Comparative Fatigue Study of Age Hardening Al-alloys Under Residual Stress Effects

M. Benachour¹,*, N. Benachour¹,², M. Benguediab³

¹IS2M Laboratory, Mechanical Engineering, University of Tlemcen, Tlemcen, Algeria
²Physics Department, University of Tlemcen, Tlemcen, Algeria
³LMSR Laboratory, Department of Mechanical Engineering, University of Sidi Bel Abbès

*Corresponding author: bmf_12002@yahoo.fr

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Abstract In this study, applied tensile plastic preload in 2024 and 7075 Al-alloys plates with central hole generate residual stress field. Around the central hole compressive residual stress was generated when finite element method was used and Von Mises criterion was applied for plastic preload. The level of compressive residual stress increase in increasing of applied plastic preload. Fatigue life and fatigue crack growth rate (FCGR) depend on the level of plastic preload. Consequently fatigue life increase and FCGR decrease. No high effect of level of applied plastic preload was shown for 7075 Al-alloy on fatigue behavior.

Keywords: Al-alloys, plastic preload, fatigue crack, compressive residual stress

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1. Introduction

Generally, the notch could be a site of stress concentration and crack initiation. Levels of stresses generated around the notch depend on levels of applied loads. The total fatigue life depends on the presence of the residual stresses. These residual stresses present static load and affect the mean fatigue load (cyclic load). The residual stresses present diverse origin and several shapes [1-7]. The stress field is beneficial if the stress is in compressive state [8,9,10,11]. Pre-strain is a process when preload induced plastic deformation, induced intentionally or not and create a residual stress field. The level and nature of these residual stresses depend on the amplitude and direction of applied load. In the investigation of Kamel et al. [12] effects of tensile and compressive residual stress in fracture mechanics specimens by the application of a mechanical pre-load were studied using ‘C’ shape specimen. Finite element analysis is performed to simulate the pre-loading and the subsequent fracture loading of the cracked specimen. Recently, effect of residual stress on the fatigue behavior of 2024 Al-alloy was studied experimentally and numerically using FEM by Al-Khazraji et al. [13]. In other work, effect of residual stress induced by plastic predeformation was investigated by Jones [10] on 2024 T351 Al-alloy using four bent specimen. It was found that the fatigue life was influenced by the plastic preload. An increasing in fatigue life was shown by increasing of the level of plastic preload. The fatigue crack growth rates at low stress intensity factor were decreased by the presence of compressive residual stress. In other study conducted by Jones and Dunn [11], fatigue crack growth from a hole with residual stress introduced by pre-yielded hole was predicted using linear elastic fracture mechanics (LEFM) and the principle of superposition. Fatigue crack growth rates through a residual stress field are usually predicted using LEFM and the principle of superposition [14,15]. In the principle of superposition, stress intensity factors are determined as the sum of stress intensity factors from applied and residual stresses.

The main objective of this paper is to predict fatigue crack growth from hole for pre-yielded tensile sheet with 4mm thickness using finite element method in aged hardening Al-alloys using superposition-based LEFM. The studied materials are from of family of high-strength aluminium alloys widely used in aerospace applications due to a very favourable strength-to-weight ratio. Strengthened aluminium alloys, such as those of the 2000 xxx and 7xxx series, exhibit, despite high tensile strength values (greater than 450 MPa). Additionally level of applied preload was investigated on level of residual stress distribution and fatigue crack growth of high strength Al-alloys 2024 and 7075.

2. Modeeling of Residual Stress by Plastic Preload

2.1. Finite Element Modeling

The FE model used in simulation of plastic preload (PP) was a plate assumed to be made from Al-alloys 7075 T6 and 2024 T351. The mechanical properties of both
materials are shown in Table 1. In order to analyze the respect of elasto-plastic behavior, a true stress–true strain curves as shown in Figure 1 and used as an input property of FE analysis. As shown in Figure 2, the dimensions of the plate containing Ø6 diameter hole and thickness (t) = 4 mm.

Table 1. Mechanical properties of Al-alloys

| Al-alloys     | E (GPa) | σ_Y (MPa) | UTS (MPa) | ν  |
|---------------|---------|-----------|-----------|----|
| 7075 T6 [16]  | 70.71   | 520       | 570       | 0.33 |
| 2024 T351 [17]| 74.08   | 363       | 477       |     |

Figure 1. True stress–strain curves of both Al-alloys

To generate a residual stress field, the applied load must exceed the elastic limit is to say that the force generated during the loading phase of plastic deformation where the isotropic plasticity model of Von Mises was used to account of the plasticity of material. Levels of preload characterized by ratio \( \sigma_p/\sigma_Y \) for both materials are presented in Table 2.

Table 2. Levels ratio of plastic preload

| Al-alloys     | \( \sigma_p/\sigma_Y \) |
|---------------|------------------------|
| 7075 T6       | 1.034                  |
| 2024 T351     | 1.047 1.077 1.102 1.212 1.350 |

2.2. Residual Stress Fields

Under applied loading levels, respective residual stress fields were generated. Figure 4 and Figure 5 shown respectively distribution of residual stress around hole \( \sigma_{yy} \) for 7075 T6 and 2024 T351 Al-alloys. X-axis presents privileged path for propagating of crack. Interesting distributions of these residual stresses are along X-axis. Distributions of residual stresses \( \sigma_{yy} \) along X-axis for 7075 T6 and 2024 T351 Al-alloys at specified preload levels are shown respectively in Figure 6 and Figure 7.
Figure 4. Stress contour for 7075 T6 at $\sigma_p/\sigma_Y$: (a) 1.034; (b) 1.077

Figure 5. Stress contour for 2024 T351 at $\sigma_p/\sigma_Y$: (a) 1.047; (b) 1.102; (c) 1.212 (d) 1.350

Figure 6. Residual stress along X-axis for 7075 T6

Figure 7. Residual stress along X-axis for 2024 T351
2.3. Fatigue Crack Growth Model

The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters and is given by Eq. 1.

\[
\Delta K = \sigma \sqrt{\pi a} \beta (a/r)
\]  

(1)

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

\[
\beta (a/r) = 1 - 0.15\ell + 3.46\ell^2 - 4.47\ell^3 + 3.52\ell^4
\]  

(2)

where \( \ell = 1/(1 + (a/r)) \).

In this study Forman/Mettu equation [18] was applied and then expressed bellow (Eq. 3):

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

(3)

Furthers details of all parameters were detailed in AFGROW user manuals code [19]. For constant amplitude loading, the function \( f \) was determined by Newman [20]. Crack growth parameters of Forman/Mettu equation (Nasgro equation) for both materials are presented in Table 3.

| Alloys       | C         | n   | Kc | p | q |
|--------------|-----------|-----|----|---|---|
| 7075 T6      | 4.021x10^-10 | 2.95 | 59.34 | 0.5 | 1 |
| 2024 T351    | 1.707x10^-10 | 3.0  | 74.72 | 0.5 | 1 |

3. Residual Stress Effect on FCGRs

Figure 8 shows the evolution of FCGRs in function stress intensity factor for 7075 T6 Al-alloy for plastic preload \( \sigma_p/\sigma_Y=1.034 \). At a stress ratio \( R \) equal to 0.25, the FCGRs increase from \( 4.75x10^{-7} \) m/cycle to \( 4.23x10^{-9} \) m/cycle with introducing compressive residuals stresses at the notch (around of the hole). The effect of stress ratio “R” on the FCGRs is most striking from \( \Delta K=18 \) MPa(m)^1/2 where the residual stresses were reduced (see distribution of residual stresses in Figure 6).

The evolution of effective stress ratio accounting of residual stress field “Reff” along the crack path is shown in Figure 9 for \( R=0.1 \) and \( R=0.25 \). This change in specified level of plastic preload shows that the residual stress are dominant with respect to stress ratio “R” at the beginning of the cracking. From the crack length \( a=2 \) mm, the actual stress ratio is approximately 4. At the indicated position \( a=2 \) mm residual stresses are in tensile state with maximum value of 100 MPa. Effectives stress ratios are stabilized at 0.3 and 0.11 respectively for \( R \) equal to 0.25 and 0.1. Figure 8 shows also that the fatigue crack growth, for same stress ratio \( R=0.25 \), an increasing in FCGR in absence of residual stress (SCR) comparatively to the FCGR with the presence of compressive residual stress at notch at same stress intensity factor rage. The difference in FCGR is in order to \( 2.0x10^{-7} \) m/cycle.

The variation of the fatigue crack growth rates (FCGR) as a function of the amplitude of the stress intensity factor \( \Delta K \) through residual stresses fields obtained for different preload levels for 2024 T351 Al-alloy is shown in Figure 10. The result shows that FCGR depends on the magnitude of the compressive residual stresses developed at edge of hole. We note that the FCGR increases while decreasing the plastic preload level. At preloading level \( \sigma_p/\sigma_Y=1.350 \), FCGR is about \( 1.6x10^{-9} \) m/cycle to crack initiation; against by a low level i.e at \( \sigma_p/\sigma_Y=1.047 \), the FCGR is \( 1.75x10^{-7} \) m/cycle. This reduction is influenced by the decrease in residual stress intensity factor \( K_r \) whose variation is shown on Figure 11; Factor \( K_r \) past from \( -13.83 \) MPa(m)^1/2 to \( -4.65 \) MPa(m)^1/2.
range (20 MPa(m)^{1/2}), fatigue crack growth rates are for both materials and for same stress intensity factor (Figure 12). The presence of compressive residuals fatigue crack growth is also affected by plastic preload (m/cycle). The evolution of effective stress ratio during stresses decrease the effective stress ratio consequently comparatively to 2024 T351.

Figure 11. Effect of preload levels on residual stress intensity factor Kr for 2024 T351 Al-alloy

In absence of residual stress, FCGR is about 3.83×10^{-7} m/cycle. The evolution of effective stress ratio during fatigue crack growth is also affected by plastic preload (Figure 12). The presence of compressive residuals stresses decrease the effective stress ratio consequently FCGRs is also decreased. Approximately at same preload for both materials and for same stress intensity factor range (20 MPa(m)^{1/2}), fatigue crack growth rates are respectively 2.0×10^{-6} m/cycle and 3.0×10^{-6} m/cycle for 7075 T6 and 2024 T351. The minimum of FCGR for 2024 T351 is around to 2.0×10^{-7} m/cycle but for 7075 T6 FCGR is 3.0×10^{-8} m/cycle. Comparative results show that 7075 Al-alloy present a high fatigue crack growth resistance comparatively to 2024 T351.

Figure 12. Plastic preload effect on stress ratio Reff for 2024 T351 Al-alloy at R = 0.25

4. Conclusion

Effect of compressive residual stress on fatigue crack growth rate (FCGR) behavior was investigated on two Al-alloys: 7075 T6 and 2024 T351. The residuals stresses induced by plastic preload in tension were calculated numerically by finite element method (FEM). FEM computations were performed using a constitutive equation including isotropic hardening for both materials. Forman/Mettu equation was used to investigate the FCG through residuals stresses field when effective stress ratio was applied for including effects of residuals stresses. The main results of this study are:

- A decreasing in FCGR was shown in the presence of compressive residuals stresses at notch (hole).
- FCGR is affected by increasing in the level of plastic preload and depend on residual stress intensity factor which was determined numerically.
- Aluminum alloy 7075 T6 present high fatigue crack growth rate comparatively to 2024 T351 Al-alloy.

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