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Prediction of Fatigue Crack Growth of Aeronautical Aluminum Alloy

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***Abstract*—**In this paper fatigue crack growth behavior of aeronautical aluminum alloy 2024 T351 was studied. Effects of various loading and geometrical parameters are studied such as stress ratio, amplitude loading, etc. The fatigue crack growth with constant amplitude is studied using the AFGROW code when NASGRO model is used. The effect of the stress ratio is highlighted, where one notices a shift of the curves of crack growth. The comparative study between two orientations L-T and T-L on fatigue behavior are presented and shows the variation on the fatigue life. L-T orientation presents a good fatigue crack growth resistance. Effects of crack closure are shown in Paris domain and that no crack closure phenomenons are present at high stress intensity factor.

***Keywords*—**Fatigue crack, orientation effect, crack closure, aluminum alloy.

I. INTRODUCTION

FATIGUE is damage caused by oscillating stress below the fracture stress. 90% of all mechanical failures can be attributed to fatigue [1]. The prediction of the fatigue crack growth rate at constant loading, loading or random variable is of practical interest for many aerospace applications, aerospace, automotive, structures, machines, pipes…etc. The major problem is to take into account the various parameters that affect the fatigue crack growth rate in both the intrinsic and extrinsic parameters as well as the estimation of the fatigue life. In general, the fatigue process is depicted by three distinct regions. Region I is associated with the growth of cracks with low ΔKth, and is commonly believed to account for a significant proportion of the fatigue life of a structure. Region II has received the greatest attention as it is in this region where the ‘‘Paris’’ crack growth law [2] can be applied. Several different variants of the Paris crack growth law have evolved [3-5]. Finally, region III is associated with rapid crack growth.

Three orientations for aluminum alloy 2024 T3 are studied by Sarioglu and Orhaner [6] such as T-L, L-T and 60° with respect to the rolling direction. The results show the crack propagation is faster in T–L direction than in L–T and 60° directions. Especially, the differences are pronounced at low ΔK values. Theses differences may be explained by the change of slip characteristics. Fatigue crack growth rate for 6061 fabricated by PM and IM alloy in the T4 and T6 tempers in L-T and T-L directions are compared [7] when the L-T offered better fatigue crack growth resistance than the T-L orientation. The effect of the orientation is marked at low stress intensity factor. In others works [8] attributed the differences observed between the fatigue crack growth rate for two load ratio (R=0.1 and R=0.8) in both directions T-L and L-T for the alloy Ti-6Al-4V unlike the level closure. The model of fatigue crack growth rate developed by Paris and used by others authors cannot for another’s materials describe the totality of fatigue crack curve. Model accounting the totality of fatigue crack growth curve has been developed in NASA named NASGRO model [9]. The aim of this work is to shown crack orientations and crack closures effects on fatigue crack growth behavior using NASGRO model of the aluminum alloy 2024 T351.

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II. SIMULATION OF FATIGUE CRACK GROWTH

A. Fatigue crack growth model

Many models of fatigue crack growth rates are proposed by authors. Elber [10] proposed a modification to the Paris growth law by using the effective stress intensity range to calculate the crack propagation under constant amplitude loads, taking into account the crack closure concept. The model is defined by the relationship:

$$\frac{da}{dN} = C(K_{max} - K_{op})^m = C.(K_{eff})^m \qquad (1)$$

Strip-yield model from the NASGRO software has been applied to predict fatigue crack growth in two different aircraft aluminum alloys [11] under constant amplitude loading and programmed and random variable amplitude load histories. NASGRO model are expressed bellow:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_{crit}}\right)^q} \qquad (2)$$

f present the contribution of crack closure and the parameters C, n, p, q were determined experimentally and ΔKth is the crack propagation threshold value of the stress-intensity factor range. NASGRO model implemented in AFGROW code by Harter [12] is used for this work and by others authors [13].

B. Material and specimen

The material used in this study is the aluminum alloy 2024-T351 as rolled plates. Two orientations are subjected to numerical fatigue tests such as T-L and L-T orientations. The basic mechanical properties for aluminum alloys 2024-T351 are given in Table 1. Numerical fatigue crack growth tensile tests used Single Edge Notch Tensile "SENT" specimen shown on Fig. 1.

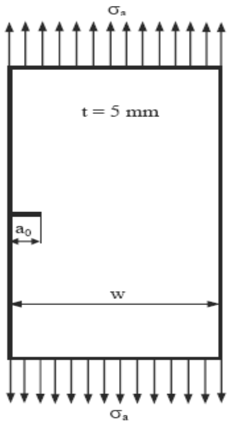

Fig. 1 Single Edge Tensile specimen

The stress intensity factor for the studied specimen with through crack is developed by Tada [13] and implemented in AFGROW code. The equation of this factor depends on several parameters and is written bellow:

TABLE I
MECHANICAL PROPERTIES OF ALUMINUM ALLOY 2024 T351
DATABASE OF AFGROW CODE

Orientation	$\sigma_{0.2}$ MPa.	K_{IC} MPa.(m)$^{1/2}$	K_{IC} MPa.(m)$^{1/2}$	E MPa
L-T	372.00	36.26	72.53	73.10
T-L	358.53	31.87	63.73	73.00

$$K = \sigma_a \sqrt{\pi a}\ .\ f(a/w) \quad (3)$$

The function f(a/w) for the specified specimen is defined bellow:

$$f\left(\frac{a}{w}\right) = \frac{\left(0.752 + 2.02\left(\frac{a}{w}\right) + 0.37\left(1 - sin\left(\frac{\pi a}{2w}\right)\right)^3\right)}{cos\left(\frac{\pi a}{2w}\right)} \sqrt{\frac{2w}{\pi a} tg\left(\frac{\pi a}{2w}\right)} \quad (4)$$

III. RESULTS AND DISCUSSIONS

A. Stress ratio effect

Single Edge Notch Tensile (SENT) specimen in two orientations is subjected to a constant loading with various load ratios. The K_{max} fracture criteria are adopted for the limit of crack growth. Figs. 2 and 3 showed the effect of stress ratio on fatigue life N. As the stress ratio increases, the fatigue life increases. Theses results are in agreement with the literature results [14]. For R=0.40, the maximum crack length is 20.50 mm, contrary to the crack length for R=0.01 and R=0.1. After crack length (a=15 mm), the specimens are growth under the same crack growth rate.

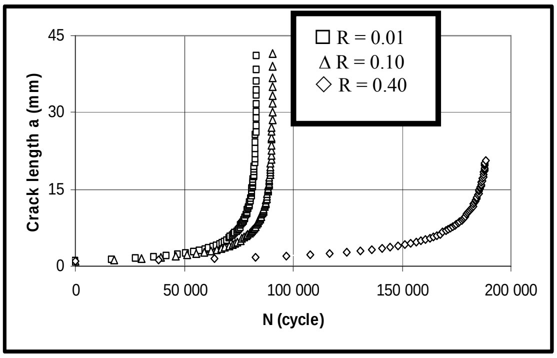

Fig. 2 Fatigue crack growth curves in L-T orientation

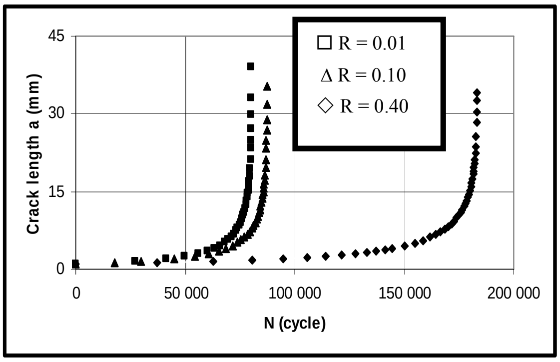

Fig. 3 Fatigue crack growth curves in T-L orientation

B. Crack orientation effect

The analysis and the comparison of Figs. 2 and 3 show the effect OF CRACK orientation on the fatigue crack growth life according for to the two directions. For the same crack length, the difference for the fatigue life is not important (≈3000cycles) for the two orientations at R =0.1 (Fig. 4). For R =0.4, we show the difference in the final crack length.

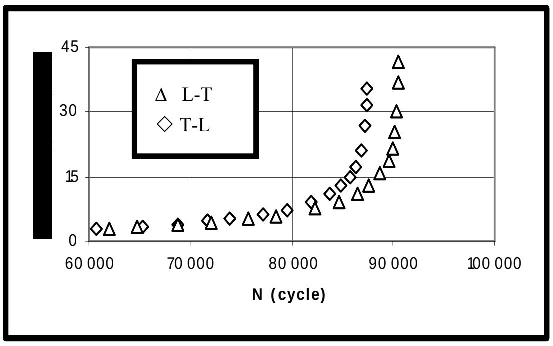

Fig. 4 Effect of crack orientation on fatigue crack growth for R = 0.1

C. Effect of crack closure

The closure model in AFGROW is a fairly simple single-parameter plasticity model, based on the Elber works. Others works justified the closure of crack on the presence of significant compressive residual stress in front.

The crack closure model implemented in AFGROW code is based on evaluation of closure factor C_f, defined as the ratio of the opening stress to the maximum applied stress and was demonstrated to be a function of stress ratio ($R=\sigma_{min}/\sigma_{max}$).

$$C_f = 1.0 - \left[(1 - C_{f0})(1 + 0.6R) \; 1 - R \right] \qquad (5)$$

the closure factor is defined as:

$$C_f = \sigma_{open} / \sigma_{max} \qquad (6)$$

The AFGROW closure model converts ΔK_{eff} to an equivalent ΔK based on the relationship between the closure factor (C_f) and stress ratio (R).

$$\begin{aligned} \Delta K_{eff} &= K_{max} - K_{open} \quad if \quad K_{open} \geq K_{min} \\ \Delta K_{eff} &= K_{max} - K_{min} \quad if \quad K_{open} < K_{min} \end{aligned} \qquad (7)$$

For the input data C_{f0} is specified and represent the closure factor for R=0.

Fig 5 shows the variation of crack length (a) under crack closure effect for stress ratio R =0.1 and the closure factors Cf0=0.25. On the presence of crack closure effect, we notice the same effect with the change of crack growth orientation (L-T, T-L). Fig. 6 shown the fatigue crack growth rate for R =0.1 with the presence of crack closure phenomenon in two orientation (L-T and T-L). At high of effective stress intensity factor the crack growth data are not in the same curve. This result shows the absence of crack closure effect in the specified orientation.

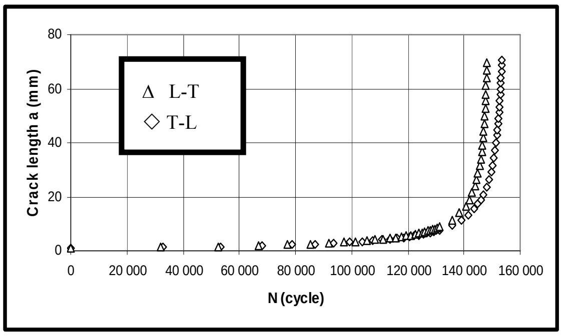

Fig. 5 Effect of crack orientation on fatigue crack growth with the presence of crack closure

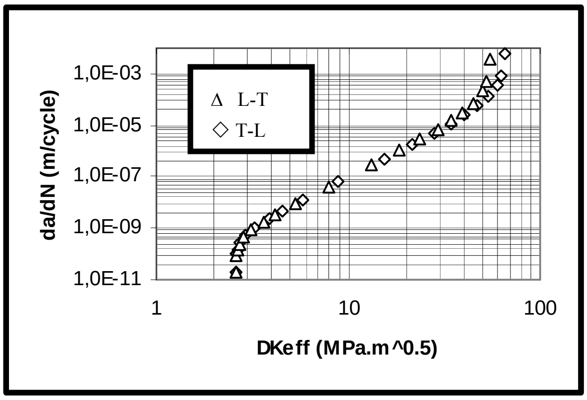

Fig. 6 Fatigue crack growth rate in two crack orientations with the presence of crack closure

IV. Conclusion

In this paper simulation of fatigue crack growth of single edge notch tensile (SENT) specimen for aluminum alloy 2024 T351 are presented. Many parameters effects are studied such as stress ratio, crack orientation and crack closure effect. The stress ratio R affects the total fatigue life. The increasing of this ratio, increase the fatigue life. Crack orientation L-T or T-L affect the fatigue crack growth. Results show the good fatigue resistance in L-T orientation comparatively to the T-L orientation. No crack closure effects have shown at high effective stress intensity factor. In future, this work was accomplished by experimental work when others effects will be considered and associated such as residual stress, overload, under-load, etc.

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