

Notch Fatigue Crack Initiation and Propagation Life under Constant Amplitude Loading Through Residual Stress Field

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Abstract. The purpose of this paper is to estimate the number of cycles for fatigue crack initiation in notched plate under constant amplitude loading through tensile residual stress field of Aluminum alloy plate. Residual stress field was generated by plastic deformation using finite element method. Simulation of fatigue behavior was made on AFGROW code. It was shown that the fatigue crack initiation and propagation were affected by level of residual stress field. In this investigation, the presence of tensile residual stresses reduces considerably the total fatigue life. Loading parameter namely stress ratio was studied. The decreasing in this parameter reduces the fatigue crack growth rate (FCGRs).

Introduction

Engineers and researchers divide fatigue damage in 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. Stress concentration will be produced in these discontinuities 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. Crack initiation occurs as a consequence of micro structural changes in metallic materials during fatigue process. Different mechanisms are responsible for their formation [2]. If it is accepted that for given materials states at comparable load amplitudes increasing amounts of plastic strain amplitudes lead to decreasing numbers of crack initiation cycles N_I , it follows that residual stresses may extend, shorten, or leave unchanged the number of cycles to crack initiation. Fatigue life prediction of structures with discontinuities has been extensively studied [3, 4]. Fatigue crack initiation lives have been predicted by many researchers [4-8] using different approaches. These approaches are based on nominal stresses, stress concentration factor, local stress-strain concepts and equivalent strain-energy density method. In, all paper, it is argued that fatigue life in propagation stage is small comparatively to the fatigue initiation life.

Fatigue life of materials and structures depends on several parameters. In initiation stage, fatigue life is linked strongly to metallurgical, geometrical, loading parameters and residual stress. Effect of stress ratio was investigated by several researchers, principally in stable crack propagations on some materials [9-11]. The residual stresses present diverse origins and several shapes [12-16] namely shot-penning, expansion of hole, overloads, under-load, welding, predeformation or pre-yielded The stress field is beneficial if the stress is in compressive state [17], then tensile residual stresses increase fatigue crack growth rate [18]. In the investigation of Kamel et al. [19] effects of tensile and compressive residual stress in fracture mechanics specimens by the application of a mechanical pre-load were studied. This is considered in the context of a 'C' shape specimen which is mechanically pre-tensioned or pre-compressed to produce, respectively, a compressive or tensile

residual stress in the region where the crack is introduced. Finite-element analysis is performed to simulate the pre-loading and the subsequent fracture loading of the cracked specimens. In the investigation of Al-Khazraji et al. [20], effect of residual stress on the fatigue behavior of 2024 aluminum alloy was studied experimentally and numerically using finite element method. Residual stresses were imparted to the fatigue tests specimens by heat treatment, pre-strain and welding. Effect of predeformation on fatigue crack initiation in pipeline steel was studied by Zheng et al. [21]. 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 aluminum alloy 2024-T4 was investigated by Grosskreutz and Shaw [22]. Recently, fatigue crack initiation performed on 2024 T351 Al-alloy was studied by Ranganathan et al [23]. In this work crack initiation phase has been considered in the estimation of total fatigue life when short crack growth approach was used and results have showing an increasing in fatigue life initiation with increasing stress ratio and maximum remote stress in measured and predicted results.

In this attempt, effect of stress ratio and tensile residual stress at notch (hole) were investigated on crack initiation life and fatigue crack growth using double through crack at hole of plate specimen. The present study was performed on 2024-T351 Al-alloy. Stage initiation and stable fatigue crack growth are based respectively on local strain approach at the notch and on NASGRO model.

Prediction of Residual Stress Field by Preloading

Bi-dimensional FEA calculations of residual stress due to the pre-deformation effect were carried out using ANSYS, Version 11. The model consisted of full integration elements of type plane 183. The mesh was more refined in the region of the notch root (Fig. 1). Numerical study was performed on 2024 T 351 Al-alloy. Mechanical properties are shown on Table 1 and true strain stress curve is illustrated on Fig. 2.

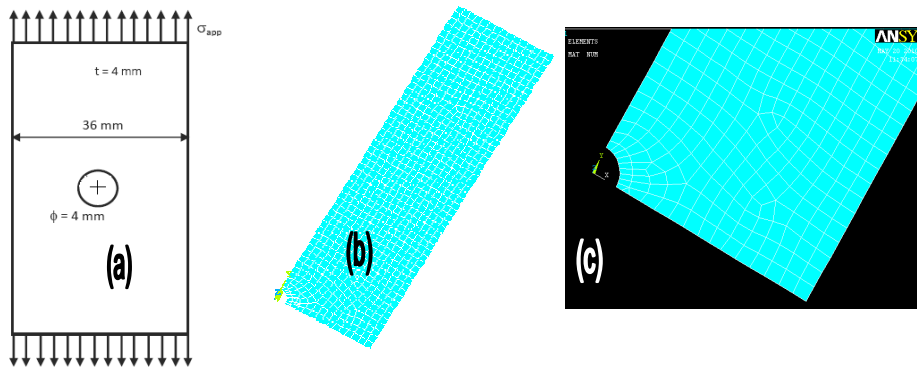


Fig. 1. Specimen study with uniform load (a) geometry (b) Mesh of notched plate (c) $\frac{1}{4}$ of plate detail of mesh around hole

Table1: Mechanical properties of 2024 T351 Al-alloy

$\sigma_{0.2}$ [MPa]	UTS [MPa]	A%	E [GPa]	ν
363	477	12.5	74	0.33

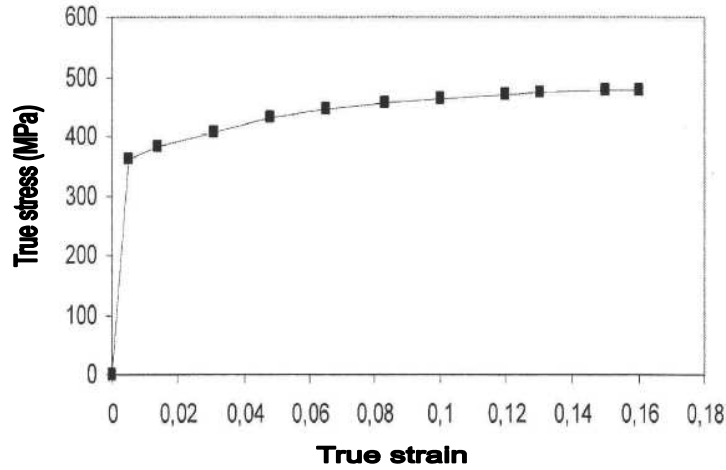


Fig. 2. Strain-stress curves for 2024 T351 Al-alloy

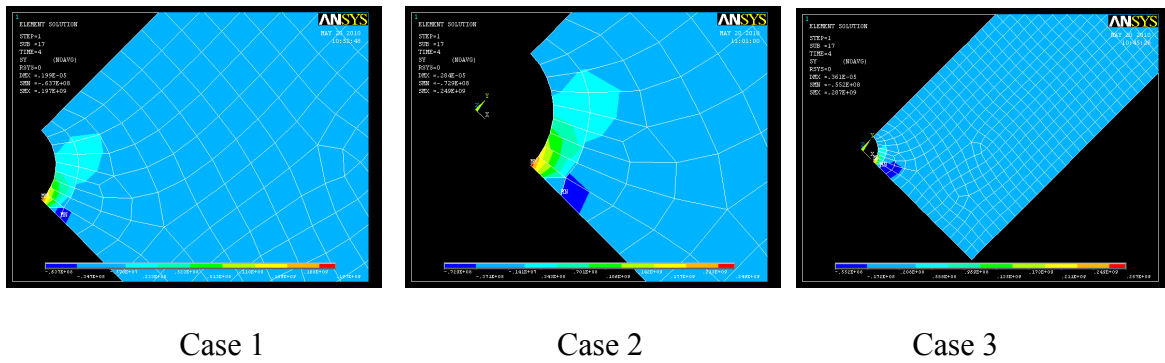


Fig. 3. Distribution of stress around hole for different levels of applied plastic load

Under reversed loading using pre-stress module with large displacement option, a residual stress field was generated when different levels of loading were applied in compression. Fig. 3 shows distribution of residual stress around hole. Distributions of stress σ_{yy} for all level of applied load in supposed crack growth patch are shown in Fig. 4. It was shown at free surface of hole a high tensile stress. From 0.8 mm to 2.40 mm distance of hole, stress is compressive.

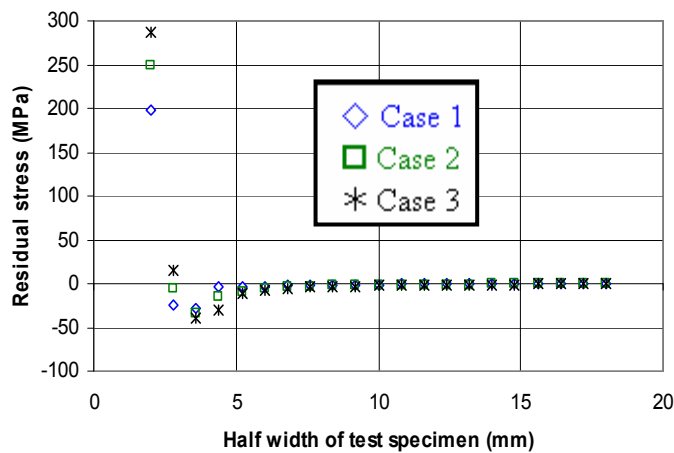


Fig. 4. Distribution of stress σ_{yy} in predicted crack growth path

Models of fatigue crack initiation and fatigue crack growth

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

$$\Delta K = \sigma \sqrt{\pi a} \beta \frac{a}{r} \quad (1)$$

where β is the geometry correction factor is expressed below (Eq. 10):

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

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

Local strain approach. Fatigue resistance of metals can be characterized by a strain-life curve. Tuegel initially provided the strain-life based fatigue crack initiation module [24]. In AFGROW code [25], 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 [26]. In Glinka's approach the local strains and stresses should represent energy equivalence as compared the remote loading conditions, leading to the following equation (Eq. 3):

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

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 (Eq. 4).

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

The relationship between total strain amplitude, $\Delta \epsilon/2$ and life to failure, $2N_f$, can be expressed in the form [27]:

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{2E} (2N_f)^b + \epsilon'_f (2N_f)^c \quad (5)$$

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.

Table 2 lists basic cyclic strain-life properties used in fatigue crack initiation analysis for studied material of the notched specimen (AFGROW Database).

Table 2: 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

Fatigue crack growth model. The interest model is NASGRO model when totality of fatigue crack growth curves is considered. NASGRO model are expressed bellow (Eq. 6):

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

f present the contribution of crack closure and the parameters C, n, p, q were determined experimentally and ΔK_{th} is the crack propagation threshold value of the stress–intensity factor range. For constant amplitude loading, the function f determined by Newman [28] can be written as (Eq. 7). Principal crack growth parameters of NASGRO model are presented in Table 3.

$$f = \frac{K_{op}}{K_{max}} = \text{Max} \left(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3 \right) \quad R \geq 0 \quad (7)$$

Table 3: Parameters of crack growth model

C	N	p	q
1.71×10^{-10}	3.353	0.5	1

Effects of stress states on fatigue initiation and FCG

Notched plate specimen in L-T orientation was subjected to constant amplitude loading ($\sigma_{app}=100$ MPa) with different R-ratio. The K_{max} failure criteria were adopted for the limit of crack growth. In absence of tensile residual stress, Table 4 shows 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. In presence of tensile residual stresses fatigue crack initiation life has been reduces considerably for different cases (see Fig. 3). Theses diminutions were affected by increasing in residual stress intensity factor K_r .

Table 4. Effect of stress ratio and tensile residual stress at hole on fatigue crack initiation life

Tensile residual stress	R = 0.1	R = 0.2	R = 0.4
Without RS	1.21×10^6	3.43×10^6	1.85×10^7
Case 1	2.14×10^5	4.32×10^5	1.15×10^6
Case 2	1.76×10^5	3.07×10^5	6.02×10^5
Case 3	1.78×10^5	2.71×10^5	7.84×10^5

In absence of residual stress, stress ratio effect on fatigue crack growth life (N_p) is presented in Fig. 5 when fatigue initiation life was dissociated. An increasing in fatigue life was shown in increasing of R-ratio. Without residual, fatigue life in propagation stage is very small comparatively to the fatigue initiation life (see Table 4 and Fig. 5). The evolution of the crack length through residual stresses fields according to the fatigue life is shown on Fig. 6. It is noticed that an increasing in the level of pre-strain increased the level of tensile residual stresses at the edge of the hole, then affect crack growth rates.

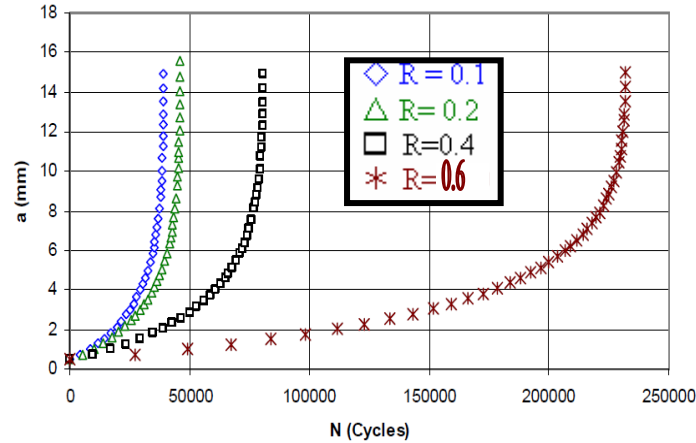


Fig. 5. Effect of stress ratio on fatigue life without residual stress

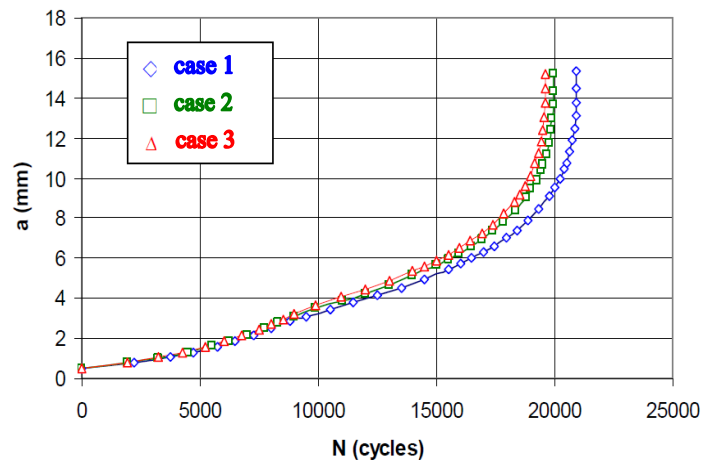


Fig. 6. Effect of tensile residual stress on fatigue life

Effect of residual stress generated by prestress in compression on the crack growth rate is shown in Fig. 7. The crack growth is plotted against effective stress intensity factor ΔK_{eff} . Note well the calibration curves of cracking. From $\Delta K_{\text{eff}} = 10 \text{ MPa (m)}^{1/2}$, we notice a decrease in crack growth rate due to the presence of compressive residual stresses. Effective stress intensity factor is expressed by Eq. 8. Residual stress intensity factor K_r was evaluated numerically by Gauss method. Evolution of K_r , against crack length is shown in Fig. 8. There was a decrease in K_r through residual stresses from tensile to compressive.

$$\begin{aligned} K_{\text{max-eff}} &= K_{\text{max}} + K_r \\ K_{\text{min-eff}} &= K_{\text{min}} + K_r \end{aligned} \quad (8)$$

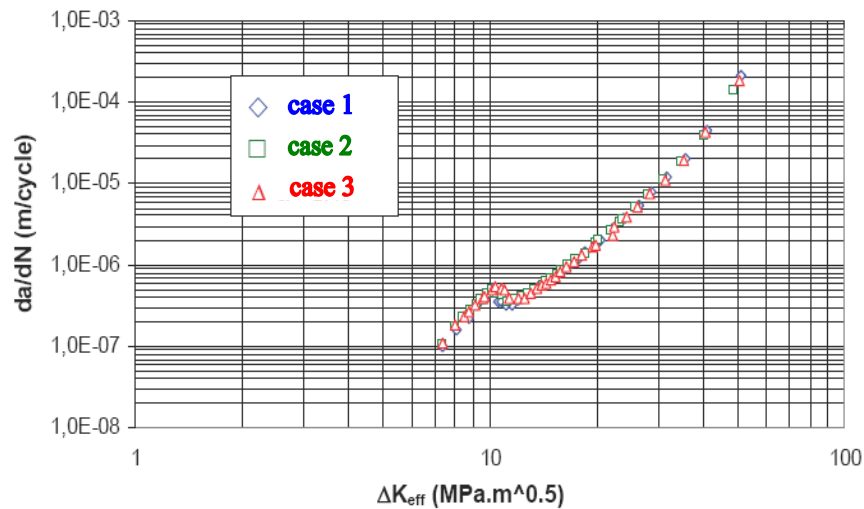


Fig. 7. Fatigue crack growth rate through residual stress field

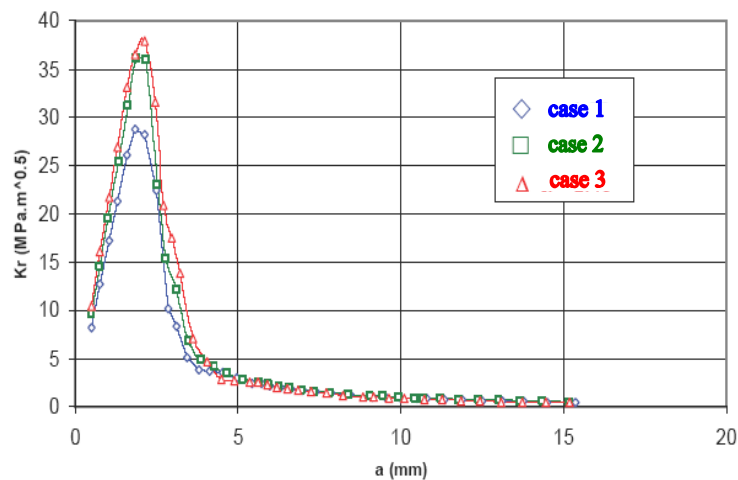


Fig. 8. Evolution of residual stress intensity factor K_r

Conclusion

Fatigue crack initiation and fatigue crack growth rate of 2024 T351 through residual stress field on the double through crack at hole for plate specimen are investigated in this work. In absence of residual stress residual stress, fatigue crack growth was affected by stress ratio. Main conclusions showing effects of residuals stresses are resumed below:

- * Initiation fatigue life is strongly related to cyclic loading characterized by the effect of stress ratio.
- * Nature of residual stresses showed the detrimental effect of tensile stress and beneficial effect of compressive stress on fatigue initiation stage and fatigue crack growth.

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