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Effect of compressive residual stress generated by plastic preload on fatigue initiation of 6061 Al-alloy

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Abstract

In this paper the effect of compressive residuals stresses generated by plastic preload on fatigue crack initiation and performed on 6061 Al-alloy finite plate with central hole was studied. Finite element analysis (FEA) was used to generate residual stress field. The effect of residual stress on the fatigue crack initiation was investigated for cyclic tension. Based on elasto-plastic analysis at notch, fatigue initiation lives were predicted using fatigue code. Results shown that the fatigue initiation lives were affected by the presence of compressive residual stress at notch and total residual field. Intuitionally, stress ratio effect in presence of residual stress was highlight.

Keywords: fatigue crack initiation, compressive residual stress, stress ratio, 6061 Al-alloy ;

1. Introduction

Failure due to fatigue accounts for nearly 90% of all mechanical failure (Dieter, 1986). Aluminum in its solid forms has good workability and high strength to weight ratio as an alloy. 6xxx series aluminum alloys were produced by mixing magnesium (Mg) and silicon (Si) to pure aluminum (Van Horn, 1967). Typical uses of the 6xxx series aluminum alloys are found in automotive, aerospace, marine and structural applications (hydraulic pistons, electrical fittings and connectors…etc, (Archer and Jefferies, 1967).

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Nomenclature

σ_a	applied stress
σ	resulting local stress values corrected for the notch effect
ε	resulting local strain values corrected for the notch effect
K_t	stress concentration factor
K_f	fatigue notch factor
$\Delta\varepsilon/2$	total strain amplitude
$2N_f$	failure life,
σ'_f	fatigue strength coefficient
b	fatigue strength exponent
ε'_f	fatigue ductility,
c	fatigue ductility exponent

Discontinuities and notches in mechanical components and structures are a site of stress concentration resulting of external load. Notches could be sites of crack initiation. Stress state (compressive or tensile) at theses notch depend on several parameters (machining process, deformation, material structures, and geometrical parameters of notch…etc; this state affect fatigue behavior. It will be know that fatigue behavior is divided in three stages: fatigue crack initiation, stable crack propagation and unstable crack propagation. Fatigue initiation life and fatigue crack growth life of materials and structures depends on several parameters. In initiation stage, fatigue life is linked strongly to stress concentration stress factor, loading parameters…etc. However, the stresses resulting from applied service loading are not the only stresses of significance for fatigue. Many components also contain residual stresses that were established prior to placing the component into service and which remain in place during the service life. Residual stresses are static load and affect the mean or maximum value of the load in each fatigue cycle. The residual stresses present diverse origin and several shapes (Pavier et al. 1999, John et al. 2003, Wang et al. 1999, Benedetti et al. 2004). The stress field is beneficial if the stress is in compressive state (Wagner et al. 1988). Mechanical pre-deformation is a process when preload induced plastic deformation, induced intentionally or not and create a residual stress field.

In the study conducted by Lee et al. (2010), the fatigue crack initiation and fatigue lives of the treated specimens of 6061 T6 Al-alloy with the UNSM technology was delayed and extended by the UNSM effects that are the increase of surface hardness, and the reduction of the surface roughness. The effect of prestrain on fatigue crack growth characteristic of age-hardened Al-alloy 6061-T6 was investigated by Ikematsu et al. (2009) using prestrained specimens. The experimental results showed the fatigue crack growth rates decelerated a little due to prestrain. Effect of plastic pre-deformation by bending to create deep residual compressive stresses on the fatigue strength of steel specimens and compressor blades was studied by Ezhov and Sidyachenko (1994). It was found that plastic pre-deformation increases the fatigue strength by about 20%. Fatigue crack initiation in Al-alloy was affect by the presence of compressive residual stress generated with Laser Shock Processing worked hole (Ren et al. 2013).

The compressive residual stresses generated by cold expansion on 6005 Al-alloy are the factor which has an influence on the initiation of the fatigue crack (lifetime) (Amrouche et al. 2003). The zone of compressive residual stresses (ZCRS) and the zone of plastic deformation (ZPD) are the parameters that seem to have an important influence on the initiation and propagation of the fatigue crack. Empirical investigation on fatigue crack initiation and propagation in 2024 T351 aluminium alloy using constant amplitude loading was conducted by Benachour et al. (2011). In initiation stage, local strain approach at the notch was used. In absence of residual stress an increase in stress ratio have increased the fatigue initiation life. In the work conducted by Meggiolaro and Castro (2004), an extensive statistical evaluation of the existing Coffin–Manson parameter estimates the fatigue crack initiation based on monotonic tensile and uniaxial fatigue properties of different metals (steel, aluminum alloys, and titanium alloys). In the investigation, fatigue crack initiation life around hole in plate was studied under residual stress effects and stress ratio. Residual stress field was generated by plastic preload using finite element method.

2. Numerical modeling of residual stress

The FE model used in simulation of plastic preload (PP) was a plate assumed to be made from Al-alloy 6061 T6. The mechanical properties of this material are shown in Table 1. In order to analyze the respect of elasto-plastic behavior, a true stress–true strain curve as shown in figure 1 was used as an input property of FE analysis. As shown in figure. 2, the dimensions of the plate containing Ø 6 diameter holes and thickness (t) = 4 mm.

Level of applied preload characterized by non dimensional ratio σ_p/σ_Y is varied, where σ_p is applied preload in tension and σ_Y is yield stress. The finite element mesh is shown in figure 3. Only four quart of the entire plate has been modelled considering of the symmetry. More finite elements than those in other regions are put closer to the boundary of holes. Since we are interested of the residual stress variation according to the X axis from hole edge to free surface, two-dimensional analysis has been carried out with uniform distributed plastic preload σ_p. The program used in the FE analysis was ANSYS, Ver. 11. The mesh element type was "PLANE183".

Table 1. Mechanical properties for 6061 T6

E (GPa)	σy (MPa)	UTS (MPa)	ν
69.04	252	360	0.30

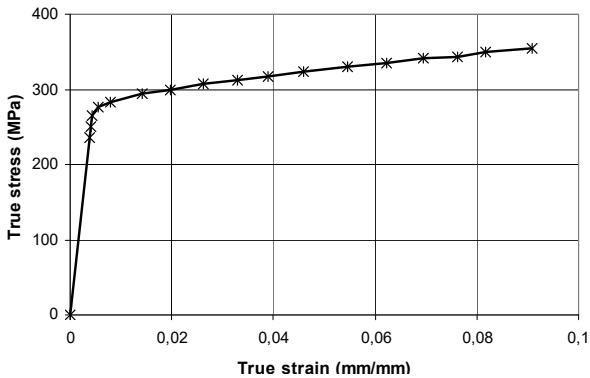

Fig. 1. Trues stress–strain curve for 6061 T6 of Al-alloy

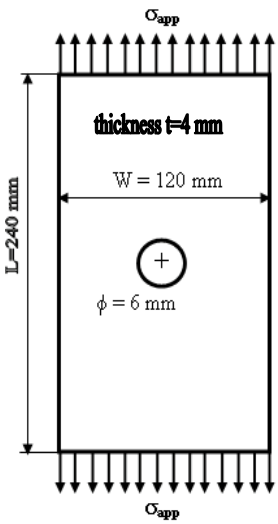

Fig. 2. Geometrical model analysis

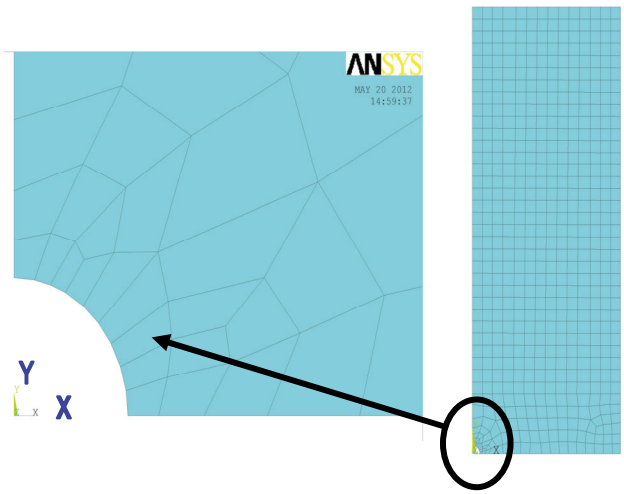

Fig. 3. Quarter of FE mesh with central hole

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. The applied loading/ unloading sequences to generate residual stress by preload is shown in figure 4. Two levels of preload characterized by ratio σ_p/σ_y are respectively 1.23 and 1.39.

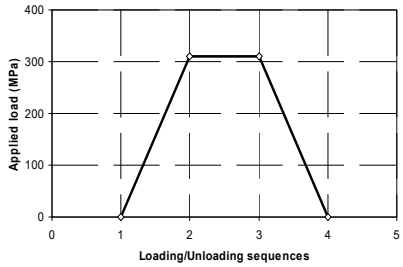

Fig. 4. Loading sequences to generate residual stress (i.e. $\sigma p/\sigma_Y$= 1.23)

Under applied loading levels, respective residual stress fields were generated. Figure 5 shown residual stress distribution around hole σ_{yy} for 6061 T6 Al-alloy. Interesting distributions of these residual stresses are along X-axis. X-axis is a planned path for crack propagation in mode I. Distributions of residual stresses σ_{yy} along X-axis for 6061 T6 Al-alloy at specified preload levels are shown in figure 6. No high difference of residual stress at edge of hole was shown. The residual stress in tension is maximal at 2 mm deep from the edge of the hole still; it is of the order of 30 MPa.

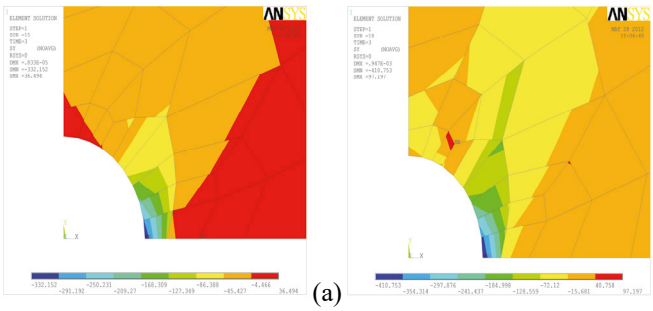

Figure 5. Stress contour under different plastic preload levels for 6061 T6 σp/σy: (a) 1.23 ; (b) 1.39

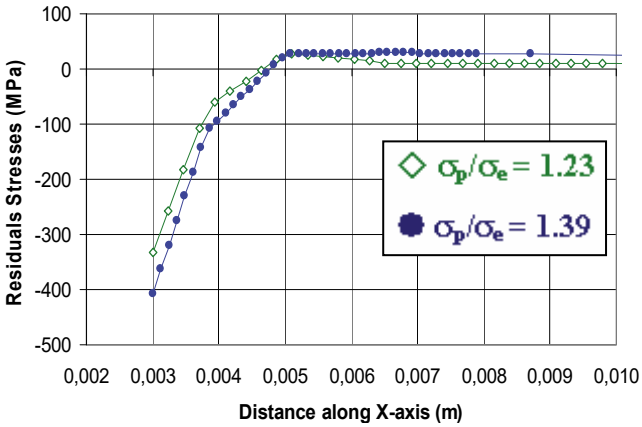

Fig. 6. Residual stress field along X-axis for 6061Al-alloy

3. Local strain approach for crack initiation

Fatigue resistance of metals can be characterized by a strain-life curve. Tuegel (1996) initially provided the strain-life based fatigue crack initiation module. In AFGROW code (Harter, 2006), 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 (Neuber, 1960) expressed in following form:

$$\frac{\left(K_f.\Delta\sigma_a\right)^2}{4E}=\frac{\Delta\sigma.\Delta\varepsilon}{2} \tag{1}$$

where "σ" and "ε" are the resulting local stress and strain values corrected for the notch effect.

The fatigue notch factor, (K_f), is essentially the K_t value corrected to account for the notch sensitivity for the given material (Peterson, 1974). It is determined as follows:

$$K_f=1.0+\left(\frac{K_f-1.0}{1.0+\left(\alpha/r\right)}\right) \tag{2}$$

where "α" is an empirically determined material constant (Hall et al. 1973) and r is the notch root radius

In Glinka's approach the local strains and stresses should represent energy equivalence as compared the remote loading conditions, leading to the following equation where K' and n' correspond to the material's cyclic hardening law:

$$\frac{\left(K_f.\Delta\sigma_a\right)^2}{2E}=\frac{\Delta\sigma^2}{4E}+\frac{\Delta\sigma}{n'+1}\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{3}$$

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).

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\sigma}{2E}\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{4}$$

The relationship between total strain amplitude, Δε/2 and life to failure, $2N_f$, can be expressed in the form (Coffin, 1954):

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

The cyclic materials parameters for the studied Al-alloy are presented in Table 2.

Table 2. Low cycle fatigue parameters for aluminum alloy 6061 T6 (Zakaria et al., 2014)

σ'_f	ε'_f	B	c	n'	K'
371	0.14	-0.122	-0.509	0.239	595

4. Results and discussion

Fatigue crack initiation of flat plate in L-T orientation with central hole, subjected to constant amplitude loading with two levels of residuals stresses fields and R-ratio is investigated. The maximum loading is σmax = 80 MPa. Evolution of fatigue crack initiation life with and without compressive residuals stresses at notch for different stress ratio are presented on figures 7, 8 and 9. An increasing in fatigue initiation life is shown in increasing of stress ratio from 0.01 to 0.5. This increasing is due to the reduction of amplitude loading Δσ, from 79.2 MPa to 20 MPa. Evolution of fatigue initiation under stress ration is characterized by equation of 4th polynomial degree.

Also, the presence of compressive residuals stresses at notch has affected strongly the fatigue initiation life (Ni). For example at R=0.2, Ni=25655 cycles without residuals stresses, but for the same stress ratio and the presence of compressive residuals stresses (level 1), Ni=142337 cycles. The ratio of two fatigue initiation life is about 5.55 times. The increase in the levels of plastic preload (i.e. compressive residuals stresses at notch) induces an improvement in lifetime similarly to cold expansion effect (Amrouche et al., 2003).

Figure 10 represents the effect of plastic preload levels (pre-deformation) on the fatigue initiation life. From level 1 to level 2 and at low stress ratio(R=0.01 and 0.05), no residual stress effect was significance in variation of fatigue initiation life. The ratio of fatigue initiation life is about equal 1, but for others stress ratio, this ratio varies from 1.4 to 2.0. The initiation life is greater than the propagation life for the same level and stress ratio (Benachour et al., 2016). At stress ratio R=0.25, the initiation life is 182691 cycles and in propagation stage the fatigue life is about 13400 cycles with the presence of residuals stresses. In this case, the fatigue life ratio in fatigue initiation life represents 13.6 times the fatigue life in propagation phase. This shown the beneficial effect of compressive residual stress at notch.

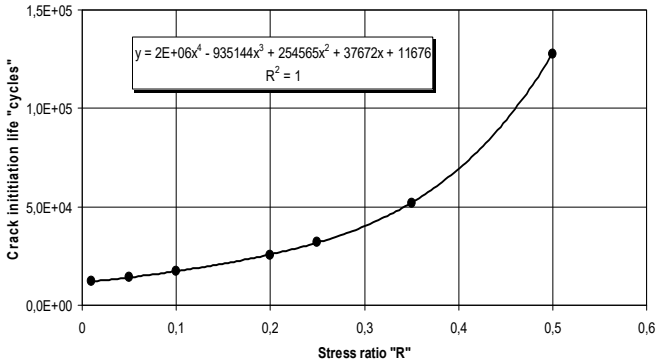

Fig. 7 Effect of Stress Ratio on Fatigue Crack Initiation life without residual stress

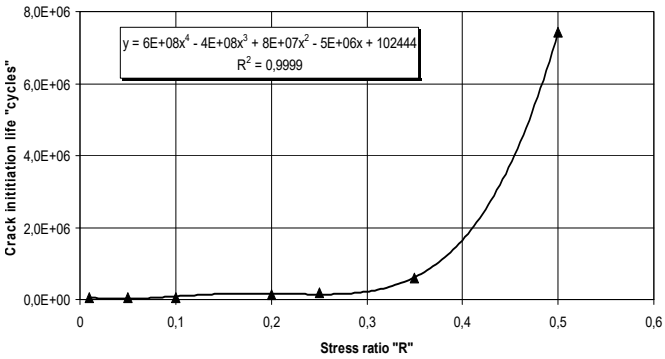

Fig. 8 Effect of Stress Ratio on Fatigue Crack Initiation life at level σ_p/σ_e=1.29

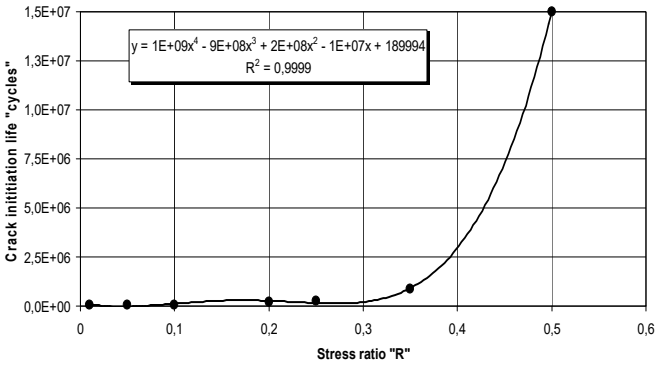

Fig. 9 Effect of Stress Ratio on Fatigue Crack Initiation life at level σ_p/σ_e=1.39

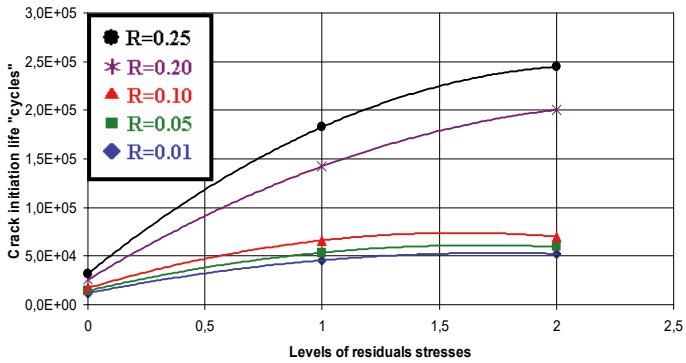

Fig. 10 Effect of residuals stresses levels for different stress ratio on fatigue crack initiation life

5. Conclusion

This investigation was conducted to predict fatigue initiation life of flat plate in 6061 T6 Al-alloy under compressive residuals stress at notch (central hole in finite plate). Residual stress fields were generated by mechanical plastic preload. Levels of compressive residuals stresses at notch depend on the ratio σ_p/σ_Y (applied plastic load to elastic strength). Analysis of fatigue crack initiation results showed that:

* In the presence of compressive residual stresses at the hole, the fatigue crack initiation life was increased.
* Fatigue initiation life depends on stress ratio. At the same residuals stress field and low stress ratio, the difference in initiation life is not too great comparatively to the case in high stress ratio.

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