

# Fatigue Crack Initiation and Propagation through Residual Stress Field

M. Benachour, N. Benachour, and M. Benguediab

**Abstract**—In this paper fatigue crack initiation and propagation in notched plate under constant amplitude loading through tensile residual stress field of 2024 T351 Al-alloy plate were investigated. Residual stress field was generated by plastic deformation using finite element method (FEM) where isotropic hardening in Von Mises model was applied. 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 at notch (hole) reduces considerably the total fatigue life. It was shown that the decreasing in stress reduces the fatigue crack growth rates.

**Keywords**—Residual stress, fatigue crack initiation, fatigue crack growth, Al-alloy.

## I. INTRODUCTION

FATIGUE damage is divided in three stages [1]: fatigue crack initiation, stable crack propagation and unstable crack propagation. Generally, mechanical components and structures contain geometrical discontinuities and notches. 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.

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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 decrease 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 work, effect of stress ratio and tensile residual stress at notch (hole) were studied 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 for initiation stage and on NASGRO model for propagation.

## II. 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 I and true strain stress curve is illustrated on Fig. 2.

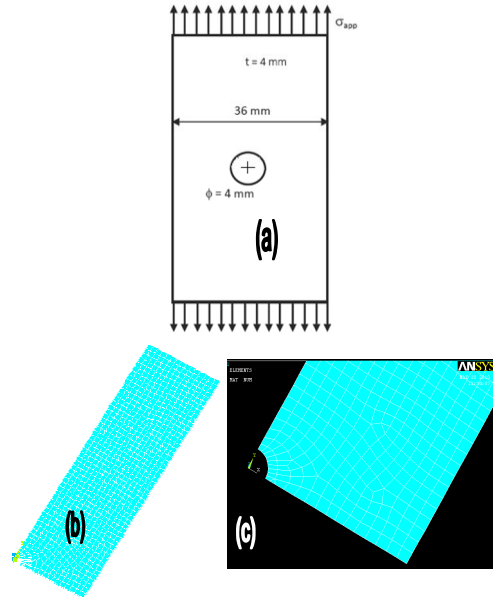


Fig. 1 Specimen study with uniform load (a) geometry (b) Mesh of notched plate (c) ¼ of plate detail of mesh around hole

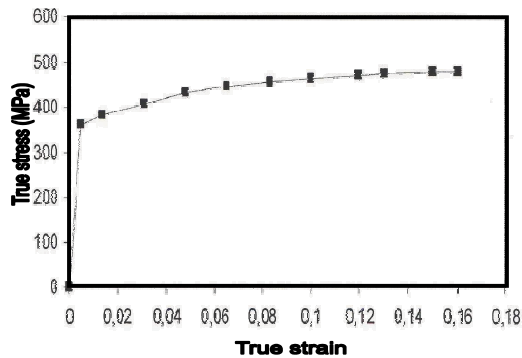


Fig. 2 True strain-stress curves for 2024 T351 Al-alloy

TABLE I  
 MECHANICAL PROPERTIES OF 2024 T351 AL-ALLOY

$\sigma_{0.2}$ (MPa)	UTS (MPa)	E (GPa)	A%
363	477	74	12.5

Under reversed loading using pre-stress module with small 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  $\sigma_{yy}$  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.

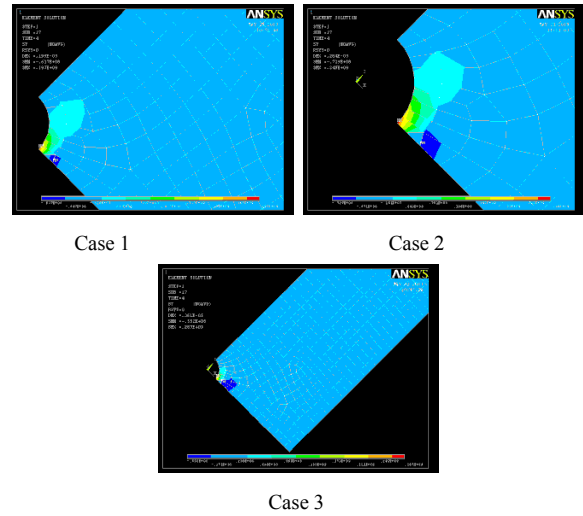


Fig. 3 Distribution of stress around hole for different levels of applied plastic deformation

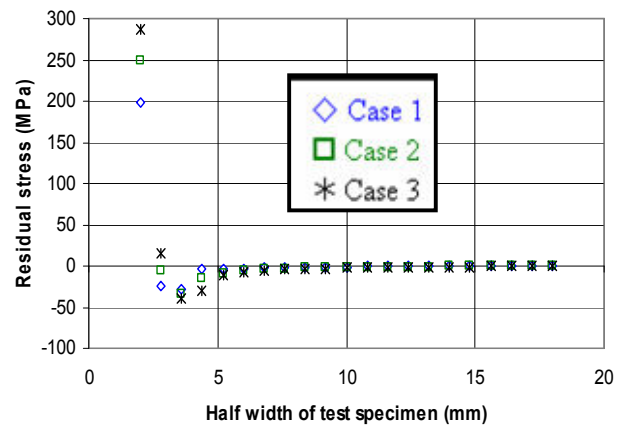


Fig. 4 Distribution of stress  $\sigma_{yy}$  in predicted crack growth path

## III. 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 Eq. 1.

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

where  $\beta$  is the geometry correction factor is expressed below (Eq. 2):

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

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

### A. 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:

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

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 (equation 4).

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} \frac{\Delta\sigma}{2K'} \frac{1}{n'} \quad (4)$$

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

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

where: " $\sigma'_f$ " is the fatigue strength coefficient; " $b$ " is the fatigue strength exponent, " $\varepsilon'_f$ " is the fatigue ductility, " $c$ " is the fatigue ductility exponent.

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

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

$\sigma'_f$	$\varepsilon'_f$	$b$	$c$	$K_f$	$K'$	$n'$
1013.53	0.21	-0.11	-0.52	$0.5 \times 10^{-4}$	$\frac{78}{6}$	0.09

### B. 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):

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

$f$  present the contribution of crack closure and the parameters  $C$ ,  $n$ ,  $p$ ,  $q$  were determined experimentally and  $\Delta K_{th}$  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):

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

Principal crack growth parameters of NASGRO model are presented in Table III.

TABLE III  
 PARAMETERS OF CRACK GROWTH MODEL

C	n	p	q
$1.71 \times 10^{-10}$	3.353	0.5	1

### IV. EFFECTS OF STRESS STATES ON FATIGUE INITIATION AND FATIGUE CRACK GROWTH

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 IV 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  $K_r$ .

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 IV 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.

TABLE IV  
 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	$1.21 \times 10^6$	$3.43 \times 10^6$	$1.85 \times 10^7$
Case 1	$2.14 \times 10^5$	$4.32 \times 10^5$	$1.15 \times 10^6$
Case 2	$1.76 \times 10^5$	$3.07 \times 10^5$	$6.02 \times 10^5$
Case 3	$1.78 \times 10^5$	$2.71 \times 10^5$	$7.84 \times 10^5$

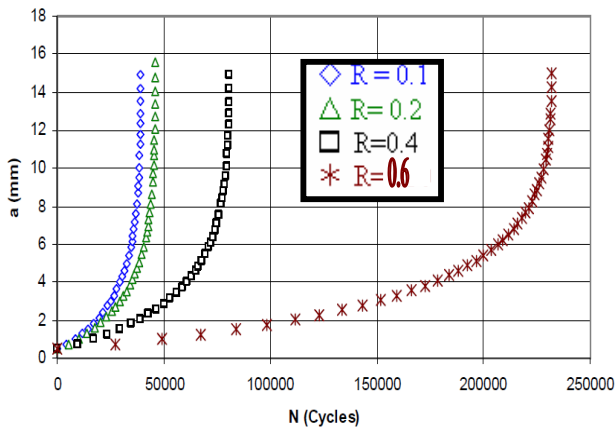


Fig. 5 Effect of stress ratio on fatigue life without residual stress

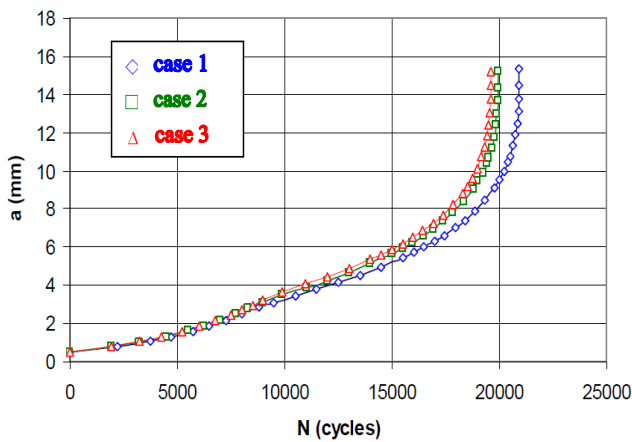


Fig. 6 Effect of tensile residual stress on fatigue life

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  $\Delta K_{eff}$ . Note well the calibration curves of cracking. From  $\Delta K_{eff}=10 \text{ MPa(m)}^{1/2}$ , 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 implemented in AFGROW code. 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.

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

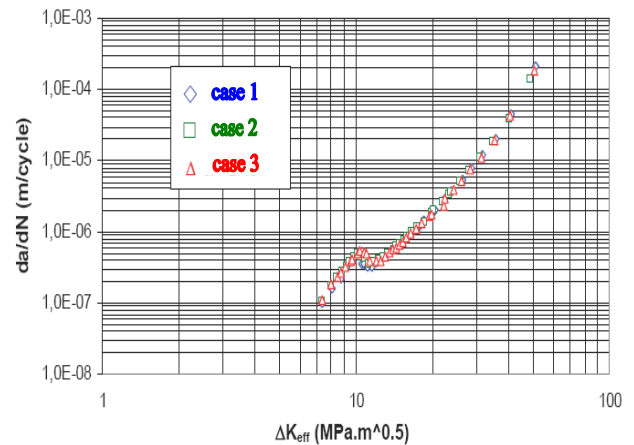


Fig. 7 Fatigue crack growth rate through residual stress field

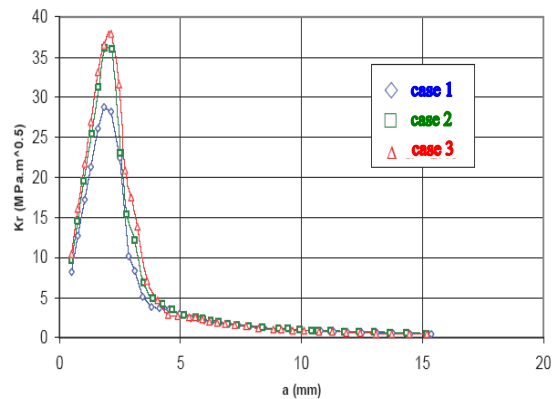


Fig. 8 Evolution of residual stress intensity factor  $K_r$

## V. 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 effect of residual stress 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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