Focussed on Structural Integrity and Safety: Experimental and Numerical Perspectives

Visual Abstract

Experimental investigation of fatigue crack initiation from notches in 2024 T351 Al-alloy

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ABSTRACT. In this investigation, fatigue crack initiation criterion was established from notches in aged hardening aluminum alloy. This criterion was used to predict the residual lifetime in aeronautical structures subjected to constant amplitude loading using concept of local stress at notch. Charpy V-notch specimens were taken from sheet plate and the notch radius accurately machined at value of 0.2mm. The local stresses were determined numerically and validated analytically. In experimental investigation, the V-notched specimens were loaded in four point bending fatigue with a stress ratio R=0.1 and variation in amplitude loading.

KEYWORDS. Fatigue crack initiation; Notch; Finite element method; Stress field; Aluminum alloy.

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INTRODUCTION

Generally, aeronautical structures are subjected to cyclic loading. Discontinuities and notches in mechanical components and structures present a site of stress concentration resulting of external load that could be sites of crack initiation. The fatigue life of structural components is determined by the sum of the numbers cycles required to initiate a fatigue crack and to propagate this crack up to the critical dimension. Many approaches may be classified in different manner to analyses fatigue crack initiation from notch. The global elastic analysis, it takes into account linear fracture mechanics. Firstly, this approach was sued by Heckel et al. [1] by introducing the loading parameter ($\Delta K/\rho 1/2$). ΔK is the amplitude loading of stress intensity factor and ρ is the radius of the tip of notch. This approach was used by some researchers. Suresh and Ritchie [2] have applied this approach for some alloys (steel and Al-alloy). Also Bauss [3] and DuQuesnay [4] have used this approach respectively for high strength steel, 2024 T351 Al-alloy and SAE 1045 steel. These authors noted that this correlation for small numbers of cycles at radius notch les than critical value does

not give good satisfactory results. A non local fatigue criterion has been proposed by Schwob et al. [5], with a single additional parameter compared to traditional criteria, by averaging a classical criterion over a damaged area.
The analyzed domain by the global approach is between 10^2 and 10^5 cycles [6]. In experimental investigation, Hammouda and El-Batanony [7] have established a criterion in estimation of fatigue crack initiation life for notched plate under amplitude loading, stress ratio and radius at notch tip effects. The local elastic analysis was takes into the local stress amplitude $\Delta\sigma_{\theta\theta}$ at a distance "d" from the tip of the notch. This approach was applied by Devaux et al. [8] in establishment a fatigue crack initiation criterion for low fatigue cycle. The established criterion was given by the curve ($\Delta\sigma_{\theta\theta}$, N_I). This method was applied successfully by Batise at al. [9] in predicting of fatigue crack initiation of X65 pipeline steel. In Neuber's analysis [10], a number of authors noted that this analysis overestimates the notch effect on fatigue crack initiation [11-13]. In study conducted by Ranganathan et al. [14] a short crack approach has been developed to determine the fatigue crack initiation life at notch tip. This approach is compared to conventional local-strain approach and it is shown that the short crack approach gives acceptable predictions as compared to experiments, in the 2024 T351 alloy. In the investigation of Agbessi et al. [20] an analysis of high cycle multi-axial fatigue crack initiation modes based on SEM observations is conducted. Also it is concluded that different modes of high cycle fatigue micro cracks initiation were observed under complex loading conditions at stress levels close to the median fatigue limit of the material at 10^6 cycles. A physics-based multi scale approach was developed by Zhang et al. [21] to predict the fatigue life of crystalline metallic materials. An energy-based damage and slip-based damage criterion is developed to model two important stages of fatigue crack initiation: the nucleation and the coalescence of micro cracks.
In the present study, elastic analysis based on the knowledge of the local stresses amplitude at a distance from the tip of the notch presents best approach and is applied in 2024 T351 Al-alloy. Local's stresses amplitude at distance "d" are determined numerically by finite element analysis and validated analytically using Creager approach.

EVALUATION OF DISTRIBUTION OF STRESS NEAR THE NOTCH ROOT INITE ELEMENT

In order to shown the effect of stresses concentrations on fatigue crack initiation, distribution of stress fields near the notch was determined analytically and numerically. This study was applied in aged hardening Al-alloy in four bend specimen with V-notch. The analytical calculations was made using the formulation of Creager approach [19] which gives the stress field near the tip of a hyperbolic notch loaded in tension (Fig. 1).

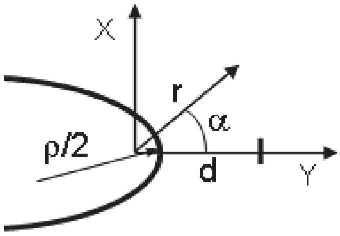

Figure 1: System coordinate applied in the calculation of stresses in the notch root

In opening mode, Creager equations are given by:

$$\begin{cases} \sigma_{xx} = \dfrac{K_I}{\sqrt{2\pi.r}}\cos\dfrac{\alpha}{2}\left[1+\sin\dfrac{\alpha}{2}\sin\dfrac{3\alpha}{2}\right] + \dfrac{K_I}{\sqrt{2\pi.r}}.\dfrac{\rho}{2.r}\cos\dfrac{3\alpha}{2} \\ \sigma_{yy} = \dfrac{K_I}{\sqrt{2\pi.r}}\cos\dfrac{\alpha}{2}\left[1-\sin\dfrac{\alpha}{2}\sin\dfrac{3\alpha}{2}\right] - \dfrac{K_I}{\sqrt{2\pi.r}}.\dfrac{\rho}{2.r}\cos\dfrac{3\alpha}{2} \\ \tau_{xx} = \dfrac{K_I}{\sqrt{2\pi.r}}\sin\dfrac{\alpha}{2}\cos\dfrac{\alpha}{2}\cos\dfrac{3\alpha}{2} - \dfrac{K_I}{\sqrt{2\pi.r}}.\dfrac{\rho}{2.r}\sin\dfrac{3\alpha}{2} \end{cases} \tag{1}$$

In Eqn. 1, K_I is the stress intensity factor given by Murakami [22] considering notch as a crack. The radius r and α are cylindrical coordinates shifted by ρ/2 with respect the notch root. We are interested in the component σxx given by Eqn. 2 (stress opening in cracking plane).

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi(d+\rho/2)}}\left[1+\frac{\rho}{2(d+\rho/2)}\right] \quad (2)$$

Numerical calculations of stresses at notch root are led by finite element ANSYS code. Some researches were applied finite element analysis to determine the stress distribution at notch root, stress intensity factor, crack opening stress, …etc. [23-25]. Half of the sample is considered taking into account geometric symmetry and applied loading. The mesh, the boundary conditions and loading are shown in Fig. 2. At specified boundaries conditions and according to the direction x, displacement Ux is equal to zero. The modelling was done by two-dimensional finite element (PLANE 82) in plane strain condition. PLANE82 is a higher order version of the two-dimensional, four-node element (PLANE42). It provides more accurate results for automatic meshes and can tolerate irregular shapes without as much loss of accuracy. The 8-node elements have compatible displacement shapes and are well suited to model curved boundaries. The 8-node element is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions (Fig. 3). The element may be used as a plane element or as an axisymmetric element. The element has supplementary capabilities as plasticity and large strain. Automatic mesh option was used with refined meshing at notch where the number of element is 363 elements. The number of gauss integration point per element is equal to 4. The studied material is 2024 T351 Al-alloy, quenched and tempered at room temperature. Based on elastic local stress concept approach at notch, elastic isotropic material model is used. The mechanical properties are given in Tab. 1 in T orientation. This study is conducted for radius at notch equal to 0.2 mm.

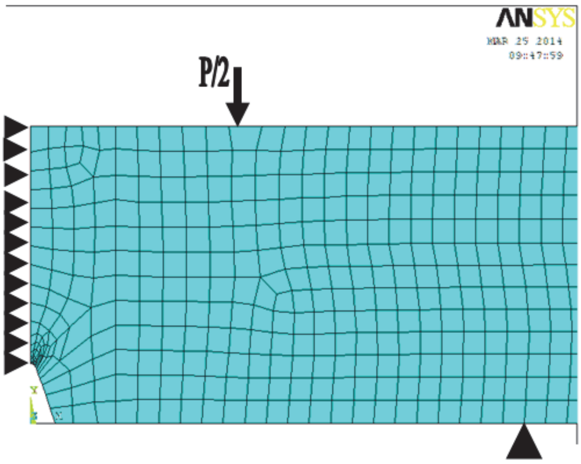

Figure 2: Mesh of V-notch specimen: applied load and boundary conditions

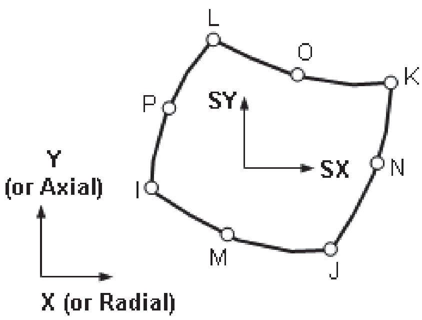

Figure 3: Eight node isoparametric element: PLANE82

E (GPa)	$\sigma_{Y0.2}$ (MPa)	UTS (MPa)	A(%)	ν
74.0	363	465	22.1	0.33

Table 1: Mechanical properties of 2024 T351 Al-alloy

Fig. 3 shows the effect of applied loading on the concentration and the stress distribution near the notch for notch radius ρ=0.2 mm using analytical solution. An important difference at notch root is found. For P=3.99 KN, the developed stress represents 1.45 times the stresses in applied loading of 2.755 KN. The variation in the opening stress obtained numerically $\sigma_{\theta\theta} = \sigma_{xx}$ in the plane of the slot depending on the distance to the tip there of to a radius ρ = 0.2 and a variable loading P, is shown in Fig. 4. The same tendency is obtained with respect to analytical results by application of Creager formulation (Fig. 3), where the gap is important in stress at the tip of the notch (high stress concentration). A good correlation was found between the numerical results and analytical results. The high difference is found at the tip of the notch where the difference not exceeds 7.4%.

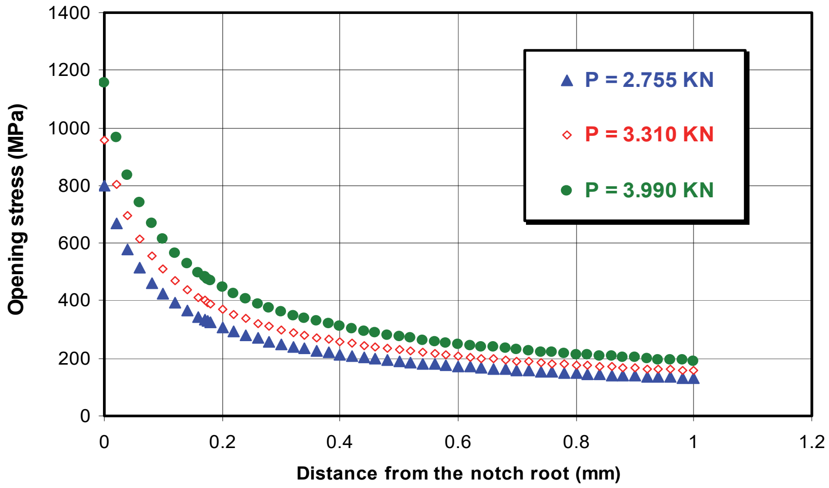

Figure 3: Analytical results of applied loading effect on stresses near the notch root

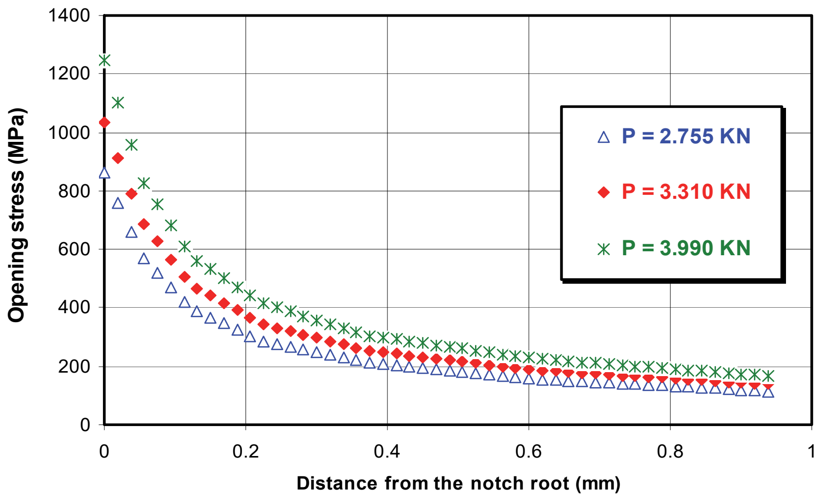

Figure 4: Numerical results of applied loading effect on stresses near the notch root

EXPERIMENTAL PROCEDURES

Fatigue crack growth tests were conducted on V-notch four points bending specimen in T-S orientation. The notch is machined in short direction (S). To detect the starting and monitoring of crack, a polishing was performed to remove surface scratches. The geometrical model and dimension of specimens are represented in Fig. 5. Fatigue tests were conducted at constant amplitude loading at room temperature (23 °C) with a frequency of 10 Hz on a servohydraulic machine "MTS 810" with capacity 100 KN. Fatigue tests were conducted at R-ratio (R = 0.1) with variation of the levels of amplitude loading (P_{max}=2.755 ; 3.31 ; 3.99 KN).

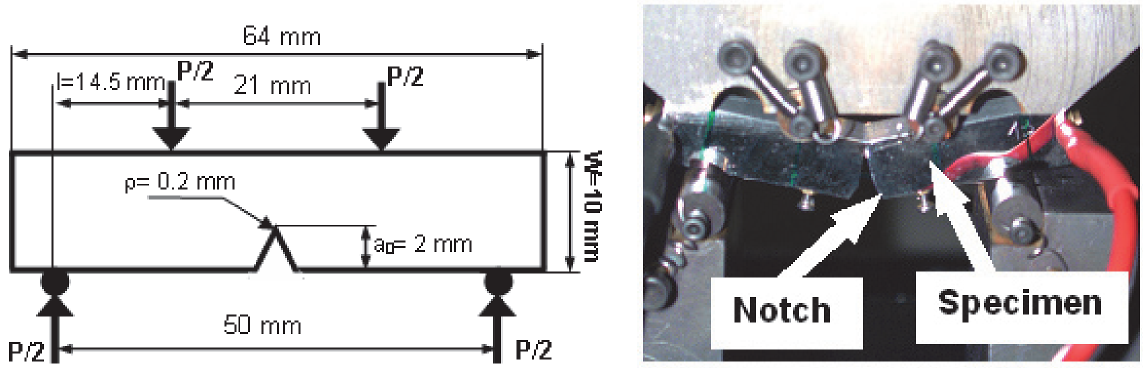

Figure 5: V-notch specimen in four points bending tests in 2024 T351 Al-alloy

RESULTS AND DISCUSSION

The effect of mean stress on fatigue crack is characterized either by variation of R-ratio or amplitude of loading. This work presents the effect of the amplitude loading on fatigue crack initiation in 2024 T351aluminum alloy. Tab. 2 summarizes the lifetimes of initiation crack for a crack initiation length between 170 and 180 μm. The considered lengths are in the order of the average grain size of studied material. The applied cyclic loading ΔP is characterized by the amplitude loading where the maximal amplitude loading for the three tests are respectively P_{max}=3.99 KN, 3.31 KN and 2.755 KN. It should be noted that the lifetime of the crack initiation decreases with increasing in the amplitude loading for the same order of magnitude of the detected length. The transition in the amplitude loading ΔP from 2.48 to 2.98 KN has reduced the number of cycles of 22.000 cycles to 12,800 cycles. This represents a decrease of 1.72 times. According to the high applied load, the lifetimes in crack initiation are negligible comparatively to fatigue life in crack growth stage where the percentage in lifetime varies from 3% to 6.6% [26]. The greatness in results was confirmed by Ranganathan et al. [14] under a high load (3%).

Fatigue tests	P_{max} (KN)	ΔP (KN)	a_i (μm)	Ni (cycles)
S1	2.755	2.480	175	22000
S2	3.310	2.980	170	12800
S3	3.990	3.591	180	3000

Table 2: Effect of amplitude loading on fatigue initiation life at R=0.1 for 2024 T351 Al-alloy

In order to establish fatigue criterion to predict crack-initiation at the tip of a notch in aged hardening aluminum alloy from experimental results, an attempt is conducted for critical length from notch tip "d=175 μm" where the evolution in opening stress $\sigma_{\theta\theta} = \sigma_{xx}$ for three amplitude loading determined analytically and numerically (Figs 3 and 4). Analytical results of opening stress $\sigma_{\theta\theta} = \sigma_{xx}$ are used for curves given the fatigue initiation criterion. The curve giving the opening stress versus number of initiation cycles at critical distance d=175 μm is shown in Fig. 6.
The criterion for fatigue crack initiation thus obtained is given by Eqn. 2 where "$\sigma_{\theta\theta} = \sigma_{xx}$" is expressed in MPa and "N_i" in cycles. This criterion remains valid for cycle numbers between 10^3 and 3×10^4 cycles.

$$\sigma_{xx} = 2761.1\left(N_i\right)^{0.209} \quad (3)$$

The obtained results are in good agreement with those in the literature [15-18] for the same material and remain in the validity domain of the results in endurance tests for the same material (Al-alloy 2024 T351).

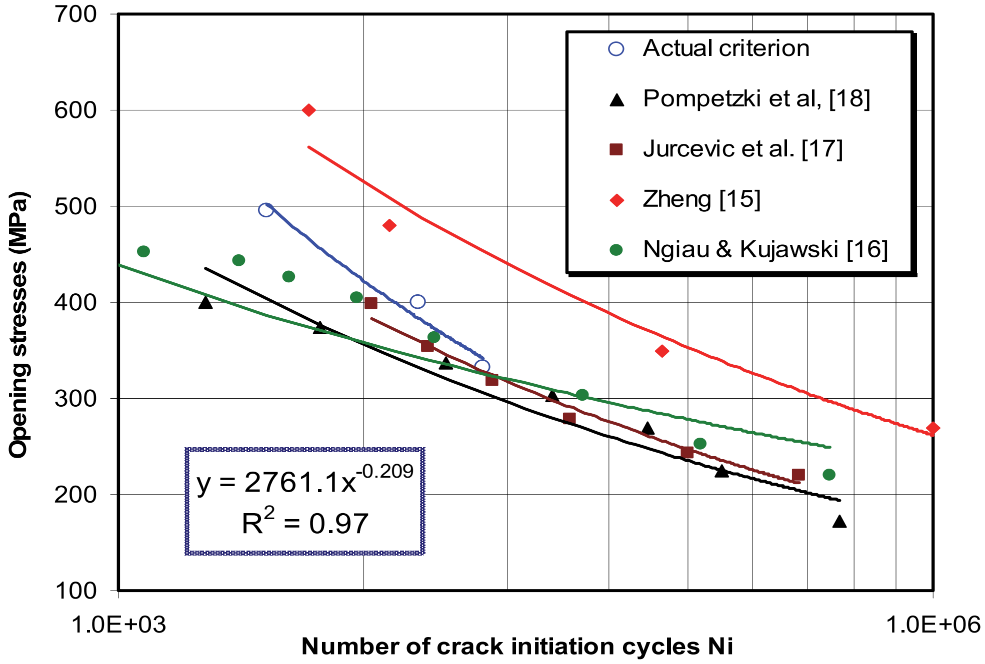

Figure 6: Crack initiation criterion.

Conclusion

The present investigation is conducted in order to evaluate the of fatigue crack initiation criterion in the 2024 T351 Al-alloy. Numerical and analytical approaches were applied to evaluate the stress distribution in Four V-notched specimens. From this investigation, we can conclude that:

- The fatigue crack initiation lifetime increases in decreasing of the amplitude loading (i.e. mean loading).
- The opening stresses determined numerically are validated analytically and depends on the level of applied load
- A fatigue crack initiation criterion at notch root for 2024 T351 Al-alloy showed the advantages in many applications. This criterion gives a satisfactory in prediction of fatigue crack initiation lifetimes comparatively to others published results.

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