Evaluating the Effects of Overload and Welding Residual Stress in Fatigue Crack Propagation

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Received: 13 April 2018, Revised: 18 July 2018, Accepted: 27 September 2018

Abstract: In this paper, a suitable method is presented to predicate fatigue crack propagation for cyclic loading with overload in residual stresses field resulted by weld. For this, first effective stress intensity factor (SIF) and effective cycle ratio (R) are introduced as function depending on SIFs resulted by external load, weld residual stress and overload. Weight function is applied to calculate SIF resulted by weld residual stress. Also, a method is introduced to determine overload SIF and overload stress ratio. Then fatigue crack propagation equation is modified for our purpose. In other words, a simple and efficient method is presented in this paper for predicting fatigue crack propagation rate in welded joints when the overload is happening. Finally, for evaluating this modified equation, experimental methods are applied. Test samples were M(T) geometry made of aluminum alloy with a longitudinal weld by the Gas Tungsten arc welding process. Modified equation has a good agreement with the experimental model presented in this field.

Keywords: Fatigue Crack Propagation, Residual Stress, Stress Intensity Factor, Weight Function

Reference: Ali Moarrefzadeh, Shahram Shahrooi and Mahdi Jalali Azizpour, M., "Evaluating the Effects of Overload and Weld Residual Stress in Fatigue Crack Propagation", Int J of Advanced Design and Manufacturing Technology, Vol. 12/No. 1, 2019, pp. 83–91.

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1 INTRODUCTION

The main reason for the danger of fatigue fracture is that it occurs without prior knowledge and visibility. Despite of the significant advantages of different methods of welding, produced residual stresses are inevitable detriment in manufacturing processes. The residual stresses caused by heating and cooling workpieces during the welding process and irreversible deforming have a significant effect on the fatigue life. Large tensile residual stresses in the weld area may cause brittle fracture, reduced fatigue life and developments of cracks caused by corrosion stresses. Hence, the study of these phenomena and of any method that would lead to the prediction and estimation of fatigue life of parts in the industry will be important.

Most of engineering structures are affected by cyclic loading that this subject results in consisting plastic zone at crack tip. The interference of this plastic zones in different loadings results in increasing or decreasing of FCP. The study of how this changes take place in special overload cases gives a deeper estimate of FCP.

In the recent researches, several studies were done on the residual stresses in weldments. It was determined that the welding has some important effects on the strength of materials: the properties of the base metal on near zones of welded areas were changed. The properties of weld metal were different and weaker than the base metal. The welding process induces tension residual stresses in the weld affected zones. Different types of faults such as cracks may be created in the metal. Residual stresses and weld defects together have critical and risky effects on the structures. Under fatigue loading, the static residual stresses change the life of components. These variations are introduced in both initiation and growth of fatigue cracks [1-3]. Also crack growth affects the residual stresses distributions [4-6]. Welding also produces adverse effects on fatigue crack propagation (FCP) rate due to thermal residual stresses, local distortions (especially in thin alloy sheets and the microstructure changes in the heat-affected zones (HAZ). Whereas all of these affect the FCP rates, thermal residual stress has been identified as the most influential factor, and this was demonstrated in the friction stir welds [7] and plasma welds [8]. Efforts have been devoted to the investigation of residual stress effect on FCP rates.

Teng and Chang [9], accomplished a research on residual stress effect on FCP during which they determined the residual stress by elastoplastic analysis. Suresh and Varghese [10], accomplished a numerical simulation of weld residual stress and obtained temperature field and residual stress of workpiece. The principal reason for the poor performance of superposition-based finite element model was attributed to inaccuracies in the pre-existing RS field determination and lack of consideration of the redistribution of residual stress field due to FCP [11]. During the FCP process, forward and backward plasticity zones are developed at the crack tip and a plastic wake is left on the path of the growing crack. A direct consequence of these effects is the crack closure effect discovered by Elber [12].

Many experimental tests were accomplished to evaluate the overload effect on FCP. Kumar [13], studied FCP for 1020 steel after loading and presented an equation for FCP corresponding to overload effect. A similar research was accomplished by Borresgo and Ferreira [14] on aluminum alloy. Shuter and Geary [15], proved that the rate of FCP depends on thickness, SIF and stress ratio. Tur and Vardar [16], studied the overload effect on FCP for different materials and expressed that the most decrease of the rate of FCP takes place when overloading distance are half of cycles resulted by overload.

In this paper, a simple and efficient method is presented in this paper for predicting fatigue crack propagation rate in welded butt joints considering presence the overload. For this purpose, first SIF and FCP for the workpiece possessing weld residual stress were studied. Then, this study was conducted for overload effect on FCP. Finally, coincident effects of overload and residual stress on FCP were studied and presented a modified FCP equation. Evaluating this introduced equation with experimental models show a good agreement. In fact, taking into Concurrent effects of tensile residual stress due to overload and compressive residual stress caused by welding, indicates the importance and novelty of this research.

2 MATERIALS AND SAMPLES

In this research, according to "Fig. 1", the workpiece is supposed to possess butt joint under variable cyclic loading with overload ("Fig. 2"). Test samples were M(T) geometry made of aluminum alloy with a longitudinal weld by the Gas Tungsten arc welding process. The residual stress distribution is as shown in "Fig. 3" and mechanical properties of 2024-T351 are according to "Table 1".

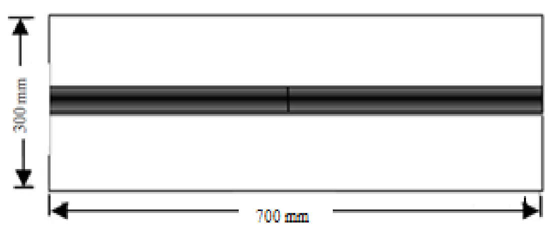


Fig. 1 Workpiece: dimension and weld position (thickness = 3mm).

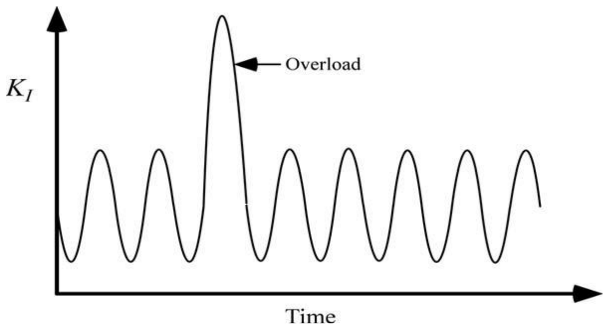


Fig. 2 Cyclic loading with overload.

Table 1 The mechanical properties of 2024-T351

E	σy	UTS	POISSONS RATIO
73.1GPa	324MPa	469MPa	0.33

3 STRESS INTENSITY FACTOR (SIF)

The application of fracture mechanics principles bears largely upon the stress intensity factor. An essential part of the solution of a fracture problem in linear elastic fracture mechanics is the establishment of the stress intensity factor for the crack problem under consideration.

3.1. The SIF in the Residual Stress Field

When there are residual stresses in the materials, the effective values of SIF (K_{eff}) according to superposition principle is defined. So the effective SIF is equal to the SIF due to the external load (K_{ext}) plus the SIF for residual stresses (K_{res}):

$$K_{eff} = K_{ext} + K_{res} \tag{1}$$

Where (K_{ext}) is calculated by:

$$K_{ext} = f\left(\frac{a}{w}\right)\sigma_{ext}\sqrt{\pi a} \tag{2}$$

And (K_{res}) is obtained by the following weight function method:

$$K_{res} = \int W(x,a)\sigma_{res}(x)dx \tag{3}$$

Where $\sigma_{res}(x)$ denotes residual stress distribution, and W(x, a) is weight function depending on loading, boundary and geometric condition of workpiece. Liljedahl [6] obtained solution for SIF in case where residual stress field is shown in “Fig. 3”, for example, they used Green function for the solution of SIF in case where the crack is located in the center of a sheet with infinity thickness according to “Fig. 4”.

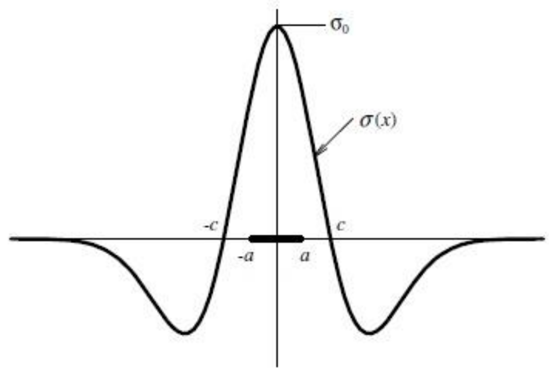


Fig. 3 Residual stress distribution.

According to Green function i.e. G(x) weight function is defined by:

$$W(a,x) = \frac{8G(x)}{1+k}\frac{1}{k_1^{(1)}}\frac{\partial v^{(1)}}{\partial a} \tag{4}$$

Where $v^{(1)}(a,x)$ and $k_1^{(1)}$ are respectively crack faces displacement and mode I of SIF, and for plane stress and plan strain k respectively is defined by $k = (3-4\nu)$:

$$k = \frac{(3-4\nu)}{(1-\nu)}.$$

Therefore, for the case according to “Fig. 4” equation (4) can be written by:

$$W(a,x) = \frac{1}{\sqrt{\pi a}}\left(\frac{a+x}{a-x}\right)^{\frac{1}{2}} \tag{5}$$

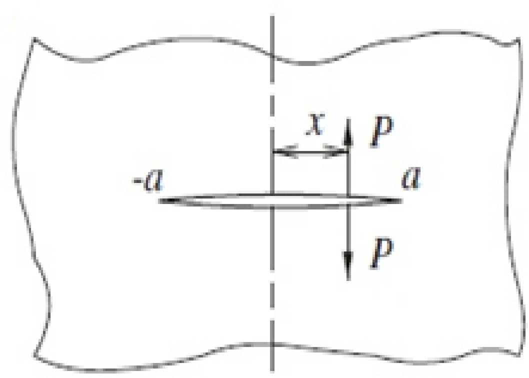


Fig. 4 Configurations of infinite sheet with center.

When residual stress distribution is obtained by equation (6), one can calculate K_{res} according to “Fig. 1” and equation (7).

$$\sigma(x) = \sigma_0 e^{-\frac{1}{2}(\frac{x}{c})^2}\left[1-(\frac{x}{c})^2\right] \quad (6)$$

$$K_{res} = \sigma_0\sqrt{\pi a}e^{-0.42(\frac{a}{c})^2}\left[1-\frac{1}{\pi}(\frac{a}{c})^2\right] \quad (7)$$

3.2. Survey of Overload Effected on SIF

In the case of fatigue crack propagation, there is a large interaction effect of cycles of different amplitudes. This can be demonstrated by applying overloads in a constant amplitude test. After the application of an overload in such a test, crack growth during subsequent constant amplitude cycling will be extremely slow. The overload has introduced a large plastic zone as is shown in “Fig. 5”. The material in this zone is stretched to a permanent deformation, but after unloading it still has to fit in the surrounding elastic material. The elastic material resumes its original size, but the material in the plastic zone does not. The plastic zone is too large for its elastic surroundings if the latter contract upon load release. Then the elastic material has to make it fit.

Consequently, the surrounding elastic material will exert compressive stresses on the plastically deformed material at the crack tip. The resulting residual stress system is depicted diagrammatically in “Fig. 6”.

In this case, effective SIF resulted by overload can be defined by:

$$K_{eff\ (ol)} = K_{ext} - K_{overload} \quad (8)$$

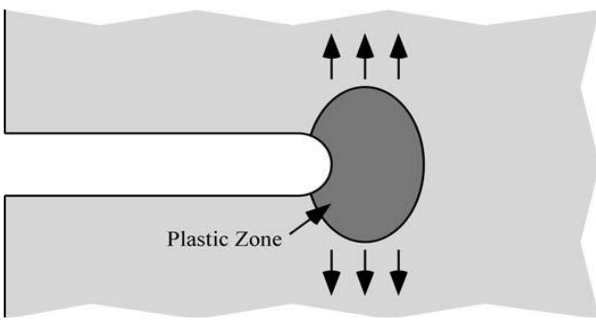


Fig. 5 Plastic zone as a result of overload.

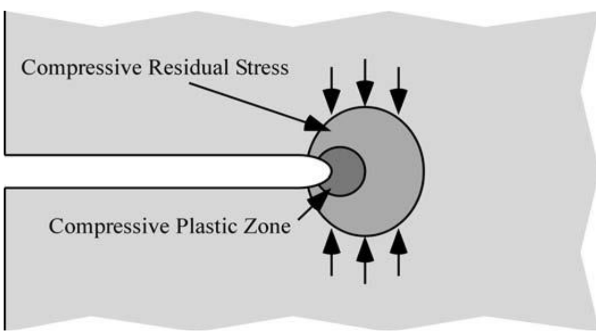


Fig. 6 Residual compressive stresses at crack tip as a result of overload [17].

3.3. SIF Resulted by Weld Residual Stress and Overload

In this case, welded workpiece has cyclic loading with overload. Certainly, according to superposition principle, effective SIF (K^*_{eff}) is defined by sum of SIF resulted by external load, weld residual stress da/dN and overload.

$$K^*_{eff} = K_{ext} + K_{res} - K_{overload} \quad (9)$$

4 FATIGUE CRACK PROPAGATION (FCP)

The stress intensity factor and cycle ratio are sufficient parameters to describe the whole stress field at the tip of a crack. If two different cracks have the same stress environment, the same stress intensity factor, they behave in the same manner and show equal rates of growth. The rate of fatigue crack propagation per cycle, da/dN, is governed by the stress intensity factor range and cycle ratio (da/dN= f (ΔK, R)).

4.1. FCP in Residual Stress Field

The rate of FCP in per cycle, depends on SIF variation. Experimental curves show that it depends on ΔK and $R = \frac{K_{\min}}{K_{\max}}$. Walker equation is as (10), (11):

$$\frac{da}{dN} = c(\overline{\Delta K})^n \quad (10)$$

$$\overline{\Delta K} = K_{\max}(1-R)^m \quad (11)$$

Now, if a material possesses weld residual stress, then according to super position principle, ΔK is obtained by:

$$\begin{aligned}\Delta K_{tot} &= \Delta K^{\max}_{eff} - \Delta K^{\min}_{eff} = \\ &(K^{\max}_{ext} + K_{res}) - (K^{\min}_{ext} + K_{res}) = \Delta K_{ext}\end{aligned} \quad (12)$$

One can write (10) by:

$$\frac{da}{dN} = c(\Delta K_{ext}(1-R_{eff})^{m-1})^n \quad (13)$$

Where effective cycle ratio (R_{eff}) is defined by:

$$R_{eff} = \frac{K^{\min}_{ext} + K_{res}}{K^{\max}_{ext} + K_{res}} \quad (14)$$

Therefore,

$$\frac{da}{dN} = c(\Delta K_{ext}(\frac{\Delta K_{ext}}{K_{ext}^{\max} + K_{res}})^{m-1})^n \quad (15)$$

4.2. Survey of Overload Effect on FCP

Wheeler introduces a retardation parameter ϕ. It is based on the ratio of the current plastic zone size and the size of the plastic enclave formed at an overload ("Fig. 7").

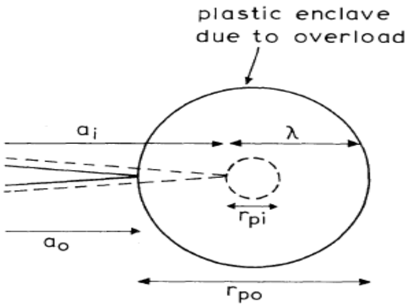


Fig. 7 The model of Wheeler (Situation after overload) [17].

This plastic zone is still embedded in the plastic enclave of the overload; the latter proceeds over a distance λ in front of the current crack a_i. Wheeler assumes that the retardation factor ϕ will be a power function of $\frac{r_{pi}}{\lambda}$.

Since $\lambda = a_0 + r_{po} - a_i$ the assumption amounts to:

$$(\frac{da}{dN})_{retadation} = \varphi(\frac{da}{dN})_{ordinery} = \varphi f(\Delta K) \quad (16)$$

With $\phi = (\frac{r_{pi}}{a_0 + r_{po} - a_i})^m$ as long as $a_i + r_{pi} < a_0 + r_{po}$.

4.3. FCP Resulted by Weld Residual Stress and Overload

In this case, variation of SIF is defined by (17). So, considering overload effects and weld residual stress, FCP can be obtained by (18). In fact, equation (18) is the modified form of walker equation that estimate rate of FCP considering effects of external loads, overload and weld residual stress.

$$\Delta K_{tot} = \Delta K_{eff}^{\max} - \Delta K_{eff}^{\min} = (K_{ext}^{\max} + K_{res} - K_{overload}) - (K_{ext}^{\min} + K_{res} - K_{overload}) = \Delta K_{ext} \quad (17)$$

$$\frac{da}{dN} = c(\Delta K_{ext}(1 - R_{eff}^{*})^{m-1})^n \quad (18)$$

Where effective cycle ratio(R_{eff}^{*})is defined by:

$$R_{eff}^{*} = \frac{K_{ext}^{\min} + K_{res} - K_{overload}}{K_{ext}^{\max} + K_{res} - K_{overload}} \quad (19)$$

Therefore,

$$\frac{da}{dN} = c(\Delta K_{ext}(\frac{\Delta K_{ext}}{K_{ext}^{\max} + K_{res} - K_{overload}})^{m-1})^n \quad (20)$$

Walker equation has an appealing advantage for predicting FCG rates in tensile residual stress fields due to welding and compressive residual stress fields due to overload.

5 FATIGUE LIFE ESTIMATE MODEL

In equation (17), variation of effective SIF was determined. According to the effect of overload on closing crack, effective SIF (ΔK^{*}_{eff}) is a suitable parameter for considering crack growth after overload. Therefore, equations (21) are presented for crack growth.

$$\frac{da}{dN} = c_1(\Delta K_{eff})^{n_1} \quad (21-1)$$

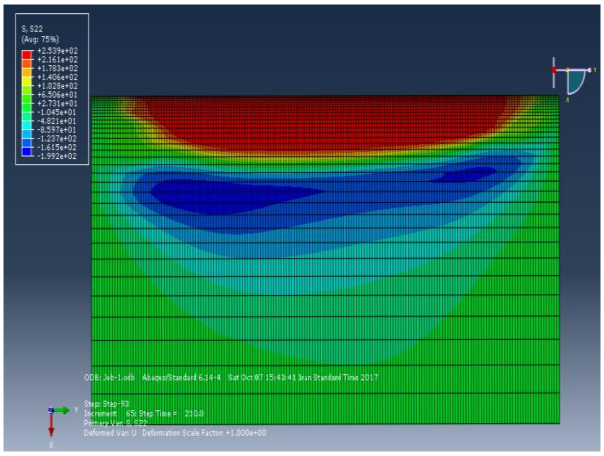
$$\frac{da}{dN} = c_2(\Delta K_{eff}^{*})^{n_2} \quad (21-2)$$

Equations (21-1) and (21-2) are respectively used before and after of over loading. c_1, n_1 are exactly coefficients associated to material properties that are determined by fatigue test without overload. Coefficients c_2, n_2 are obtained by studying equations (21-2) on crack growth test data and considering the effect of crack closing. Fatigue life of workpiece from initial crack length to final crack length can be determined by integrating on equation (21). Nothing that the crack grows discontinuously, this integral turns to a sum and is written as:

$$N = \sum_{a_i}^{a_{ol}} (\frac{da}{c_1(\Delta K_{eff})^{n_1}}) + \sum_{a_{ol}}^{a_f} (\frac{da}{c_2(\Delta K_{eff}^{*})^{n_2}}) \quad (22)$$

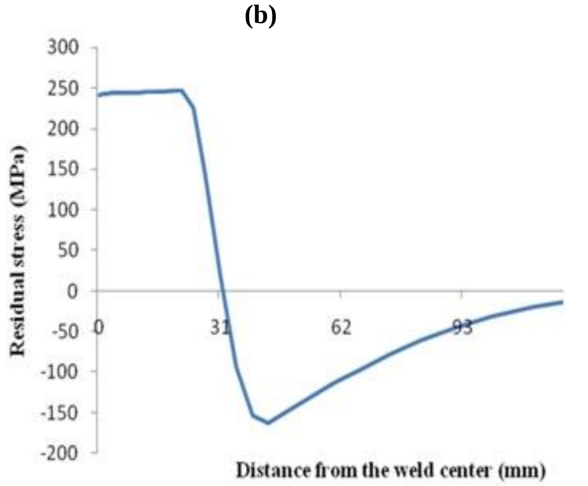
6 CASE STUDY-COMPARISION OF EQUATIONS

In this paper, workpiece is the plate that its material is aluminum alloy (2024-T351) and has butt joint. "Fig. 7". shows residual stress and stress intensity factor in terms of crack length. The effect of SIF and the rate of fatigue crack propagation in the situation that the material possesses weld residual and overload for two cases are studied. In both cases, K_{res} is obtained according to data of equation (3) and "Fig. 7".



(a) Residual stress distributaion.

(b)



(c) Longitudinal residual stress.

Fig. 8 (a, b): Residual stress distributaion (K_{res}).

In the first case, according to "Table 2", $\Delta\sigma = 40MPa, R = 0$ and in 2nd case, according to "Table 5", $\Delta\sigma = 46.4MPa, R = 0.1$. In both cases according to data of equation (3) and "Fig. 8", residual stress distribution (from Finite Element) and K_{res} are obtained. Analyses were performed by 2D FE models using the commercial code ABAQUS. Quadrilateral 4-node shell elements with reduced integration were used. The mesh size near the weld region (Heat Affected Zone) was 0.5 * 0.5 mm. Because of the geometrical symmetry, only a half of the plate was modeled.

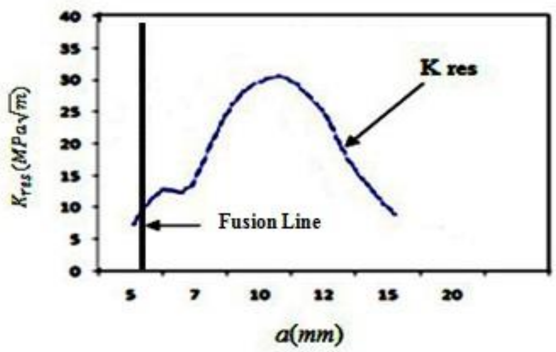


Fig. 8 (c): SIF for residual stresses (K_{res}).

Table 2 Result of the first case study

a (mm)	K_{ext} $(MPa\sqrt{m})$	K_{res} $(MPa\sqrt{m})$	ΔK_{eff} $(MPa\sqrt{m})$	$\frac{da}{dN}$ $(m/cycle)$
5	5.011	9	14.011	$1.194*10^{-6}$
7	5.93	11.5	17.43	$2.483*10^{-6}$
10	7.08	12.3	19.38	$3.543*10^{-6}$
12	7.76	18.6	26.36	$9.940*10^{-6}$
15	8.68	24.2	32.88	$2.085*10^{-5}$
20	10.02	26.7	36.72	$3.020*10^{-5}$

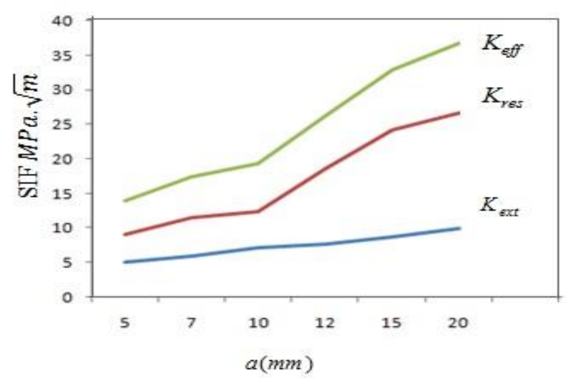


Fig. 9 Variation of SIF (first case).

6.1. Case study I

For the first case, according to "Table 2" for different situation of crack length, Effective and External SIF (ΔK_{eff}, ΔK_{ext}) are respectively calculated by equations (1) and (2) according to "Fig. 9". Also, rate of FCP is calculated by equation ($\frac{da}{dN}=1.71*10^{-10}(\Delta K_{eff})^{3.353}$). In this case, it is supposed that overload happens in situation that crack length is $a_0 = 5mm$, consequently stress variation doubles. For calculated overload SIF (K_{ol}), Wheeler equation is used. Therefore, we calculated by equation (23), the radius of plastic zone before and after overloading. The result of equation (23) are as the following ("Table 3")

Table 3 The radius of plastic zone

r_{pi}	r_{po}	$\lambda = a_0 + r_{po} - a_i$
1.23*10^{-5}m	$5.09*10^{-5}m$	5.09*10^{-5}m

According to equation(6), ϕ is calculated:

$$\phi = (\frac{r_{pi}}{\lambda})^{3.165} \tag{24}$$

Thus, by equation (16) and "Table 2", the rate of FCP is obtained:

$$(\frac{da}{dN})^* = 0.0122*1.194*10^{-6} = 1.456*10^{-8} \tag{25}$$

Also, $(\frac{da}{dN})^* = 1.71*10^{-10}(\Delta K^*_{eff})^{3.353}$, we can calculate ΔK^*_{eff} by:

$$\Delta K^*_{eff} = \sqrt[n]{\frac{1}{c}(\frac{da}{dN})^*} \tag{26}$$

On the other hand, $K_{ol} = \Delta K_{eff} - \Delta K^*_{eff}$, so for this case: $K_{ol} = 14.011 - 3.3774 = 10.237$.

Now, for the validation of calculated overload SIF, we can use modified equation (18). In this case(R=0), equation is revised as the following:

$$(\frac{da}{dN}) = C(\Delta K^*_{eff})^n \tag{27}$$

Table 4 The comparison between equations (Case I)

$\frac{da}{dN}$ (modified equation)	$1.468*10^{-8}\ m/cycle$
$\frac{da}{dN}$ (Wheeler equation)	$1.456*10^{-8}\ m/cycle$

Considering overload effects and weld residual stress, the rate of fatigue crack propagation is obtained. According to "Table 4", it is seen that the rate of fatigue crack propagation has a good agreement. So, calculated K_{ol} with this method has a high accuracy.

6.2. Case study II

In 2nd case (R=0.1), according to "Table 5" and according to "Figs. 10, 11" for different situation of crack length, effective cycle ratio and FCP rate, are respectively calculated. "Fig. 10" shows the effect of residual stress caused by welding on cycle ratio. "Fig. 11" shows the predicted FCP rates for the R = 0.1 case at constant applied stress. For comparison the base material growth rate is also shown which was calculated by the modified Walker equation. In this case, the variation of experimental FCP [6] is compared to presented equation. It is known that overload causes delay in crack propagation. This can be demonstrated by applying overloads in a constant amplitude test. After the application of an overload, crack growth during subsequent constant amplitude cycling will be extremely slow. This subject is shown in "Fig. 12". This Figure illustrates this retardation effect of overloads on crack propagation.

Table 5 Result of 2nd case study

a (mm)	K_{ext} $(MPa\sqrt{m})$	R_{eff}	$\frac{da}{dN}$ $(m/cycle)$
5	5.93	0.62	$4.41*10^{-9}$
7	7.08	0.64	$6.81*10^{-9}$
10	8.63	0.61	$1.42*10^{-8}$
12	9.44	0.67	$1.53*10^{-8}$
15	10.93	0.70	$2.16*10^{-8}$
20	13.68	0.67	$5.01*10^{-8}$

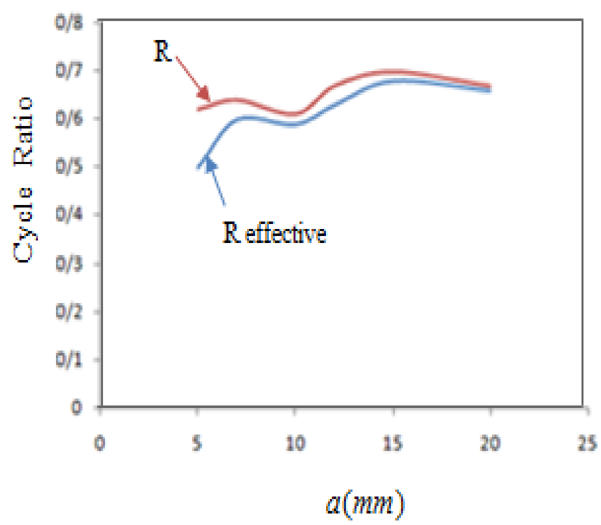


Fig. 10 Calculated effective stress ratio.

While experimental equation (16) can be used to calculate $(\frac{da}{dN})^*$, then by calculating R^*_{eff} according to equation (28), K_{ol} is obtained by equation (29).

$$R^*_{eff} = 1 - \sqrt[(m-1)]{\{\frac{\sqrt[n]{(\frac{(\frac{da}{dN})^*}{C})}}{\Delta K_{ext}}\}} \quad (28)$$

$$K_{ol} = \frac{R^*_{eff}.K_{\min} - K_{\max} + (1 - R^*_{eff})K_{res}}{R^*_{eff} - 1} \quad (29)$$

Certainly, calculated overload SIF from two method have good agreement. According to modified FCP equation (18) and Wheeler experimental equation, Table. 6 presents agreement of the rate of modified fatigue crack propagation.

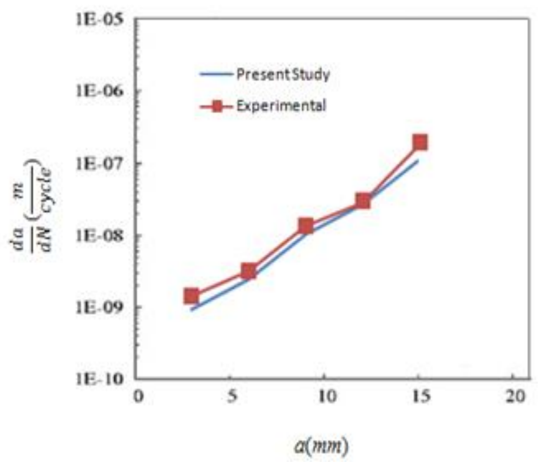


Fig. 11 Predicted and experimental, Fatigue Crack Propagation (FCP).

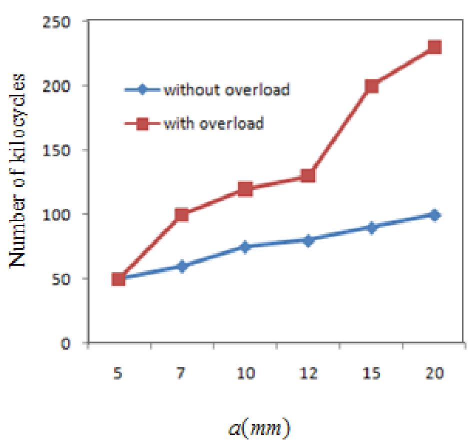


Fig. 12 Effects of overload.

Table 6 The comparison between equations (Case II)

$\frac{da}{dN}$ (modified equation)	$5.368*10^{-11} m/cycle$
$\frac{da}{dN}$ (Wheeler equation)	$5.380*10^{-11} m/cycle$

7 CONCLUSION

In this paper, the effects of weld residual stress and overload on FCP were studied. For this purpose, weight function is applied to calculate SIF resulted by weld residual stress stresses. Also, a method is introduced to determine the overload SIF, K_{ol} (equation(29)).

Consequently, effective SIF resulted by experimental load, weld residual stress and overload is presented. Using effective SIF or effective cycle ratio, R^*_{eff} (equation(19)), modified Walker equation by considering coincident effects of overload and residual stress on FCP is introduced (equation(20)).

The agreement of the results of modified equation with experimental models shows that the calculations of residual stress effects resulted by weld and overload, accomplished according to the presented methods, are suitable.

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