



ORIGINAL RESEARCH ARTICLE

A Fatigue Life Prediction Approach for Resistance Spot Welded Joints with Consideration of the Stress Ratio Effect

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Fatigue lives of ST12 lap-shear resistance spot welded joints have been tested under the stress ratios of $R = 0.4, 0.2$ and 0.06 . The experimental results reveal that fatigue lives are significantly affected by stress ratios. Subsequently, the growth rate curves for fatigue cracks on ST12 low carbon steel plates under the stress ratios of $R = -1.0, -0.3, 0.2$ are tested, respectively, and the $da/dN - \Delta K_{eff}$ curve of the material is derived by using the Newman's opening stress equation. Finally, with the findings of the study, a new approach for predicting fatigue lives of spot welded joints which can take the stress ratio effect into consideration is proposed. The accuracy of the approach has been verified using experimental data, which demonstrates good agreement of the fatigue lives from the predictions and the experimental measurements. These findings have important implications for understanding the spot welded joints with respect to their fatigue behaviors under cyclic loadings, particularly in scenarios where fatigue lives may be significantly impacted by stress ratios.

Keywords crack closure, fatigue crack growth, fatigue life prediction, spot welded joint, stress ratio

1. Introduction

Determining how to rapidly and accurately assess the durability, and therefore ensuring the structural safety under both current and future operational environment is an important issue (Ref 1-4). All existing assessment methods have their own limitations. It has great significance to develop and improve new durability assessment methods. Resistance spot welding is a common and important technology in connecting metal plates by applying pressure and heat. It has advantages in welding efficiency and quality for automation and be widely used in fabricating sheet assemblies like vehicles, truck cabins, rail vehicles. As an example, a contemporary automotive body assembly requires 8000-10,000 welding spots (Ref 5). Due to the high stress concentration around a weld nugget edge, welding spots are often the weakest parts in an entire structure. Meanwhile, when a spot welded joint is subjected to cyclic loadings, fatigue cracks will firstly initiate at the weld nugget edge with high stress concentration and then will propagate along the plate thickness direction until final failure. Fatigue problems occur frequently and are recognized as the main mode of failure. Enhancing the predictions of fatigue lives for resistance spot welded joints can shorten the development cycle

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List of symbols

da/dN	Crack growth rate
c, m	Paris material constants
ΔK_{eff}	Effective stress intensity factor range
K_{max}	Maximum stress intensity factor
K_{op}	Crack opening stress intensity factor
ΔK_{eff}	Effective stress intensity factor range
$\sigma_{n,max}$	Maximum nominal stress
m_1	Material constants
K_I	Mode I global stress intensity factor
K_{II}	Mode II global stress intensity factor
P	Load applied to the sheet
d	Nugget diameter
t	Sheet thickness
k_I	Mode I local stress intensity factor
k_{II}	Mode II local stress intensity factor
α	Kink angle
k_{eq}	Equivalent stress intensity factor
γ	Empirical constant
U	Crack open ratio
R	Stress ratio
$\Delta k_{eq,eff}$	Effective stress intensity factor range for the local equivalent stress intensity factor
$k_{eq,max}$	Maximum local equivalent stress intensity factor
$k_{I,max}$	Maximum local mode I stress intensity factor
$k_{II,max}$	Maximum local mode II stress intensity factor
$K_{I,max}$	Maximum global mode I stress intensity factor
$K_{II,max}$	Maximum global mode II stress intensity factor
P_{max}	Maximum applied load
S_{max}	Maximum applied stress
S_{op}	Crack opening stress
β	Constraint factor
σ_O	Flow stress

and reduce the development cost for a spot welded structure in design phase, and ensure that the structure can operate within a safe lifespan without or with less major accidents during a service period. These factors drive the establishment of fatigue life prediction methods for the joints.

Given the significance of this issue, many different fatigue life prediction methods have been developed for spot welded joints, e.g., the S–N curve method, the local stress-strain method (Ref 6), the volumetric method (Ref 7), the natural frequency method (Ref 8, 9), the interpolation-extrapolation method (Ref 10), the damage tolerance reliability analysis Method (Ref 11), the strain energy density factor method (Ref 12), the structural stress method (Ref 13), the thermodynamic entropy Method (Ref 14), the notch stress approach (Ref 15), the maximum principal strain approach (Ref 16).

As is known to all, a material's fatigue life includes typically two distinct components: One is the fatigue crack initiation life, the other is the fatigue crack growth life (Ref 17). However, with regard to spot-welded joints, sharp notches present on the edge of a weld nugget (Ref 18) make it possible to neglect the fatigue crack initiation life and to predict the total fatigue life with calculation using a crack growth method based on fracture mechanics (Ref 19-25). To model how the stress intensity factor (SIF) range is correlated together with the fatigue crack growth rate in a spot welded joint, researchers often turn to the Paris' law (Ref 26, 27). This correlation is typically expressed using Eq 1, which has been shown to be effective in describing the growth rate of a fatigue crack to the SIF range.

$$\frac{da}{dN} = c(\Delta K)^m \quad (\text{Eq 1})$$

herein a is defined as the crack length, N as the cycle life or number, ΔK as the range for the SIF, whereas c and m represent the material constants. Despite its usefulness, the Paris' law only considers the correlation of the fatigue crack growth rate with the SIF range (ΔK). However, in practice the fatigue crack rate depends not only on ΔK but also on the stress ratio R . This means that a single set of c and m values may not be sufficient to accurately capture the effect of R for fatigue cracks with respect to their growth rates. Therefore, the influence of R over the rate of crack growth may not be fully accounted for when using Paris' law for the predictions of the fatigue lives for spot welded joints. To address this limitation, more sophisticated approaches that incorporate the influence of R over the growth behaviors of fatigue cracks are required.

Since crack growth rates are correlated with stress ratios in the description of crack growth with the driving force of the SIF range, Elber proposed to use the effective SIF range instead of the total SIF range as the driving factor to describe crack growth behaviors (Ref 28), and to employ a single curve unifying the rate curves for crack growth in varied stress conditions (Ref 29). The definition of the effective SIF range (ΔK_{eff}) is as follows:

$$\Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{op}} \quad (\text{Eq 2})$$

Here K_{max} denotes the maximum SIF in a load cycle, and K_{op} represents the crack opening SIF. The relation between the growth rate of a fatigue crack da/dN and ΔK_{eff} is expressed in following Eq 3:

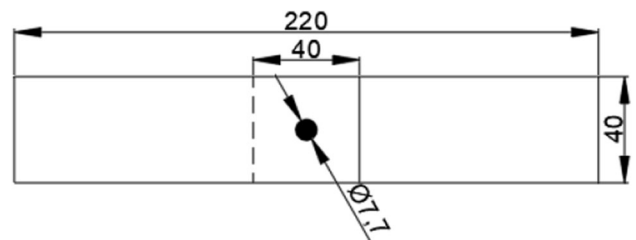
$$\frac{da}{dN} = c_1(\Delta K_{\text{eff}})^{m_1} \quad (\text{Eq 3})$$

In this equation, c_1 and m_1 are the material constants that differ from those in Eq 1 represented by c and m , respectively.

Stress ratios are one of the important influence factors for fatigue lives of spot welded joints. Greater errors will occur if the influence of stress ratios is ignored. In this manuscript, ΔK_{eff} instead of ΔK is used as the crack growth driving force to deal with the problem of the mixed mode (I and II) crack growth behavior during the failure process of a spot welded joint, and then a fatigue life prediction method for lap-shear resistance spot welded joints made of low carbon steel which can consider the influence of stress ratios on fatigue lives is established. To verify the effectiveness of this established method, fatigue lives of ST12 lap-shear resistance spot welded joints under the different stress ratios ($R = 0.4, 0.2, 0.06$) have been tested. In addition, for obtaining the $da/dN - \Delta K_{\text{eff}}$ curve of the material, we have conducted fatigue crack growth tests on ST12 low carbon steel plates under the loading conditions of stress ratios $R = -1.0, -0.3, 0.2$. By comparison of the fatigue lives calculated using the established method with the test results, a great effectiveness is observed for the established method.

2. Experiments

Figure 1 shows the lap-shear spot welded joint specimen used in fatigue life tests and the test process. The material is ST12 low carbon steel plates with a thickness of 1.6 mm. The chemical composition as well as the welding parameters of the specimen is summarized in Tables 1 and 2, separately. A 10 Hz sinusoidal loading waveform is adopted in the tests. In all the tests, complete rupture is applied as the failure criteria. Fatigue lives under three varied stress conditions ($R = 0.4, 0.2, 0.06$) are tested. The tested fatigue lives are illustrated in Fig. 2. The



(a) Specimen (mm)



(b) Fatigue life test

Fig. 1 Specimen and fatigue life test. (a) Specimen (mm). (b) Fatigue life test

Table 1 Chemical composition (wt.%) of ST12 low carbon steel plate (Bal: the rest of composition)

C	Si	Mn	P	S	Fe
≤ 0.08	≤ 0.10	≤ 0.50	≤ 0.035	≤ 0.035	Bal

Table 2 Welding parameters

Welding current, A	Welding time, cycle	Electrode pressure, N	Diameter of electrode end face, mm
7150	15	2000	6



Fig. 4 Fatigue crack growth test

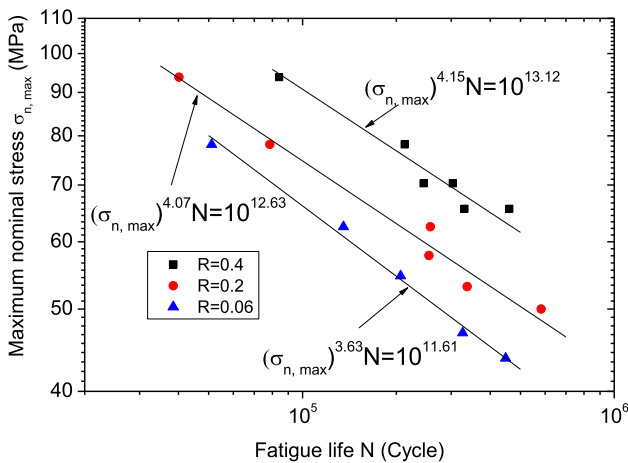


Fig. 2 Tested fatigue lives of Spot-Welded joints

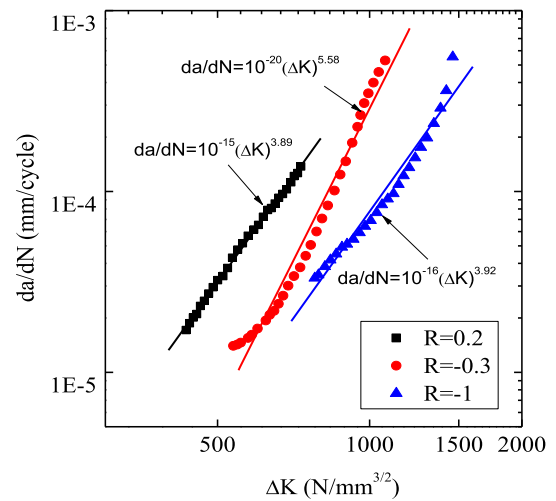


Fig. 5 Fatigue crack growth rates under different stress ratios

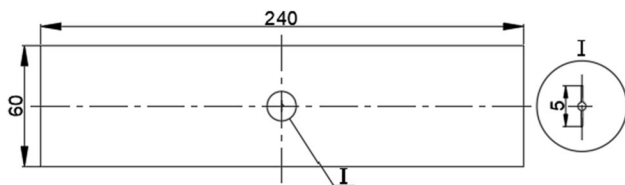


Fig. 3 Center cracked tensile specimen (mm)

results reveal an clear increase in the fatigue life with an increase of the stress ratio when the maximum nominal stress is held constant, and a significant influence of stress ratios on ST12 lap-shear welded joints with respect to their fatigue lives.

The center-cracked tensile (CCT) fatigue specimen tested for fatigue crack growth rates is shown in Fig. 3. The material is ST12 low carbon steel plates with a thickness of 3 mm. The growth rates of fatigue cracks under three varied stress ratio ($R = -1, -0.3$ and 0.2) are tested in accordance with ASTM E647-11 (Ref 30). A 10 Hz sinusoidal loading waveform is adopted in the tests. As shown in Fig. 4, an anti-buckling guide is utilized to prevent buckling caused by the compressive loadings at $R = -1$ and -0.3 . The test results are presented in Fig. 5. It can be found that the $da/dN - \Delta K$ data present a linear relationship and has a Paris-like form when plotted on a log-log scale. The exponents are 3.89, 5.58, 3.92 when the stress ratios are 0.2, -0.3 , -1 , respectively.

3. Proposed Approach

The life of fatigue crack initiation account for a small proportion for a spot welded joint compared with its total fatigue life. Therefore, we can establish a crack growth method to predict the total fatigue life. Obviously, the process of fatigue failure for a spot welded joint shows a three-dimensional crack behavior. As shown in Fig. 6, we firstly reduce the three-dimensional crack behavior to a two-dimensional form to simplify the calculation (Ref 31). Points A and B are the most dangerous locations where cracks will initiate because of the high stress concentration at these locations. Moreover, these locations can be regarded as crack tips, since the weld nugget edge is extremely sharp. The global SIF is then defined for the SIFs at both points A and B. The calculation of the values could be performed with the following equations (Ref 32):

$$K_I = \frac{P}{d\sqrt{d}} \left[0.964 \left(\frac{d}{t} \right)^{0.397} \right] \quad (\text{Eq 4})$$

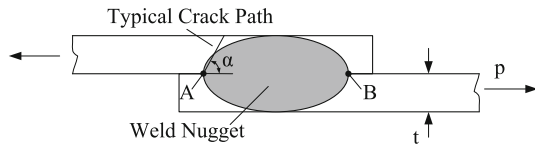


Fig. 6 A schematic of the cross section near a weld nugget

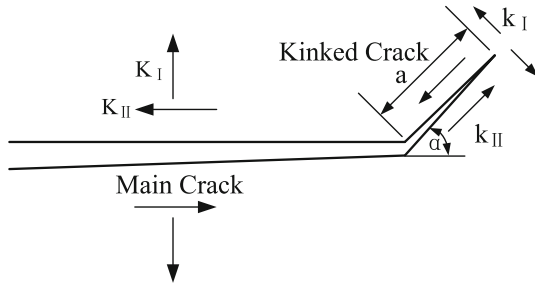


Fig. 7 A schematic of a kinked crack

$$K_{II} = \frac{P}{d\sqrt{d}} \left[0.798 + 0.458 \left(\frac{d}{t} \right)^{0.710} \right] \quad (\text{Eq 5})$$

wherein P is as the load applied to the sheet, K_I and K_{II} are as the mode I and mode II global SIFs, respectively, whereas d and t are defined to be the weld nugget diameter as well as the thickness of the sheet, separately. Specifically, d is 7.7 mm and t is 3 mm for the joints in present work.

The schematic of a kinked crack during the fatigue failure process of a spot welded joint is shown in Fig. 7. It will pass through the plate thickness direction with a kink angle α until the final unstable fracture. To make a distinction with the global SIFs, the SIFs of the kinked crack are defined to be the local SIF, which are represented by k_I and k_{II} for the mode I and mode II respectively. In the figure, the arrows point to the positive directions for K_I , K_{II} , k_I and k_{II} . From a previous study, when the length of the kinked crack is near zero, the local SIFs could be determined by their functional relationships with the global SIFs and the kink angle α (Ref 33). Specifically, we have Eq 6 and 7.

$$k_I = \frac{1}{4} \left(3 \cos \frac{\alpha}{2} + \cos \frac{3\alpha}{2} \right) K_I + \frac{3}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_{II} \quad (\text{Eq 6})$$

$$k_{II} = -\frac{1}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_I + \frac{1}{4} \left(\cos \frac{\alpha}{2} + 3 \cos \frac{3\alpha}{2} \right) K_{II} \quad (\text{Eq 7})$$

As shown in Eq 6 and 7, the kink angle α should be firstly determined when calculating the local SIFs. For determining the kink angle α , we assume that the maximum principal normal stress direction before the kinked crack growth is normal to its subsequent growth direction (Ref 32). Subsequently, the parameter kink angle α can be defined in Eq 8 based on the crack-tip singularity field equations by which the principal stress directions for the mixed mode (I and II) crack can be found (Ref 34).

$$K_I \sin \alpha = -K_{II} (3 \cos \alpha - 1) \quad (\text{Eq 8})$$

The concept of local equivalent SIF can be employed for calculating the mixed mode (I and II) crack propagation type in the fatigue failure process of a spot welded joint, which can be defined as Eq 9 (Ref 35):

$$k_{eq} = \sqrt{k_I^2 + \gamma k_{II}^2} \quad (\text{Eq 9})$$

wherein the empirical constant γ is defined for considering the sensitivity to the local mode II loading during the mixed fatigue crack growth.

Now the crack growth life for a spot welded joint can be calculated according to the concept of crack closure, where the correlation of ΔK_{eff} with ΔK is shown in Eq 10.

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{\Delta K_{eff}}{K_{max}(1-R)} \quad (\text{Eq 10})$$

where U is the crack open ratio, and related to R , the crack tip constraint, the material property and so on. R has the most serious impact and is the dominant factor among all the factors that affect U (Ref 36). As presented in Eq 11, the crack opening ratio U for structural steels was proposed to have a function relation with the stress ratio R (Ref 37).

$$U = 0.75 + 0.25R \quad (\text{Eq 11})$$

Combining Eq 10 and 11, the effective SIF range for the local equivalent SIF, $\Delta k_{eq,eff}$, could be obtained by Eq 12.

$$\Delta k_{eq,eff} = (0.75 + 0.25R) [k_{eq,max}(1-R)] \quad (\text{Eq 12})$$

where $k_{eq,max}$ is the maximum local equivalent SIF, which can be calculated with Eq. 13 from Eq 9.

$$k_{eq,max} = \sqrt{k_{I,max}^2 + \gamma k_{II,max}^2} \quad (\text{Eq 13})$$

wherein $k_{I,max}$ and $k_{II,max}$ are the maximum local mode I and mode II SIFs for the kinked crack, respectively. From Eq 6 and 7, the $k_{I,max}$ and $k_{II,max}$ can be obtained by Eq 14 and 15.

$$k_{I,max} = \frac{1}{4} \left(3 \cos \frac{\alpha}{2} + \cos \frac{3\alpha}{2} \right) K_{I,max} + \frac{3}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_{II,max} \quad (\text{Eq 14})$$

$$k_{II,max} = -\frac{1}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_{I,max} + \frac{1}{4} \left(\cos \frac{\alpha}{2} + 3 \cos \frac{3\alpha}{2} \right) K_{II,max} \quad (\text{Eq 15})$$

wherein $K_{I,max}$ and $K_{II,max}$ are the maximum global mode I and II SIFs, respectively. From Eq 4 and 5, the $K_{I,max}$ and $K_{II,max}$ can be obtained by Eq 16 and 17.

$$K_{I,max} = \frac{P_{max}}{d\sqrt{d}} \left[0.964 \left(\frac{d}{t} \right)^{0.397} \right] \quad (\text{Eq 16})$$

$$K_{II,max} = \frac{P_{max}}{d\sqrt{d}} \left[0.798 + 0.458 \left(\frac{d}{t} \right)^{0.710} \right] \quad (\text{Eq 17})$$

where P_{max} is the maximum applied load.

Now we can adopt Eq 3 to describe the fatigue crack growth in a spot welded joint as Eq 18.

$$\frac{da}{dN} = c_1 (\Delta k_{eq,eff})^{m_1} \quad (\text{Eq 18})$$

It has been noted that, when the ratio of t/d is small and the loading condition is a constant amplitude loading, it has been found that the growth rate of the kinked crack remains nearly constant during the test proceeding (Ref 38). This suggests that the local SIFs can be considered to keep approximately constant during the growth of the kinked crack. In addition, if we assume a joint will fracture when the kinked crack completely penetrates the plate thickness, it is possible to determine the overall distance of the crack growth using the kink angle α together with the parameter of sheet thickness t (Fig. 6), which is equal to $t/\sin \alpha$. Finally, the fatigue life of a spot welded joint could be achieved using Eq 19.

$$N = \frac{t}{c_1 (\Delta k_{eq,eff})^{m_1} \sin \alpha} \quad (\text{Eq 19})$$

4. Experimental Verification

4.1 Determination of $da/dN - DK_{eff}$ Curve

The $da/dN - \Delta K_{eff}$ curve is requisite when predicting fatigue lives using the proposed method from the above description. In the present work, the $da/dN - \Delta K_{eff}$ curve of ST12 low carbon steel is obtained by using the Newman's opening stress equation (Ref 39) to correlate the $da/dN - \Delta K$ values at varied stress ratios. The equation is as follows:

$$\frac{S_{op}}{S_{max}} = A_0 + A_1 R + A_2 R^2 + A_3 R^3, \quad R \geq 0 \quad (\text{Eq 20})$$

$$\frac{S_{op}}{S_{max}} = A_0 + A_1 R, \quad -1 \leq R < 0 \quad (\text{Eq 21})$$

wherein S_{max} is the maximum applied stress, and S_{op} is the crack opening stress. A_0, A_1, A_2, A_3 can be calculated with the equations below:

$$A_0 = (0.825 - 0.34\beta + 0.05\beta^2) \left[\cos\left(\frac{\pi S_{max}}{2 \sigma_O}\right) \right]^{1/\beta} \quad (\text{Eq 22})$$

$$A_1 = (0.415 - 0.071\beta) \frac{S_{max}}{\sigma_O} \quad (\text{Eq 23})$$

$$A_2 = 1 - A_0 - A_1 - A_3 \quad (\text{Eq 24})$$

$$A_3 = 2A_0 + A_1 - 1 \quad (\text{Eq 25})$$

where σ_O is the flow stress, which acts as the mean value for the ultimate tensile strength as well as the yield stress. The value of σ_O for ST12 low carbon steel equals to 200MPa. The constraint factor β is usually achieved by a trial-and-error process. It is possible to determine its value in case the growth rate data of fatigue cracks under different ratios from a wide range are well correlated. For ST12 low carbon steel, β is determined to be 0.1.

The $da/dN - \Delta K$ values under the three varied stress ratios of $R = 0.2, -0.3, -1$ in Fig. 5 are replotted as the form of $da/dN - \Delta K_{eff}$

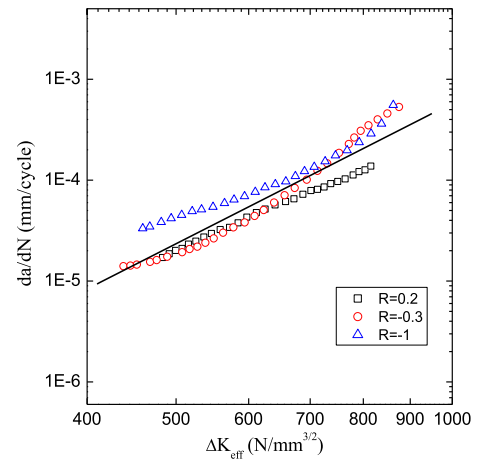


Fig. 8 $da/dN - \Delta K_{eff}$ curve for ST12 low carbon steels

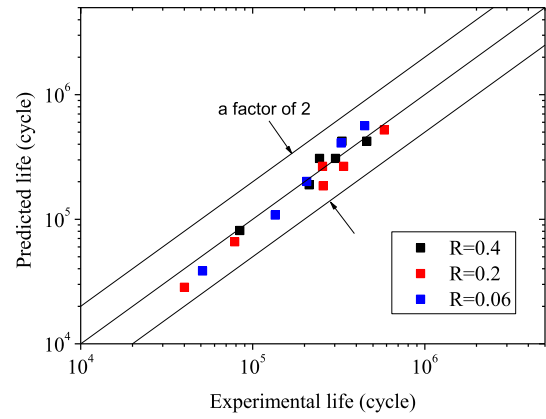


Fig. 9 Fatigue life prediction results

$dN - \Delta K_{eff}$ using the equation. The as-resulted data are presented in the Fig. 8, where the most data of $da/dN - \Delta K_{eff}$ under the varied stress ratios are observed to converge into an arrow band leading to a nearly single fatigue crack growth curve. By fitting the $da/dN - \Delta K_{eff}$ values, the two constants c_1 and m_1 of Eq 3 are calculated to be $c_1 = 10^{-17.12}$ and $m_1 = 4.63$ (da/dN with unit of mm/cycle and ΔK_{eff} of $N \text{ mm}^{-3/2}$), respectively.

4.2 Results of Fatigue Life Prediction

The fatigue lives of the ST12 spot welded joints as shown in Fig. 2 are predicted using the approach proposed in this work. The empirical constant γ in Eq 9 is taken as 1 in the predictions without attempt to adjust any value to fit experimental data. Figure 9 and Table 3 present the predicted results. A good agreement was observed between the predicted and experimental lives at the different stress ratios $R = 0.4, 0.2, 0.06$, in which the predicted fatigue lives are found to be within a scatter band of factor 2 for all the cases.

Table 3 Fatigue life predicted results

Specimen no	Maximum nominal stress, MPa	Stress ratio	Experimental fatigue life N_E , cycle	Predicted fatigue life N_P , cycle	N_P/N_E
1	78.125	0.4	212936	188760	0.89
2	65.625	0.4	331084	423153	1.28
3	65.625	0.4	460602	423153	0.92
4	70.3125	0.4	244632	307445	1.26
5	70.3125	0.4	303389	307445	1.01
6	93.75	0.4	84093	81152	0.97
7	93.75	0.2	40154	28362	0.71
8	78.125	0.2	78613	65970	0.84
9	62.5	0.2	257139	185371	0.72
10	57.8125	0.2	254577	265953	1.04
11	53.125	0.2	337487	265953	0.79
12	50	0.2	583353	520876	0.89
13	78.125	0.06	51125	38462	0.75
14	62.5	0.06	135282	108074	0.80
15	46.875	0.06	326537	409436	1.25
16	54.6875	0.06	206308	200550	0.97
17	43.75	0.06	448426	563528	1.26

5. Discussion

The fatigue lives for ST12 resistance spot welded joints at $R = 0.4, 0.2, 0.06$ are tested. A significant impact of stress ratios on fatigue lives has been observed, which indicated that the impact of stress ratios cannot be ignored in fatigue life predictions. Meanwhile, the fatigue crack growth rates of ST12 low carbon steel plates at $R = -1, -0.3$ and 0.2 are tested using CCT specimens. The $da/dN - \Delta K$ data are found to have a Paris-like form when plotted on a log-log scale, and the Paris constants c, m for the three different stress ratios are determined. Subsequently, the required $da/dN - \Delta K_{eff}$ curve when predicting fatigue lives by the proposed method is obtained by combining the tested $da/dN - \Delta K$ data and the Newman's opening stress equation.

Due to the existence of a nugget edge which can behave as a sharp crack, it is reasonable to consider that fatigue lives of resistance spot welded joints are dominated by the lives of crack growth and can be calculated based on fracture mechanics. The Paris' law is often used for the calculation of fatigue crack growth. However, the two constants of c and m for the Paris' law are related to stress ratios, and the crack growth at different stress ratios cannot be described using a single set of c and m values. Furthermore, as the fatigue lives of ST12 spot welded joints at $R = 0.4, 0.2, 0.06$ plotted in Fig. 2, the influence of stress ratios over fatigue lives for spot welded joints is obvious and cannot be neglected in fatigue life predictions. So errors are inevitable when calculating the fatigue lives of spot welded joints at varied stress ratios using single material constants of c and m . Aiming at obtaining more accurate predictions by using the Paris' law, it would require extensive crack growth experiments to determine the material constants of c and m under different stress ratios.

In the present work, a new method based on fracture mechanics for predicting fatigue lives of lap-shear resistance spot welded joints made of low carbon steel has been proposed, which can take the stress ratio effect over fatigue lives into consideration. In this method, when the loading amplitude applied to a spot welded joint is identical, the alteration of stress ratio will change the crack opening ratio U , then affect $\Delta k_{eq,eff}$,

and result in the ultimate influence on the predicted fatigue life. Different from the existing fracture mechanics methods for spot welded joints, ΔK_{eff} instead of ΔK is used as the crack growth driving force to deal with the problem of the mixed mode (I and II) crack growth during the failure process of a spot welded joint. The fatigue crack growth life is calculated according to the $da/dN - \Delta K_{eff}$ curve, where the constants c_1 and m_1 are independent of stress ratios for a given material and can be obtained by combining the tested fatigue crack growth data under the constant amplitude loading conditions of several different stress ratios with the Newman's opening stress equation. An experimental verification with varied stress ratios in a wide range confirms the validity of the developed prediction approach for analyzing the fatigue lives of spot welded joints, in which the predicted fatigue lives are found to be within a scatter band of factor 2. From the outcomes of this study, a fatigue prediction method for spot welded joints under variable amplitude loading conditions may be able to be established based on the concept of crack closure combined with a cycle count method in the future research.

Moreover, the local parts of spot weld joints are composed of the fusion zone, the heat affected zone, and the base material zone. The fatigue failure of a spot welded joint usually starts from the weld nugget edge, and the fatigue crack will pass through the different zones during an entire failure process. Strictly speaking, since the mechanical properties of the materials in the various zones are different, the fatigue crack growth curves of the materials in various zones are needed for accurate fatigue life predictions. However, it can be found that the prediction accuracy is acceptable for resistance spot welded joints made of low carbon steel using only the crack growth curve of the base material from the fatigue life prediction results in this work.

6. Conclusions

A new method based on crack closure for predicting the fatigue lives of lap-shear resistance spot welded joints made of low carbon steel under constant amplitude loading conditions is

proposed and investigated in this study. The conclusions are summarized as follows:

1. The fatigue lives of ST12 resistance spot welded joints are tested at $R = 0.4, 0.2, 0.06$, revealing an obvious influence of stress ratios on fatigue lives.
2. The $da/dN - \Delta K$ curves at $R = -1, -0.3$ and 0.2 for ST12 low carbon steel plates are tested. Stress ratios are found to have a pronounced effect on the fatigue crack growth rate, and the $da/dN - \Delta K_{\text{eff}}$ curve of the material is derived from the relevant $da/dN - \Delta K$ data at different stress ratios using the Newman's opening stress equation.
3. A new approach which considers the stress ratio effect on fatigue lives is proposed. Experimental verification demonstrates that the approach can provide accurate fatigue life predictions for resistance spot welded joints.

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