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INVESTIGATION OF RESIDUAL STRESS EFFECT ON FATIGUE CRACK INITIATION FOR 2024 T351 AL-ALLOY

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Abstract: The effect of residual stresses resulting from plastic beam bending technique on fatigue crack growth initiation was studied on 2024 aluminium alloy. The residual stresses were calculated analytically or numerically using finite element method. In the analytical calculation linear work-hardening behaviour were assumed. In the numerical calculations constitutive equations including isotropic work-hardening was introduced. Effect of applied bending load levels upper elastic behaviour generating residual stress field was studied on fatigue crack initiation. Fatigue initiation life was affected by compressive residual stress at small notch. Fatigue life was increased with increasing in levels of compressive residual stress at notch. Rubbed zone near notch was shown; this is due to compressive residual stress.

Keywords: compressive residual stress; fatigue crack initiation; aluminium alloy

1 INTRODUCTION

Research on the fatigue behaviour has shown that the life of a structure is divided into three stages [1]: fatigue crack initiation, stable crack propagation and unstable crack propagation. The most common site for fatigue crack initiation in structural components is at stress concentrators such as notches, holes or fillets. In order to increase fatigue resistance, compressive residual stresses are often purposely introduced around these concentrators through processes such as expanded hole [2,3], shot-peening [4,5], tensile pre-straining [6-9]. Given the importance of residual stresses, proper characterization of their values and effects on fatigue crack initiation and fatigue crack growth are vital. To assess the effects of notches on the behaviour 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 [10,11]. Fatigue crack initiation life has been estimated by many authors [12,13] 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 [11,14]. 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. Compressive residuals stresses at notch offer beneficial effect on fatigue behaviour and consequently delay the initiation and propagation of fatigue crack [8,15]. The investigation conducted by Taghizadeh et al. [16] on 2024 T3 aluminium alloy plate shown that the initiation life in hole was affected by residuals stress dues to expansion process. The initiation life in expanded is important at low level of applied cyclic loading compared to the same plate without expansion. Contrarily at high level of applied cyclic loading, the initiation life is not affected. The effect of residuals stresses on fatigue crack initiation of X65 pipeline steel was studied by Mézière et al. [7]. These stresses were generated by mechanical preload (pre-straining process) in four-point bending. As shown in the studied endurance domain, the compressive residuals stresses lead to increase the initiation number of cycle. In contrast, the residual tensile stress does not change significantly the endurance curve compared to samples without residual stresses. The increasing in compressive residual stress levels lead to increase the fatigue initiation life [17].

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 study conducted by Almer et al. [19], fatigue crack initiation behaviour was affected strongly by macro residual stress dues to pres-straining and press-fitting operations. The fraction of fatigue life taken up by initiation, N_i/N_f, was at least 0.44 in the specimens tested, and this ratio increased with decreasing applied stress amplitude. In this investigation, residual stresses resulting from plastic beam bending technique on fatigue crack growth initiation was investigated on 2024 T351 aluminium alloy. The crack was initiated through compressive residual stress face and tensile residual stress.

2 EXPERIMENTAL PROCEDURE

The fatigue experimentation was performed on 2024 T351 Al-alloy, widely used for aeronautical applications. This alloy was provided by the ALCAN Company of production of aluminium alloys to the profit of the Centre of Materials, School of Mines Paris, France. The chemical composition of different materials used in this study is listed in Table 1. The mechanical properties at room temperature are shown in Table 2 and the tensile stress-strain curve along L direction of studied material is shown in Fig. 1. The microstructure of aluminium alloy 2024 T351, respectively in (T-S) and (L-S) directions, is presented in other author's paper [20] where the size of the pancake shaped grains is significant (620 x 270 x 350 μm^3).

Table 1 Chemical composition of Aluminium 2024 T351

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Pb	Al
0.105	0.159	3.97	0.449	1.5	0.05	0.109	0.018	0.02	.056	Bal

Table 2 Chemical composition of Aluminium 2024 T351

E(GPa)	$\sigma_{Y0.2}$	UTS (MPa)	A%
74	363	477	12.5

Bars with a rectangular section 20x15 mm^2 were preloaded under four points bending as shown in Fig. 2. This preloading introduced residual stresses which can be either tensile or compressive depending on the position of the fatigue crack on the free surfaces. The specimens with tensile/compressive residual stresses are named TRS and CRS. A small notch with 45 degrees was machined in these bars as shown in Fig. 2. The depth of this notch was kept as small as possible to limit the importance of residual stresses redistribution after machining. These specimens were finally tested under fatigue conditions with a frequency of 10 Hz and a sinusoidal wave signal.

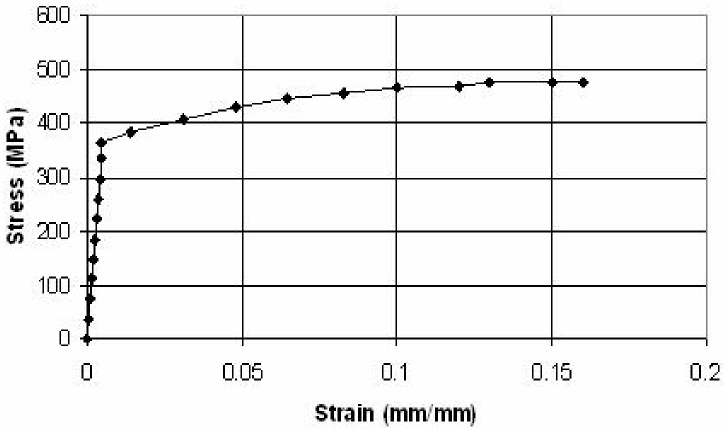

Fig. 1 Stress-Strain material properties for 2024 T351

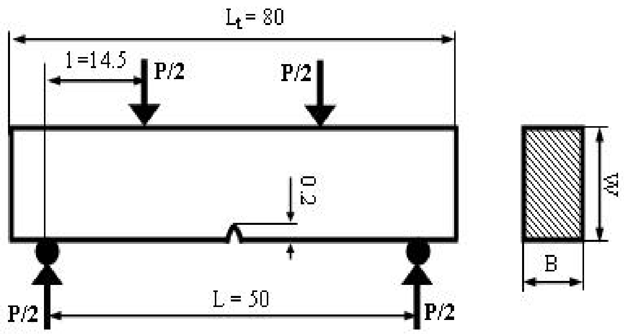

Fig. 2 V-notch specimen in four points bending test

3 EVALUATION OF RESIDUAL STRESSES IN FOUR POINTS BEND SPECIMENS

In order to assess the level of residual stresses introduced in four point bend specimens the applied preload was determined analytically and numerically. In analytical case, the distribution of residual stresses, σ_r, across the section is given by the following expressions which are valid only for perfectly plastic material:

$$\begin{cases} -h_e/2 \leq y \leq h_e/2 & \sigma_r = \sigma_Y \cdot \dfrac{y}{h_e/2} - \dfrac{12M_a}{B(h)^3}.y \\ y \leq h_e/2 & \sigma_r = \sigma_Y - \dfrac{12M_a}{B(h)^3}.y \\ y \geq h_e/2 & \sigma_r = -\sigma_Y - \dfrac{12M_a}{B(h)^3}.y \end{cases} \quad (1)$$

where "y" and "h_e" define respectively the variation through the height of specimen (W=h) and the size of the elastic core (see Figure 4 for example at α=1.40 PP)

In the present study three levels of residual stresses, denoted by the values of α parameter were investigated (Table 3). These values for α parameter were calculated using the engineering yield strength, $\sigma_{Y0.2}$ of studied material. These analytical expressions are based on the assumption that the bending bars are subjected to a pure moment, which is not necessary the case because they are not infinitely slender. This is the reason why the residual stresses were also calculated using finite element method.

Table 3 Applied preload for introducing residual stress in bending beams for 2024 T351 AL-alloy (σ_Y and σ_p indicate respectively the yield stress (MPa) and plastic stress above the yield stress)

Coefficient of preload α $\alpha = \sigma_p / \sigma_Y$	Applied preload (KN)
1.15	57.59
1.25	62.58
1.40	70.09

In numerical calculation of residual stress, finite element (FE) simulations were performed using the FE software Zebulon [21]. A fully implicit integration scheme was used to integrate the material constitutive equations. These FE calculations were performed using quadratic elements with reduced integration (8 nodes/4 Gauss points). The FE mesh used to model the specimens is given in Fig. 3, where only one half of the specimens is shown. FE simulations were carried out using 2D plane strain elements. The plastic behaviour of studied material was described using isotropic hardening based on classical potential constitutive model [22]. The isotropic work-hardening function is expressed as:

$$R_p = R_0 + Q_p\left(1 - e^{-b_p.p}\right) \quad (2)$$

where p is the accumulated plastic strain, R_0, Q_p and b_p are model's coefficients.

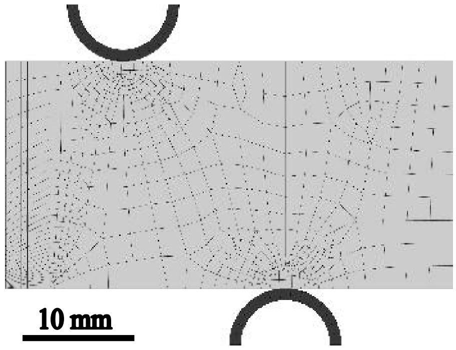

Fig. 3 Half-symmetry finite element model for 2024 Al alloy

In this material the constitutive equation was assumed to be isotropic. This constitutive equation involves three coefficients which are reported in Table 4.

Table 4 Parameters identified for elastic behaviour and work hardening of 2024 T351 Al-alloy

E (GPa)	ν	R_0 (MPa)	Qp	bp
74	0.33	336	270	10.55

The results of FE calculations of Al-alloy are reported in Fig. 4. Distribution of residual stress shown a strong asymmetry between the tensile and compressive residual stresses, which indicates that this specimen geometry is far from being subjected to a pure bending moment. The main explanation for this situation is in the fact that the aluminium alloy beam is not sufficiently slender. The comparison with the perfectly plastic (PP) model shown in Fig. 4 indicates that for a given load (α=1.40) the analytical results lead to values close to those of the FE simulation on the side with compressive residual stresses. It can be concluded that significant differences in the residual stresses distribution have been evidenced between analytical and numerical calculation, in particular in 2024 aluminium alloy.

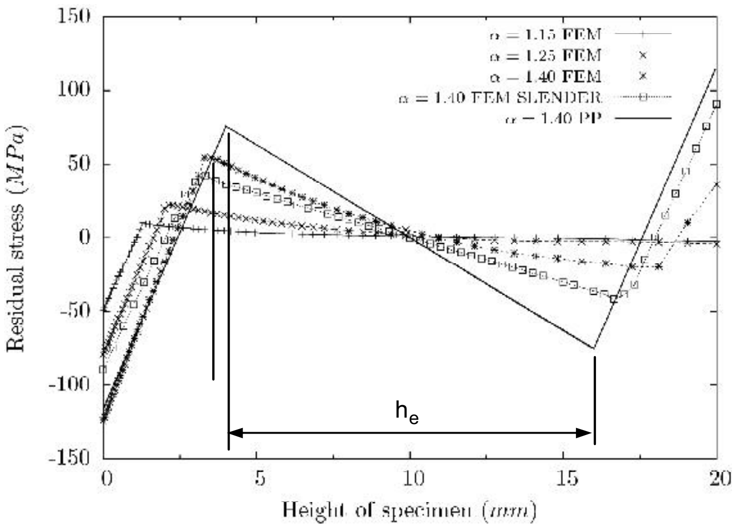

Fig. 4 Distribution of residual stress as a function of the preload coefficient, α, for 2024 T351 Al-alloy

4 EXPERIMENTAL RESULTS AND DISCUSSION

For the three levels of residual stress (Table 3), crack growth was initiated in a compressive residual stress field. Additionally, the crack growth was initiated on the tensile residual stress side at 1.25 of coefficients preload. This tensile stress is neglected, as shown previously (Fig. 4). The fatigue tests were carried out at a stress ratio R=0.1 and under a maximum load P_{max}=26.6 KN.

Figure 5 shows the effect of residual stress levels induced by preload on fatigue crack initiation at crack of 0.2 mm in length. An increasing in fatigue life initiation is shown with increasing of magnitude of compressive residual stress at free surface. The maximum compressive residual stresses were about -125 and MPa for α=1.40; -80 MPa for α=1.25 and -50 MPa for α=1.15. It should be kept in mind that the fatigue life initiation obtained on TRS1.25 specimen can be considered as that of the as-received material (WRS : without residual stress) because of the absence of any significant tensile residual stresses in this specimen, as shown in Fig. 4. Preload level "α" is considered equal to "1" reported on Fig. 5.

Correlation in the evolution of initiation life is given by 2nd order of polynomial function. The fatigue life initiation under maximum compressive residual stress field (α=1.40) is approximately twice times larger than the fatigue life of lower compressive residual stress field (α=1.15) and is third times larger than the fatigue life under tensile residual stress field or WRS. At the same preload level (α=1.25), the fatigue life under compressive residual stress is 2.5 times larger than the fatigue life without residual stress (small tensile stress at notch). Table 5 presents the ratio of the initiation life N_i at 0.2 mm of crack to the total fatigue life N_f. CRS and TRS (WRS) denote respectively the compressive residual stress and the tensile residual stress. The analysis of the obtained results showed that initiation phase varies from 40% to 50% of total life under different levels of compressive residual stress. The fatigue fracture surfaces of 2024 T351 aluminium alloy specimens were examined by scanning electron microscopy (SEM). The fractured surfaces indicate rubbing effect near the notch and in initiation zone as illustrated in Fig. 6.

Table 5 Ratio of initiation to total fatigue life under residual stress field

Coefficient of preload α	Fatigue life initiation "N_i"	Total fatigue life "N_f"	Ratio "N_f/ N_i "
1.15 (CRS)	49500	100800	0.49
1.25 (CRS)	74570	148600	0.50
1.25 (TRS)	29364	64200	0.46
1.40 (CRS)	86600	219250	0.40

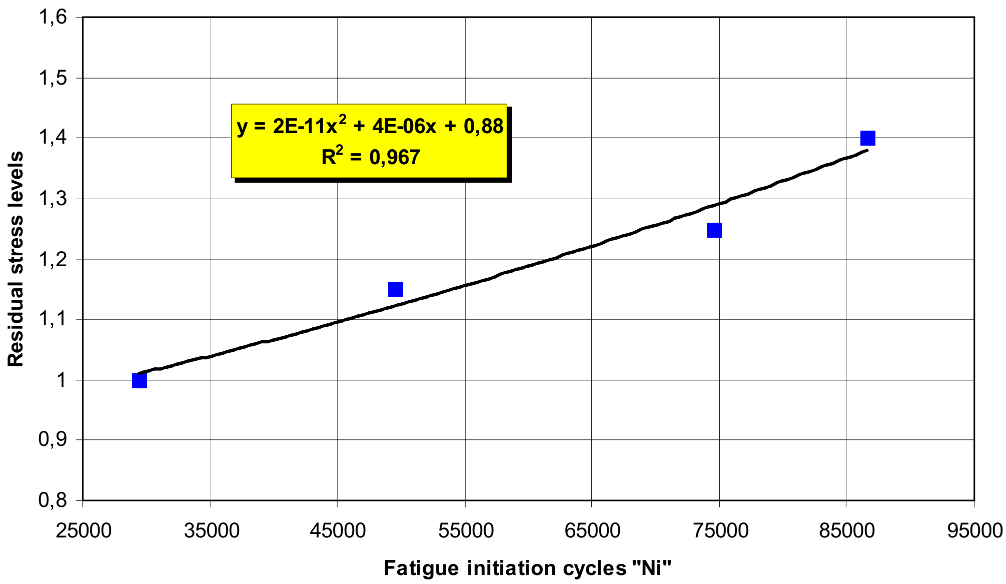

Fig. 5 Evolution of initiation life under compressive residual stress at notch for 2024 T351 Al-alloy

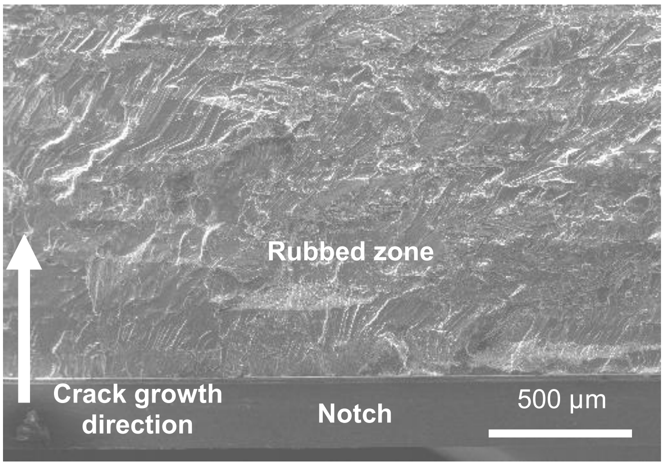

Fig. 6 Fracture surface through compressive residual stress (α=1.15)

5 CONCLUSIONS

The goal of this work is to study the effect of residual stress on fatigue initiation life in 2024 T3541 Al-alloy using four point bend specimens. Residual stress along path of crack was induced experimentally by plastic preload process. Evolution of residual stress fields under different levels of preload was predicted by finite element analysis considering isotropic hardening behaviour to this material. From the experimental results on fatigue initiation of crack, the following conclusions can be drawn:

- Level of compressive residual stress at free surface of specimen depends on applied preload.
- Numerical results has shown that the studied geometry specimen reveal that no significant tensile residual stress was produced in the other free surface (i.e. for α: 1.15 and 1.25)
- Fatigue crack initiation life is influenced by the level of compressive residual stress at notch. Increasing in compressive residual stress at notch increase the fatigue initiation life and consequently the fatigue crack growth life.
- Initiation phase varies from 40% to 50% of the total fatigue life considering different residual stress fields.
- At the same level of plastic preload, Fatigue initiation life through compressive residual stress at notch is about 2.55 times to fatigue initiation life through specimen without residual stress (neglected tensile residual stress).
- Fractured surface in compressive residual stress zone presents rubbing effect.

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