval of fatigue life.

Similarly, the interval of fatigue life could be expressed as:

$$N_f^I = \left[\underline{N_f}, \overline{N_f}\right] \qquad (22)$$

where $\underline{N_f}$ is lower bound of interval fatigue life N_f^I, $\overline{N_f}$ is upper bound of interval fatigue life N_f^I.

4. Results

According to the experimental data and Eq. (2), the asymptotic dissipation energy at different stress amplitudes and stress ratios could be calculated, as listed in Table 3. Then, the relationship between asymptotic dissipated energy and fatigue life in double logarithmic coordinates can be displayed in Fig. 10.

Table 3

Dissipated energy of butt-welded joints under cyclic loadings

Specimen number	Asymptotic dissipation energy $d_{1,AS}$, J/m³	Number of cycles
F07	157140	6562
F08	95243	16804
F09	59448	44634
F10	78835	83894
F11	46127	142021
F12	55304	94450
F13	42754	165346

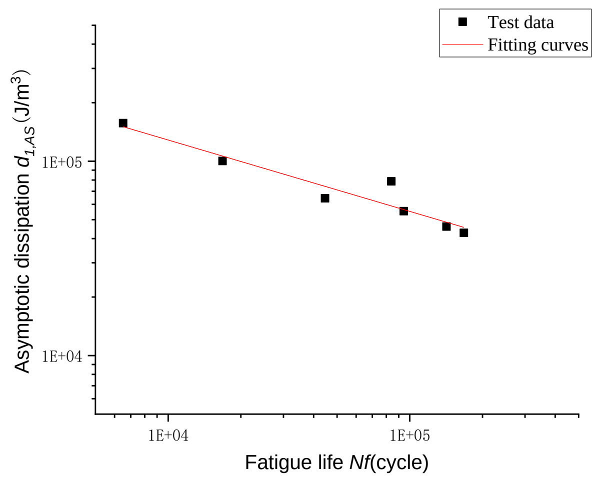

Fig. 10 Relationship between asymptotic dissipated energy and fatigue life in double logarithmic coordinates

According to Eq. (4) and experimental data, the coefficient of asymptotic dissipation energy C is 3.459×10^6, and the exponent of asymptotic dissipation energy d is -0.361. Then, the experimental data could be expanded by the interval dissipated energy method. According to the Eq. (21), the upper bound and lower bound of fatigue parameters β_1, β_2, C and d could be determined as listed in Table 4.

Then, the interval curve between asymptotic dissipated energy and fatigue life can be obtained, as shown in Fig. 11. It could be clearly seen that the interval band formed by the interval curve includes all experimental data, even some points attach the boundary line. Finally, the recorded test data and the predicted fatigue life intervals are shown in Table 5.

Based on the interval dissipated energy model, the fatigue life at different stress ratios can be evaluated by the asymptotic temperature θ_{AS} of cruciform welded joint. In fact, the asymptotic temperature θ_{AS} can be obtained from the early cyclic tests of cruciform welded joint. Then, the

Table 4

Interval fatigue parameters

Fatigue parameters	Initial value	Upper bound	Lower bound
β_1	-0.361	-0.349	-0.382
β_2	6.539	6.618	6.489
C	3.459×10^6	4.160×10^6	3.083×10^6
d	-0.361	-0.308	-0.382

Table 5

Cross-joint test data

Specimen number	Stress ratio	Actual life	Upper limit of predicted life	Lower limit of predicted life
F1	-1	5788	11935	2421
F3	0.1	76701	86133	14733
F8	0.3	112117	237861	37261
F9	0.5	237471	497289	73092

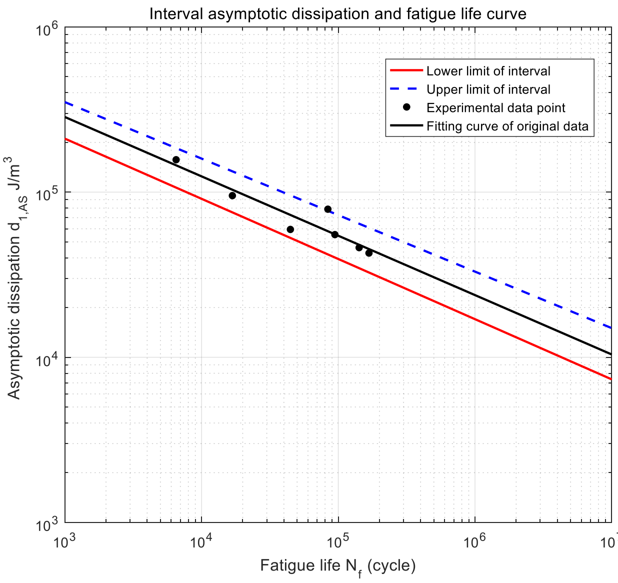

Fig. 11 Interval curve of asymptotic dissipated energy and fatigue life in double logarithmic coordinates

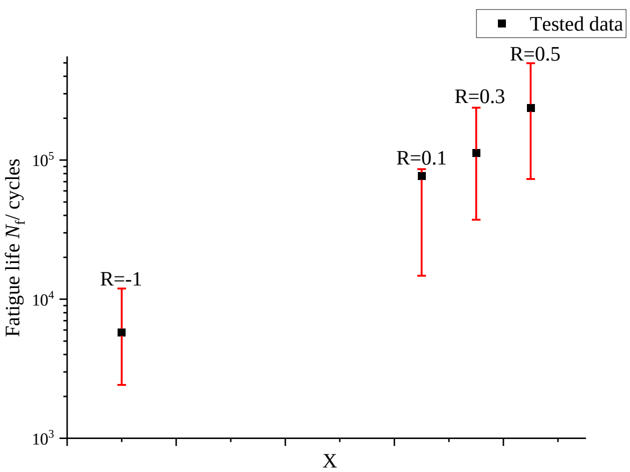

Fig. 12 Interval fatigue life estimation of cruciform welded joints under different stress ratios

predicted interval fatigue life of cruciform welded joint is shown in Fig. 12. It is clearly seen that the experimental data fells into the interval bounds, and most of them stays in the middle of interval range, which means that the calculated data agrees well with the experimental results.

5. Conclusions

The energy dissipation method can efficiently, rapidly and accurately evaluate the fatigue life of specimens under limited test sample conditions with the help of infrared thermography only. Meanwhile, to address the multi-source uncertainties generated during the welding design and manufacturing process, an interval energy dissipation-based fatigue life prediction method is constructed by combining the energy dissipation and interval analysis methods. It provides a new way of thinking for the fatigue life prediction of high-strength steel welds under the energy dissipation mechanism, so that the fatigue life of specimens can be evaluated in a more comprehensive way.

In this paper, the uncertain factors caused by the welding process are considered into the fatigue damage model, a dissipated energy-based interval fatigue life estimation approach is proposed. Infrared thermography fatigue tests of butt welded joint and cruciform welded joint under different stress amplitudes and stress ratios are performed. Then, the asymptotic dissipated energy is defined, and the interval energy dissipation model is established by rearranging and expanding the experimental data. Based on the presented model and experimental results, the interval fatigue parameters are determined. According to the interval curve of asymptotic dissipated energy and fatigue life, the predicted lifetime of cruciform welded joint under different stress ratios agrees well with the testing data.

Acknowledgments

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Conflict of interests

The authors have no conflict of interests with respect to the publication of this paper.

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FATIGUE LIFE ASSESSMENT OF CRUCIFORM WELDED JOINTS BASED ON INTERVAL DISSIPATION ENERGY METHOD

S u m m a r y

In order to take uncertain factors of welding process into account, a dissipated energy-based interval fatigue life estimation approach is presented in this paper. The infrared thermography fatigue life tests are conducted on the specimens of butt-welded joints and cruciform welded joints. Then, the dissipated energy-based interval fatigue life prediction model is built, while interval fatigue parameters are determined and interval curve of asymptotic dissipated energy and fatigue life is obtained. The lifetime assessment of cruciform welded joints based on the suggested model is performed, and the predicted results agree well with the experimental data.

Keywords: energy dissipation; fatigue life prediction; cruciform welded joints; interval method

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