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Effect of Residual Stresses Resulting from Plastic Beam Bending: Technique on Fatigue Crack Initiation

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Abstract

In this paper, effect of residual stresses resulting from plastic beam bending technique on fatigue crack growth initiation was investigated on 2024 T351 aluminium alloy. The residual stresses profiles were determined analytically and numerically using finite element method. In the analytical solution 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. Numerical calculation was applied in this investigation. Fatigue initiation life was affected by compressive residual stress at small notch. Result shows that fatigue life was increased with increasing in levels of compressive residual stress. Additionally, effect of tensile residual stress was neglected due to obtained profile with numerical calculation where tested specimen is not sufficiently slender.

Key words: Fatigue crack initiation, compressive residual stress, tensile residual stress, aluminium alloy

1. Introduction

Today, it is recognized that fatigue life is dived to three stages. Fatigue crack initiation presents the most common stage. The stresses concentrators present the important site in fatigue crack initiation for structural components. Compressive residual stresses are often purposely introduced around these concentrators in order to increase the fatigue resistance. Many processes have been used to introduce compressive residual stress such as shoot-peening [1-4], expanded hole [5-8], tensile pre-straining [9-10]. Given the importance of residual stresses, proper characterization of their values and effects on fatigue crack initiation and fatigue crack growth are vital. Fatigue life prediction of structures with discontinuities has been extensively studied [11-16]. In practice, residual stress in materials and structures will change local stress state, and thus influence the fatigue properties. It is generally accepted that tensile residual stress is detrimental while compressive residual stress is beneficial.

Fatigue crack initiation life has been estimated by many researchers [17, 18] 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 [14, 19]. 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 [20]. The presences of compressive residuals stresses at notch offer beneficial effect on fatigue behaviour and consequently delay the initiation and propagation of fatigue crack [9, 21, 22].

The investigation conducted by Taghizadeh et al. [23] 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 case is important at low level of applied cyclic loading compared to the same plate without expansion. The effect of residuals stresses on fatigue crack initiation of pipeline steel was studied by Mézière et al. [24]. These stresses were generated by 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 at notch lead to increase the fatigue initiation life [25]. In the investigation of Ranganathan et al [26], 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. The study conducted by Almer et al. [27] shown that fatigue crack initiation behaviour was affected strongly by macro residual stress dues to pres-straining. The fraction of fatigue life taken up by initiation, N_i/N_f, was at least 0.44 in the tested specimens, and this ratio increased with decreasing applied stress amplitude.

In the investigation conducted by Wang [28] on fatigue crack initiation of 2024 T3 Al-alloy, the fatigue tests indicate that the local plastic deformation has a considerable effect on the fatigue life of material, depending on the stress level.

The objective of the present study was to investigate the effect of residual stress resulting from plastic beam bending technique on fatigue crack growth initiation of aged hardening aluminium alloy 2024 T351

2. Materials and methods

The fatigue tests were performed on aged hardening aluminium alloy 2024 T351 using servo-hydraulic machine MTS 810. The chemical composition of this material 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 and T direction of studied materials are shown in figure 1. The microstructure of aluminium alloy 2024 T351, respectively in (T-S) and (L-S) directions, is presented on figure 2 where the size of

the pancake shaped grains is significant (620 x 270 x 350 µm^3).

Table 1: Chemical composition of 2024 T351 Al-alloy

Si	Fe	Cu	Mn	Mg	Cr
0.11	0.16	3.97	0.45	1.5	0.05
Zn	**Ti**	**Ni**	**Pb**	**Mg**	**Cr**
0.11	0.018	0.02	.056	1.5	0.05

Table 2: Chemical composition of 2024 T351 Al-alloy

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

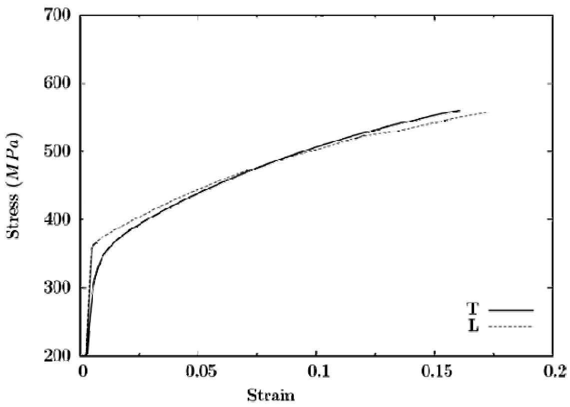


Figure 1. Tensile stress-strain curves along T and L directions for 2024 T351 aluminium alloy

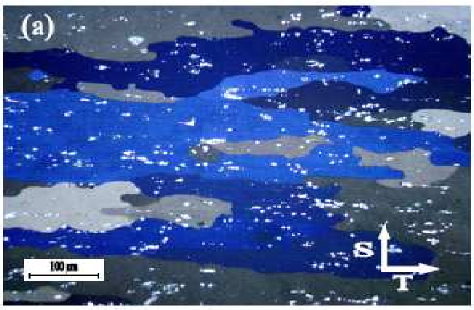


Figure 2. Microstructure of 2024 T 351 Al-alloy,

(a) T-S direction ; (b) L-S direction

Bars with a rectangular section 20x15 *mm*^{2} were preloaded under four points bending as shown in Figure 3. 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. 3. These specimens were finally tested under fatigue conditions with a frequency of 10 Hz.

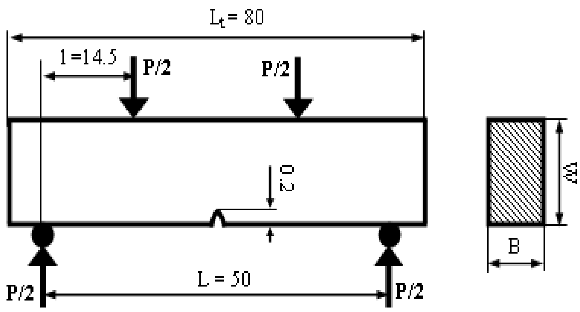
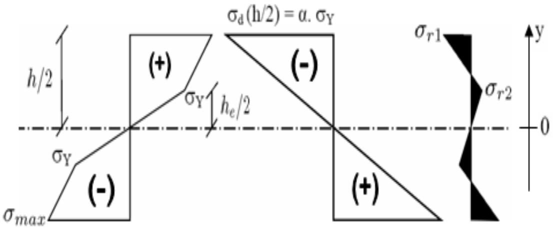


Figure 3. V-notch specimen in four points bending test

3. Residual stresses in four points bend specimens

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 elastic perfectly plastic behaviour of material. Parameters in equation 1 are indicated on figure 4.

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



Plastic loading Elastic unloading Residual stress

Figure 4. Stress profiles under four bending

Table 3. Applied preload for introducing residual stress in bending beams for 2024 T351 Al-alloy

Coefficient of preload α	Applied preload (*KN*)
1.15	57.59
1.25	62.58
1.40	70.09

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. In numerical calculation of residual stress, finite element (FE) simulations were performed using the FE software Zebulon [28]. A fully implicit integration scheme was used to integrate the material constitutive equations. The FE mesh used to model the specimen is given in figure 5 where only one half of the specimen 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 [29]. The isotropic work-hardening function is expressed as:

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

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

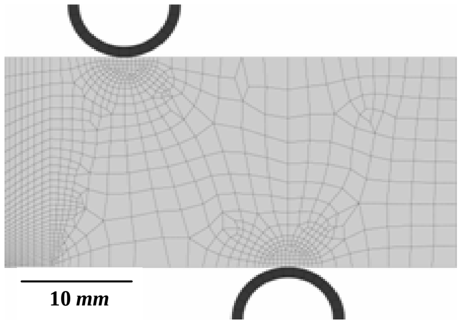


Figure 5. Half-symmetry finite element model

The results of FE calculations of Al-alloy are reported in figure 6. 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 beam is not sufficiently slender. The comparison with the perfectly plastic (PP) model shown in figure 6 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.

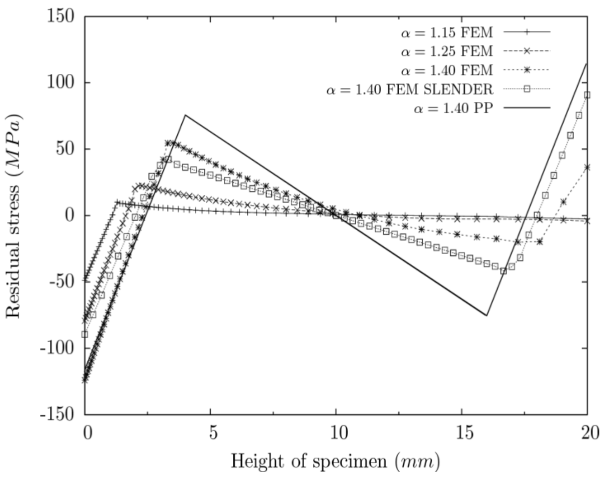


Figure 6. Distribution of residual stress as a function of the preload coefficient α

4. Results and Discussion

Crack growth was initiated in a compressive residual stress field for the three levels of residual stress (Table 3). Additionally, the crack growth was initiated on the tensile residual stress side at 1.25 of coefficients preload. This tensile stress is very small, as shown previously (figure 6). The fatigue tests were carried out at a stress ratio *R*=0.1 and under a maximum load P_{max} = 26.6 *KN*.

Figure 7 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. Best correlation in the evolution of initiation life is given by second 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. At the same preload level (α=1.25), the fatigue life under compressive residual stress is 2.5 times larger than the fatigue life under tensile residual stress (small tensile stress at notch). The Table 4 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 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 when amplitude of applied cyclic load keep constant. It is possible to consider that fatigue crack through face of tensile residual is for as-received material for low coefficient of preload. In applied variable cyclic loading, the ratio of initiation life to failure life was decreased considerably in absence of residual stress (figure 8) and the ratio of initiation life varies from 4% to 7%. Fatigue life increases in reduction of amplitude loading (i.e. increasing in stress ratio from 0.1 to 0.3) for same maximum applied load.

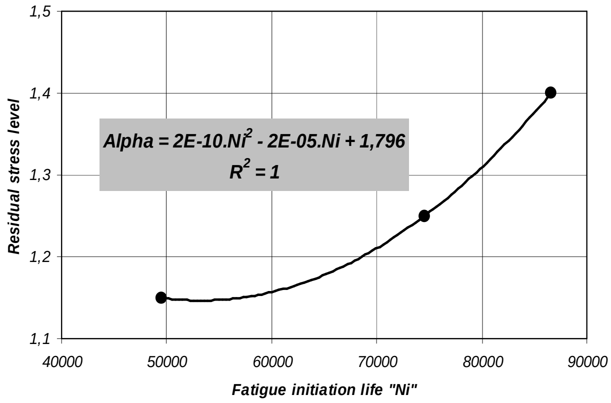


Figure 7. Evolution in initiation life under different compressive residual stress levels at notch

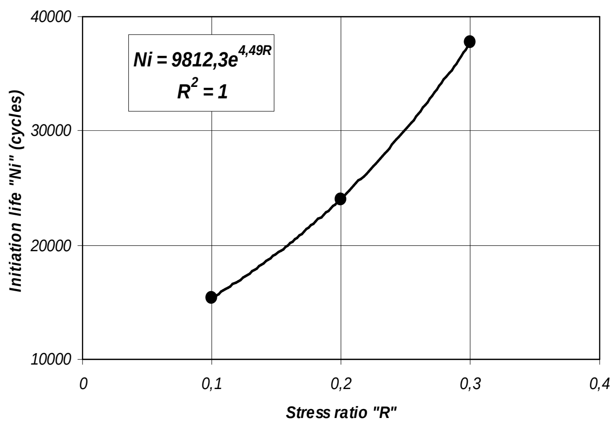


Figure 8. Stress ratio effect on fatigue initiation life

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

α	Fatigue life initiation "N_i"	Total fatigue life "N_f"	Ratio "N_i/N_f"
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

5. Conclusion

The aim of this work is to study the effect of residual stress induced by plastic preload, using four point bend specimens on fatigue initiation life in 2024 T351 aluminium alloy. From the experimental results, we can deduce the following conclusions:

- Initiation life is affected by the level of compressive residual stress. Increasing in compressive residual stress at notch increase the fatigue initiation 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 2.35 times to fatigue initiation life through tensile residual stress (As-received materials).
- Fatigue initiation life was affected by amplitude loading (i.e. stress ratio or mean stress).

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