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R-ratio effect and crack closure model in Al-alloy

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Abstract

Fatigue crack closure phenomenon is now recognised as one of the most influential mechanisms operating during fatigue. The crack closure effect helps explain a wide range of fatigue data. It has become the default interpretation of stress ratio effects. It is used in almost all fatigue life prediction models. In this investigation an attempt was made to shown effect of crack closure based on experimental fatigue crack growth data of 2024 T351 Al-alloy using fourth bending fatigue test under differents stress ratio. Elber crack closure model was applied. The results show a good calibration of cracking curves for low stress intensity factor. Although there have been bad timing curves cracking for high stress intensity factor. For this reason, coefficients of Elber model must be adjusted to have an intrinsic curve using Aliaga et al. method. The present fatigue crack growth curves are also compared to curves using several crack closure models (Katcher/Kaplan model, Schijve model, and benguediab model).

Key words: fatigue crack growth, stress ratio, crack closure models, effective stress intensity factor, Al-alloy Fatigue crack initiation, compressive residual stress, tensile residual stress, aluminum alloy

1. Introduction

Fatigue phenomenon present complex process and affected by different parameters. Spectrum load level is one of this. Crack closure is phenomenon that has been shown to have a strong effect on fatigue crack growth behavior. In the presence of crack closure phenomenon, the crack remains in a closed position even though some external tensile force is acting on the material. During this process the crack opens only at stress above a particular stress. Generally, this is due to factors such as plastic deformation or phase transformation during crack propagation, corrosion of crack surfaces, or roughness at cracked surfaces. This provides a longer life for fatigued material than expected, by slowing the crack growth rate. Plasticity-induced closure results from compressible residual stresses developing in the plastic wake. The crack closure effect helps explain a wide range of fatigue crack

growth data [1].The concept of fatigue crack closure was a conceptual breakthrough for understanding stress ratio effects on fatigue crack growth. Many researcher efforts have been made to determine the opening and/or closing stress through experimental investigations [2, 3], numerical analysis [4-6] and analytical studies [7-9].

All advanced analytical fatigue crack growth models are based on the assumption that the crack growth rate, da/dN, depends primarily on the effective stress intensity factor range ΔK$_{eff}$, firstly introduced by Elber [10].

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^{m} \qquad (1)$$

Hence the effective stress intensity factor range is:

$$\Delta K_{eff} = K_{max} - K_{op} = U.\Delta K \qquad (2)$$

where K_{max} is the maximum stress intensity in a cycle and Kop the crack opening stress intensity.

Effect of stress ratio was accounted in variation of factor U for 2024 T3 Al-alloy. Elber found that factor U is only function of stress ratio R in range from -0.1 to 0.7, that is:

$$U = 0.5 + 0.4R \qquad (3)$$

Schijve [11] has proposed a more refined expression for U, valid for stress ratio, R, from -1 to 1 expressed by equation 4 for 2024 T3 aluminum alloy.

$$U = 0.55 + 0.33R + 0.1R^{2} \qquad (4)$$

In the crack closure investigation on 7475 T735 Al-alloy, Zhang et al. [12] were used near threshold crack growth method to evaluate crack closure ratio U (equation 5) depending only on stress ratio. It was shown that crack closure is no important at high stress ratio (R>0.8). Similarly to Elber investigation, at increasing of stress ratio, linear empirical crack closure function U (equation 6) for 2219 T851 aluminum alloy was evaluated by Katcher and Kaplan [13].

$$U = 0.56 + 0.109R + 0.326R^{2} \qquad (5)$$

$$U = 0.68 + 0.91R \qquad 0.08 < R < 0.32 \qquad (6)$$

In further work, Bachmann and Munz [14] found that opening stress intensity factor Kop was independent of maximum stress intensity factor K_{max}, and crack closure ratio U increase with increasing K_{max}. Kop was found to increase with increase in stress ratio. Assuming a linear relation between K_{op} and R (K_{op}=6.67R+4.27), Bachmann and Munz proposed the expression:

$$U = \frac{1}{1-R}\left[1 - \frac{6.67R}{K_{max}} + \frac{4.27}{K_{max}}\right] \qquad (7)$$

In fatigue crack study of Guo et al. [15] and Kermanidis et al. [16] we show a shift of crack growh curves for aluminium alloy 7475 T7351 and 2024 T851 in increasing of stress ratio. Generally, an increase in R results in an increase in da/dN for a given stress intensity range, ΔK. This influence of R can essentially come from two sources: a true material dependence of crack growth rate on R (an intrinsic material effect) and/or a crack closure effect explained before.

In the present study an attempt was made to shown the application and validity of crack closure models developed by Elber, Katcher/Kaplan, Benguediab and Shijve and adjusted equivalent model based on experimental data of 2024 T351 Al-alloy in four bending fatigue tests.

2. Materials and methods

The experimental study was performed on 2024 T351 aluminum alloy (pre-strained and tempered). This material was tested along the T-S directions. The chemical composition of this material is reported in Table 1. Theirs mechanical properties at room temperature are reported in Table 2.

Table 1: Chemical composition of 2024 T351 Al-alloy

Si	Fe	Cu	Mn	Mg
0.11	0.16	3.97	0.45	1.5
Cr	Zn	Ti	Ni	Pb
0.05	0.11	0.018	0.02	.056

Table 2: Chemical composition of 2024 T351 Al-alloy

E(GPa)	$\sigma_{Y0.2}$	UTS (MPa)	A%
74	363	477	12.5

The sample of fatigue tests named V-notch with 45° angle in four bending is shown in Fig. 2. The specimens are polished to 10µm finish on the surfaces crack growth. Specimens have ($b \times w = 10 \times 10\ mm^2$) section with an initial length a_0 the notch created by pre-crack.

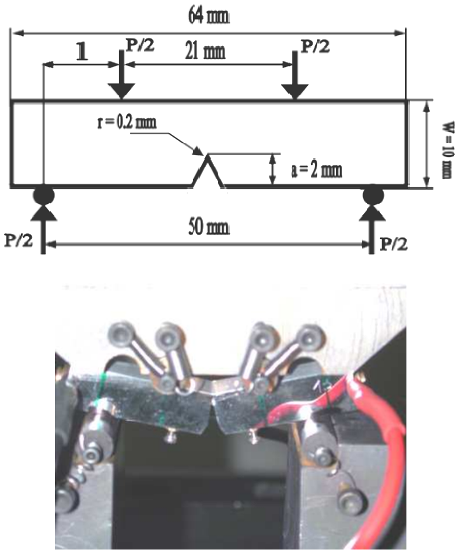

Figure 1. V-notch sample in four points bending fatigue test and dimensions

Fatigue crack growth tests were performed using closed-loop servo-hydraulic testing machine “MTS 810” with ±100 KN load capacity under applied constant amplitude sinusoidal wave loading at the frequency of 10 Hz and varying stress ratio, R, from 0.1 to 0.3. Samples are subjected to the bending fatigue tests, used by many researchers [16]. Stress intensity factor for V-notch bent specimen is expressed by the following expression [17]:

$$K = \frac{3P.l\sqrt{\pi a}}{B.h^2}.f(a/w) \tag{8}$$

where f(a/h) is the geometry function given by:

$$f(a/h) = 1.122 - 1.4(a/w) + 7.33(a/w)^2 - 13.08(a/w)^3 + 14(a/w)^4$$

where “a” is the crack length measured from the free surface of the specimens.

3. Results and Discussion

Exponential model developed initially by Mohanty et al. [18] for fatigue crack growth of 2024 T3 and 7020 T7 Al-alloy was enhanced for 2024 T351 Al-alloy [19]. Fatigue crack growth rates curves da/dN-ΔK drew in logarithmic axis for different R-ratios (R=0.1 to 0.3), are given in figure 2. It can be seen that the predicted results cover the two regions of fatigue crack growth rate (II and III regions). The effect of stress ratio is reflected by a shift of the curves da/dN-ΔK to the low values of ΔK. These results show the dependence of threshold stress intensity factor ΔK_{th} on the stress ratio. Unlike, for high stress intensity factor, the shift of curve is reverse. We notice a decreasing in FCGR with increasing stress ratio. This effect can be explained by the effect of the microstructure in the direction of propagation (T-S). Effect of crack closure using Elber model characterized by closure ratio U (equation 3) is shown on figure 3 where FCGR curves are plotted in function of effective stress intensity factor ΔK_{eff}. Fatigue crack growth results for different stress ratio

lead to a single curve represented by straight solid line. At high stress intensity factor, we notice a small difference in FCGR. The applied of Katcher and Kaplan model (equation 7) to fatigue crack growth rate of the studied material give a unique curve (Figure 4). For effective stress intensity factor greater than 10 $MPa(m)^{1/2}$, the curves are not goodly matched. The middle of single curve is represented by straight solid line. Comparison of useful of two model shown that in Elber model, the curve for minimum stress intensity factor lead to a value of 1.8 $MPa(m)^{1/2}$ at value of 2×10^{-6} mm/cycle of FCGR, but for Katcher and Kapler model and at same FCGR, the effective stress intensity factor is about of 4.3 $MPa(m)^{1/2}$.

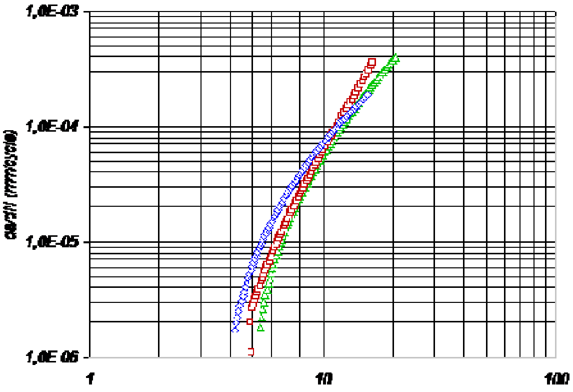

Fig 2. Effect of stress ratio on predicted of fatigue crack growth rate using enhanced exponential model in V-notch sample in four points bending tests

According to the analysis of crack closure presented by in [20], the relationship between R and U is of the form given by Elber is:

$$U = a + b.R \tag{9}$$

when stress ratio tends to 1, crack closure effect is negligible, and crack closure ratio tends to 1. This leads to a+b = 1. The parameter “a” is defined by the following expression:

$$a = \frac{K_{R1} - K_{R2}}{(1-R_1)K_{R1} - (1-R_2)K_{R2}} \tag{10}$$

The analysis of experimental data presented in figure 2 by application of equation 13, conduct to the following values “a = 0.743 and b = 0.257”. The evolution of fatigue crack growth according to effective stress intensity factor ΔK_{eff} is presented in figure 5. All curves for different stress have led to single curve presented by dashed line. Compared the results obtained by Elber and Katcher/Kaplan models to those obtained by the present model is shown on figure 5. It is noticed that the present correlated results give good correlation comparatively to the results obtained by application of Elber model. A small difference was found against to Katcher/Kaplan model.

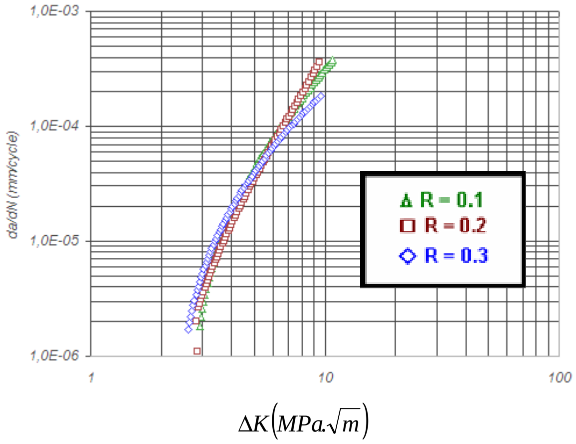

Figure 3. Crack closure effect on predicted of FCGR (Elber model) of 2024 T351

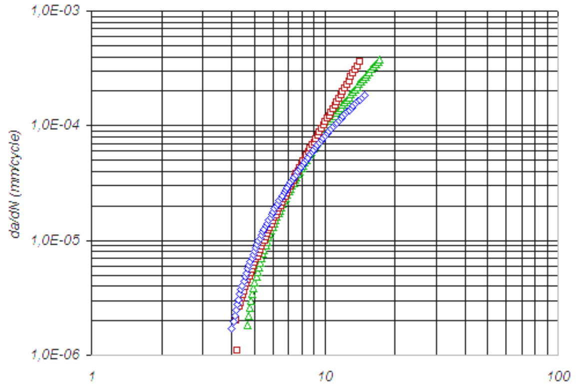

Fig 4. Crack closure effect on predicted of FCGR (Katcher/Kaplan model) of 2024 t351

4. Conclusion

The aim of this work is to study the effect of residual stress induced by plastic preload, using four point bend specimens on fatigue initiation life in 2024 T351 aluminum alloy. From the experimental results, we can deduce the following conclusions:

- **Initiation life is affected by the level of compressive residual stress. Increasing in compressive residual stress at notch increase the fatigue initiation life.**
- **Initiation phase varies from 40% to 50% of the total fatigue life considering different residual stress fields.**
- **At the same level of plastic preload, fatigue initiation life through compressive residual stress at notch is about 2.35 times to fatigue initiation life through tensile residual stress (As-received materials).**
- **Fatigue initiation life was affected by amplitude loading (i.e. stress ratio or mean stress).**

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