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Stress Ratio and Notch Effect on Fatigue Crack Initiation and Propagation in 2024 Al-alloy

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Abstract**—**This study reports an empirical investigation of fatigue crack initiation and propagation in 2024 T351 aluminium alloy using constant amplitude loading. In initiation stage, local strain approach at the notch was used and in stable propagation stage NASGRO model was applied.

In this investigation, the flat plate of double through crack at hole is used. Based on experimental results (AFGROW Database), effect of stress ratio, R, is highlights on fatigue initiation life (FIL) and fatigue crack growth rate (FCGR). The increasing of dimension of hole characterizing the notch effect decrease the fatigue life.

Keywords**—**Fatigue crack growth, initiation life, Al-Alloy, stress ratio, notch effect

I. INTRODUCTION

FATIGUE process undergoes several stages and from an engineering point of view it is convenient to divide the fatigue life of a structure into three stages [1]: fatigue crack initiation, stable crack propagation and unstable crack propagation. Generally mechanical components and structures contain geometrical discontinuities and notches. In aircraft structures especially fuselages require holes for their assembly by riveting. Stress concentration will be produced in these discontinuities (holes) as a result of external force and depend of diameter of hole. The stresses are generally higher than the nominal values, and if precautions (good quality of machining of hole, induction of residual stress …etc.) are not taken into account, notches could be sites of crack initiation and evolution of crack propagation. To assess the effects of notches on the behavior of structures, the prediction of fatigue strength compared to the challenges of design and safety is relevant. Fatigue life prediction of structures with discontinuities has been extensively studied [2-5]. Fatigue crack initiation life has been estimated by many authors [4, 6-7] when different approaches will be used, which is based on nominal stresses, stress concentration factor and local stress-strain concepts. Others researchers employed the equivalent strain-energy density method to predict fatigue crack initiation [5, 8, 9]. The cited works assumed that crack propagation part of fatigue life is small comparatively to the fatigue initiation life. Generally fatigue life of materials and structures depends on several parameters. Especially in initiation phase, fatigue life is linked strongly to metallurgical, geometrical and loading parameters. The main loading parameter is stress ratio studied by several researchers, principally in stable crack propagations on some materials [10-12]. Effect of stress on the proportion of the total life occupied by initiation and by propagation of the crack is discussed by Pearson [13]. In this work and for a crack initiated at a plane polished surface the propagation life varied from almost 100 percent of the total life at a life of about $2\text{x}10^4$ cycles to a small proportion at a total life approaching the fatigue limit. Effect of predeformation on fatigue crack initiation of X60 pipeline steel was studied by Zheng et al. [14]. In this investigation fatigue crack initiation life depends on both strength and ductility of metals. Pre-deformation does not always decreases the fatigue life of steel; it depends on the actual content of the pre-strain. Initiation of cracks at a mild notch in aluminium alloy 2024-T4 was investigated by Grosskreutz and Shaw [15]. The notch was to localise the initiation site and they used a replica method and high resolution microscopy to detect the crack. A large majority of fatigue cracks in aluminium alloy aircraft structures initiate at fastener holes in joints [16]. Effect of stress ratio on fatigue crack initiation from hole was investigated by Fujczak [17]. For positive values of stress ratio, an increase in the R-ratio decreases the number of cycles to initiate a fatigue crack while the alternating stress is kept constant. Recently, in the investigation of Ranganathan et al [18], crack initiation phase has been considered in the estimation of total fatigue life when short crack growth approach was used. The results on fatigue crack initiation of 2024 T351 aluminium alloy show an increasing in fatigue life initiation with increasing stress ratio and maximum remote stress in measured and predicted results. On other material (aluminium alloy 7449 T7951), the fatigue crack growth analysis show that for the test at 120 MPa the crack initiation period seems to be significant (30% of total life) comparatively to the test at 140 MPa when the initiation period is negligible.In this work, stress ratio and notch sensitivity (hole effect) on fatigue initiation life and fatigue crack growth were studied from the double through crack at hole flat plate specimen made of the 2024-T351 Al-alloy. The study of these stages is based on local strain approach at the notch and NASGRO model.

II. LOCAL STRAIN APPROACH & FATIGUE CRACK GROWTH MODEL

A. Local strain approach

Fatigue resistance of metals can be characterized by a strain-life curve. Tuegel initially provided the strain-life based

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fatigue crack initiation module [19]. In AFGROW code [20], strain-life based crack initiation analysis method to predict crack initiation life is incorporated. In fatigue case and at the notch tip, local strains are obtained by using the Neuber's rule or Glinka [21] expressed in following form:

$$\frac{\left(K_f.\Delta\sigma_a\right)^2}{4E}=\frac{\Delta\sigma.\Delta\varepsilon}{2} \tag{1}$$

where "σ_a" is the applied stress and "σ" and "ε" are the resulting local stress and strain values corrected for the notch effect.

The fatigue notch factor, (K_f), is essentially the K_t value corrected to account for the notch sensitivity for the given material [22]. It is determined as follows:

$$K_f=1.0+\left(\frac{K_f-1.0}{1.0+\left(\alpha/r\right)}\right) \tag{2}$$

where "α" is an empirically determined material constant [23] and r is the notch root radius.

In Glinka's approach the local strains and stresses should represent energy equivalence as compared the remote loading conditions, leading to the following equation:

$$\frac{\left(K_f.\Delta\sigma_a\right)^2}{2E}=\frac{\Delta\sigma^2}{4E}+\frac{\Delta\sigma}{n'+1}\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{3}$$

In this equation K' and n' correspond to the material's cyclic hardening law.

The local strains were determined by coupling equation (1) and (3), given local strain range in function of local stress range named cyclic stress-strain (equation 4).

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\sigma}{2E}\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{4}$$

The relationship between total strain amplitude, $\Delta\varepsilon/2$ and life to failure, $2N_f$, can be expressed in the form [24]:

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma'_f}{2E}\left(2N_f\right)^b+\varepsilon'_f\left(2N_f\right)^c \tag{5}$$

where "σ'_f" is the fatigue strength coefficient; "b" is the fatigue strength exponent, "ε'_f" is the fatigue ductility, "c" is the fatigue ductility exponent.

B. Fatigue crack growth model

AFGROW code developed by NASA [20] is used for simulation of fatigue crack growth. The interest model is NASGRO model when totality of fatigue crack growth curves is considered. NASGRO model are expressed bellow (Eq. 6):

$$\frac{da}{dN}=C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n\frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_{crit}}\right)^q} \tag{6}$$

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. For constant amplitude loading, the function f determined by Newman [25] can be written as (Eq. 7):

$$f=\frac{K_{op}}{K_{max}}=\left\{Max\left(R,A_0+A_1R+A_2R^2+A_3R^3\right)\right. \quad R\geq 0 \tag{7}$$

coefficients A_i are expressed by equation 8.

$$\begin{cases} A_0=\left(0.825-0.34\alpha+0.05\alpha^2\right)\left[cos\left(\frac{\pi}{2}.\frac{\sigma_{max}}{\sigma_0}\right)\right]^{\frac{1}{\alpha}} \\ A_1=\left(0.415-0.071\alpha\right)\sigma_{max}/\sigma_0 \\ A_2=1-A_0-A_1-A_3 \\ A_3=2A_0+A_1-1 \end{cases} \tag{8}$$

III. MATERIAL PROPERTIES AND SPECIMEN GEOMETRY

The material used in this study is the aluminum alloy 2024-T351. Plates are subjected to numerical fatigue tests in L-T orientation. The basic mechanical properties for Aluminum alloys 2024-T351 are given in Table 1. Simulation of fatigue crack initiation and crack growth used plate with double through crack at hole under tensile tests (Fig.1).

TABLE I
MECHANICAL PROPERTIES OF 2024 T351 AL-ALLOY

$\sigma_{0.2}$ (MPa)	K_C (MPa.m$^{0.5}$)	K_{IC} (MPa.m$^{0.5}$)	E (Gpa)	ν
372.32	74.72	37.36	73.09	0.33

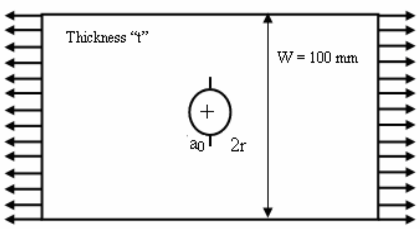

Fig. 1 Finite plate specimen (double through crack at hole)

The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters and is given by equation 9:

$$\Delta K = \sigma\sqrt{\pi . a}.\beta\left(\frac{a}{r}\right) \tag{9}$$

where β is the geometry correction factor, proposed by Newman **[10]**, is expressed below (Eq. 10):

$$\beta\left(\frac{a}{r}\right) = 1 - 0.15\lambda + 3.46\lambda^2 - 4.47\lambda^3 + 3.52\lambda^4 \tag{10}$$

where: $\lambda = 1/\left(1 + (a/r)\right)$

Table 2 lists basic cyclic strain-life properties used in fatigue crack initiation analysis for studied material of the notched specimen (AFGROW Database). Crack growth model parameters are presented in Table 3.

TABLE II
CYCLIC STRAIN LIFE PROPERTIES OF 2024 T351 AL-ALLOY

σ'_f	ε'_f	b	c	K_f	K'	n'
1013.53	0.21	-0.11	-0.52	0.5×10^{-4}	786	0.09

TABLE III
PARAMETERS OF CRACK GROWTH MODEL

C	n	p	q
1.71×10^{-10}	3.353	0.5	1

IV. RESULTS AND DISCUSSION

A. Stress ratio effect on fatigue life initiation and fatigue crack growth rate

Plate specimen in L-T orientation was subjected to constant amplitude loading with different R-ratio. The K_{max} failure criteria were adopted for the limit of crack growth. Fig. 2 showed effect of stress ratio on fatigue initiation life. For positive values of stress ratio, an increase in the R-ratio increase the number of cycles to initiate a fatigue crack while the alternating stress is not kept constant. This increasing is due to the diminution of amplitude loading range when maximum amplitude is maintained constant. The evolution of initiation life is fitted by exponential equation, see on Fig. 2. At low stress ratio, his effect is negligible. Fatigue crack growth rate of 2024 T351 aluminum alloy is presented on Fig. 3. An important effect of stress has been observed for this material at low and high stress intensity factor range ΔK. Increasing of R-ratio, decrease FCGR and threshold stress intensity factor. Threshold stress intensity factor vary from 2.1 MPa.$(m)^{0.5}$ for R=0.3 to 2.86 MPa.$(m)^{0.5}$ for R=0. In Paris region, from 4 MPa.$(m)^{0.5}$ to 30 MPa.$(m)^{0.5}$, slop of FCGR keep constant.

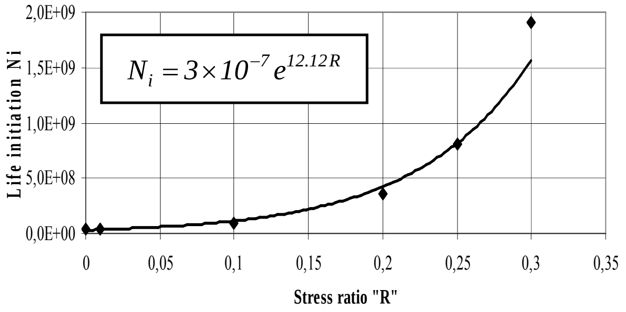

Fig. 2 Effect stress ratio on fatigue initiation life

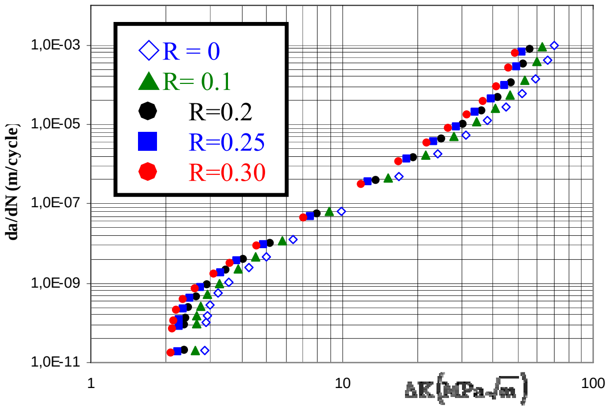

Fig. 3 R-ratio effect on fatigue crack growth rate

B. Notch effect on fatigue initiation life

Notch effect is characterized by variation of notch radius of hole. Fig. 4 shows the variation of fatigue initiation life in function of notch radius at stress ratio R=0.1. It have been shown that an increasing of notch radius decrease the fatigue initiation life. The increasing of notch radius of 2 mm to 7 mm decreases the fatigue initiation life approximately 8.5 times. The evolution of initiation life function of radius of hole is given by equation 11 with good correlation.

$$\frac{N_i}{10^6} = \left(4.10^3 - 4.10^3 r + 10^3 r^2 - 3.10^2 r^3 + 30r^4 - r^5\right) \tag{11}$$

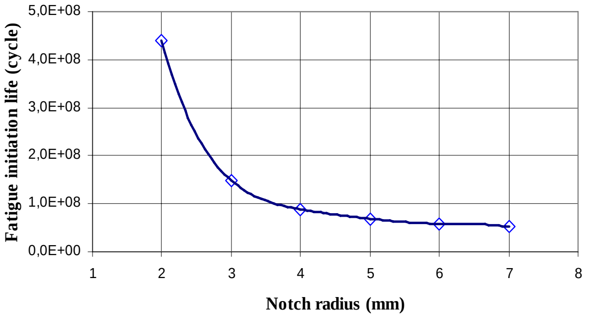

Fig. 4 Effect of notch radius (hole) on fatigue initiation life

V. CONCLUSION

Fatigue crack initiation and fatigue crack growth rate of 2024 T351 on the double through crack at hole plate specimen are investigated in this work. The main conclusions are resumed below:

- The result of this study shows that crack initiation and crack propagation were dependent on the component geometry and applied stresses.
- Fatigue life is related to crack initiation and growth. Crack initiation is related to applied mean stress (effect of R-ratio), stress concentrations and material properties.
- An increasing of stress ratio increase the fatigue crack growth rate.
- An increasing of notch radius (dimension of hole), decrease fatigue initiation life.

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