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Prediction of Fatigue Crack Growth of Aged Hardening Al-alloys Under Variable Amplitude Loading

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Abstract. In this investigation, variable amplitude loading effect was studied on aged hardening Al-alloys in series 2000 and 7000. Generalised Willenborg model was used in order to show loading interaction effects (overload effects). Variable amplitude loading under different form of spectrum has affected highly the fatigue life and fatigue crack growth rates. Fatigue lives were increased and fatigue crack growth rates (FCGRs) were decreased in increasing of overload ratio in single overload case. In application of overload band, the fatigue lives and FCGRs were affected by band overload and R-ratio of them when level in FCGRs was increased.

Introduction

Fatigue crack growth behavior of metals depend upon a number of variables namely the mechanical properties, specimen geometry, environment, applied cyclic loading, stresses and strains acting at the crack tip. Most of fatigue research has been concentrated on examining the phenomena under constant amplitude fatigue cycling for Al-alloys [1-4]. During navigation, aeronautical structures are subjected mostly to complex cyclic loading. It is well known that load fluctuations lead to fatigue crack propagation. Research on variable applied loading (VAL), determined that appreciable crack growth retardation can occur following tensile overloading [5-7]. A numbers of models have been developed to account for crack growth retardation due to tensile overloads [8-11] namely Willenborg, Wheeler model, Gallagher modified Willenborg model [12]. Crack growth retardation due to tensile overloads has been explained by several theories. The most commonly discussed theories are fatigue crack closure [13]; residual stresses [8-9], crack tip blunting and sharpening [14] and cyclic strain hardening and softening [15]. Really, all mechanisms are not dissociable. Overload retardation has been widely investigated in a range of engineering materials [4, 13, 16, 17] and many research's were oriented to the study of several form of variable amplitude and associated parameter namely single or block overloading on fatigue behavior of Al-alloys. In fatigue crack growth (FCG) investigation conducted by Bathias and Vancon [18] on 2024 and 2618 Al-alloy, fatigue crack growth rate (FCGR) was retarded after application of one or several overload. In this study, it was demonstrated that the process of fatigue crack retardation by application of overloads results from the plastic deformation at the crack tip and the nature of the test specimen surface. In study conducted by Corbly and Packman [19], fatigue crack retardation due to variable amplitude loading spectra was studied in 7075 T6511 Al-alloy. It was shown that the degree of retardation depend strongly on the relative amplitudes of the peak stress intensity, the number of stress applications N_t at the peak stress intensity, the magnitude of the constant amplitude crack growth rate at the lower stress intensity range and the number of fatigue cycles N_l at the lower stress intensity level after the last peak stress is applied. In the investigation of Vardar [20], overload ratios between 1.3 and 2.4 were considered in a 7075-T6 alloy under plane strain conditions. A linear correlation was found between the number of retardation overload cycles and the overload ratio. Experimental investigation conducted by Kermanidis and Pantelakis [21] under single overload on Al-alloy notched specimens shown in first way that delay in fatigue crack growth is due to the ductility of material. At fixed stress ratio, the effect of overload ratio on FCG of 2024 T3 Al-alloy was studied by Verma and Paney [22]. Results have shown that the delay in FCG increases with the increase in overload ratio. The study conducted by Kumar and Garg [23] on 6061 T6 Al-alloy, shown an increasing of life in applied periodic band of overload test compared to constant amplitude loading life. Loading sequences effects and theirs interactions on fatigue behavior of notched specimens was investigated by Potter [24]. This investigation confirms that residuals stresses at notch vary with cyclic loading after application of overload. The numbers of failures cycles increase in increasing of the overload period. In recent investigation of Bao and Zhang [25] on Al-alloy 2324 T39, subjected to truncated load spectra, the fatigue life was predicted using Nasgro equation and generalized Willenborg model. The aim of the present investigation is to simulate the effect of single overload cycle and band overload on the fatigue behavior of through crack at notch semi circular of aged hardening Al-alloys 2024 T351 and 7050-T74 using Generalized Willenborg model [9]. Single overload effect is characterized by overload ratio. Prediction of variable amplitude loading effects on FCG is based on experimental fatigue crack growth rates results in constant amplitude loading.

Fatigue crack growth behavior

Materials & specimen geometry. Materials used in this study are aged hardening Al-alloys extracts from AFGROW database namely 2024 T351, 2219 T87, 7075 T7351 and 7178 T7651 obtained from rolled plates in L-T orientation. The basic mechanical properties for theses materials are presented in Table 1. Simulation of fatigue crack growth in mode I used finite plate (Fig. 1) with through crack at semi circular notch at edge with initial crack a_0=0.5 mm. The stress intensity factor of the studied specimen implemented in Afgrow code depends on several parameters and is written as follows (Eq. 1):

$$\Delta K = \sigma\sqrt{\pi a}\,.\beta\ \left(\frac{a}{w},\frac{a}{r},\frac{r}{w}\right) \tag{1}$$

where β, represent the geometry correction factor proposed by Newman [26], is expressed as:

$$\beta = \beta_1.\varphi.\beta_w \tag{2}$$

for β_1 for $r/W = 1/16 \text{ et } (a+r)/W < 0.8$

The function β_1 is given by:

$$\beta_1 = 1 + 0.358\lambda + 1.425\lambda^2 - 1.578\lambda^3 + 2.156\lambda^4 \tag{3}$$

with $\lambda = 1/(1+a/r)$ and φ parameter effect between crack length and width of specimen [26].

Table 1. Mechanical properties of aged hardening Al-alloys (Afgrow database)

Materials	σ_e (MPa)	E (GPa)	K_C $\mathrm{MPa}\sqrt{\mathrm{m}}$	K_{IC} $\mathrm{MPa}\sqrt{\mathrm{m}}$
2024 T351	372.31	73.08	74.72	37.36
2219 T87	393.0	73.08	65.93	32.97
7075 T7351	427.47	71.70	63.73	31.86
7178 T7651	496.42	71.70	61.54	30.77

where σ_e, E, K_C and K_{IC} represent respectively the yield strength, young's modulus, plane stress fracture toughness and the plane strain fracture toughness.

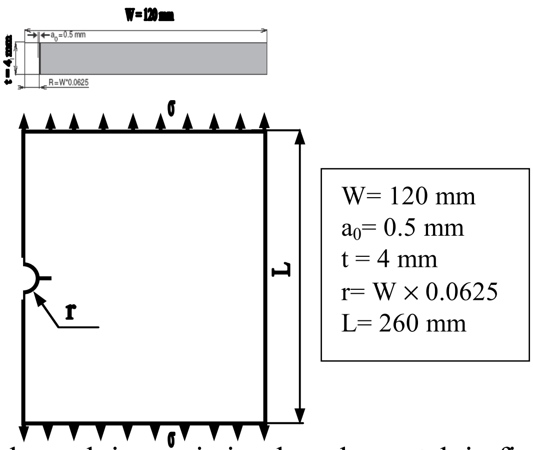

Fig. 1. Through crack in semi circular edge notch in finite plate

Fatigue crack growth & retardation model. In order to take the different stages of propagation into account Nasgro equation is used in this study (see equation 3). The different parameters of this equation are defined in the Afgrow user's manual [27]. The main parameters of Nasgro equation for the studied material are presented in Table 2.

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^{n} \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}}{\left(1-\frac{K_{max}}{K_{crit}}\right)^{q}} \tag{4}$$

The Generalized Willenborg model [9] is one of the most common load interaction models used in crack growth life prediction programs. The model use an "effective" stress intensity factor based on the size of the yield zone in front of the crack tip. The formulation of the Willenborg retardation model used in Afgrow code is given below (Eq. 5):

Table 2. Parameters of crack growth model

Al-alloys	ΔK_{tho} MPa$\sqrt{m}$	n	P	q	C
2024 T351	2.857	3.353	0.5	1	1.707×10^{-10}
2219 T87	3.187	2.487	0.5	1	1.149×10^{-9}
7075 T7351	3.297	2.529	0.5	1	6.964×10^{-10}
7178 T7651	3.297	1.800	0.5	1	3.001×10^{-9}

$$\begin{cases} K_{max(eff)} = K_{max} - K_r \\ K_{min(eff)} = K_{min} - K_r \\ R_{eff} = K_{min(eff)} / K_{max(eff)} \end{cases} \tag{5}$$

K_r is the residual stress intensity factor due to overload, it is given by (equation 5) and R_{eff} is the effective stress ratio.

$$K_r = \phi\left(K_{max(ol)}\sqrt{1-\frac{(x-x(ol))}{R_y(ol)}} - K_{max}\right) \tag{6}$$

factor ϕ is expressed by equation 7 and define the level of residual stress induced by application of overload.

$$\phi = \left(1-\Delta K_{th}/K_{max}\right)/\left(SOLR-1\right) \tag{7}$$

and the yield zone created by overload $R_{y(ol)}$ is expressed by the following equation:

$$R_y(ol) = \left(\frac{K_{max}(ol)}{\sigma_{0.2}}\right)^2 \cdot \left(\frac{1}{\alpha.\pi}\right) \tag{8}$$

Results & discussion

Plate specimens in L-T orientation for Al-Alloys (Table 1) were subjected to variable amplitude loading (VAL) associated with single overload and band overload effect. Fig. 2 shown different sequences cyclic loading applied in this investigation when “q” presents the overload band. The A K_{max} failure criterion is adopted for the limit of crack growth.

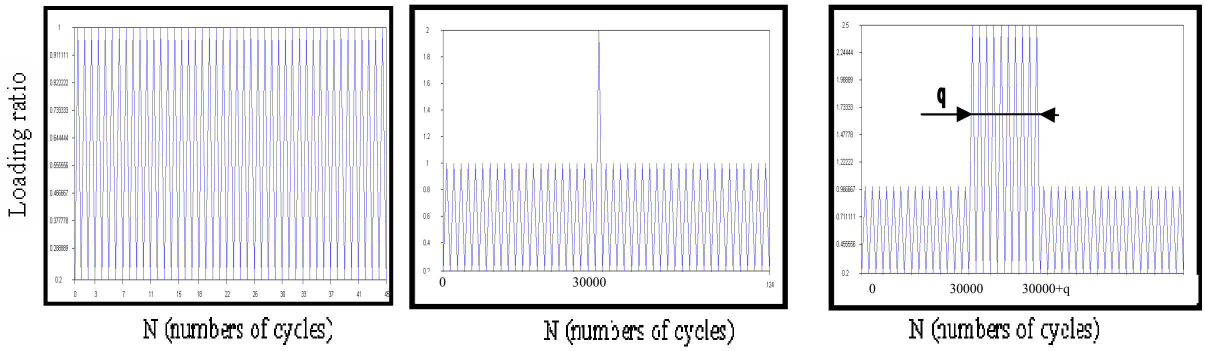

Fig. 2. Cyclic loading (a) constant amplitude loading, (b) single overload (c) band overload

Variable amplitude loading in this study is characterized by overload ratio “ORL= $\sigma_{max\text{-}overload}/\sigma_{max\text{-}CA}$” which allows to create an instantaneous yield zone resistant to crack growth. Fig. 3 shows the effect of a single overload after 30000 cycles amplitude loading for different overload ratio at stress ratio R=0.2 on the fatigue life for the alloy 2024 T351. It also shows that an increasing in overload ratio increase the fatigue life of final fracture. This is due to the delay caused by overload. This overload creates a plastic zone which prevents the spread of the plastic zone than before overload crack. The comparison between the life of constant amplitude and variable amplitude with variable amplitude loading effect has been demonstrated. The delay for a surcharge ratio ORL = 2.0 is very low compared against ORL=2.5 and 2.6. The fatigue life was increased from 10^5 at ORL = 2.0 to $1.5\text{x}10^5$ and $2.7\text{x}10^5$ cycles respectively for ORL= 2.5 and 2.6. At ORL=2.0 a delay is measured at 4200 cycles. At ORL=2.5, the delay is 38500 cycles and ORL=2.6, the total delay is about 170000 cycles with multiple level delays. The effect of a single overload of the fatigue life of Al-alloy 2219 T87 is shown on Fig. 4. The delay is relatively small compared to the delay in 2024 T351 Al-alloy and is in order of 15000 cycles. For this material, the effect of overload level does not have a great effect on total fatigue life.

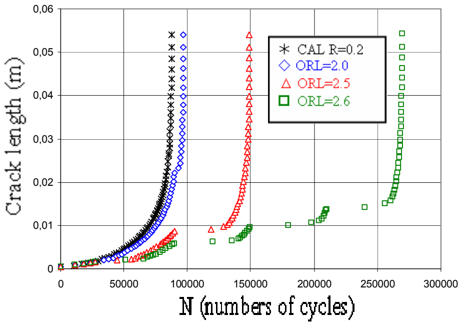

Fig. 3. Single overload effect on fatigue life `of 2024 T351 Al-alloy

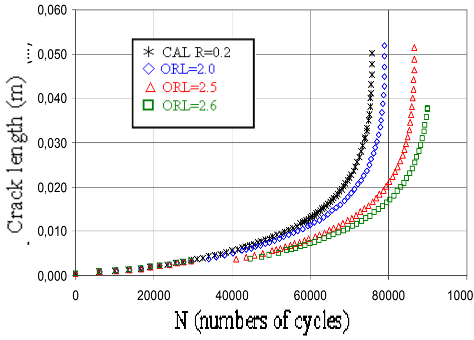

Fig. 4. Single overload effect on fatigue life of 2219 T87 Al-alloy

The effect of a single overload on the fatigue life of 7075 T7351 and 7178 T7651 of 7000 Al-alloys series is shown respectively on Figs. 5 and 6. We note that the alloy exhibits the same fatigue behavior of 2024 T351 Al-alloy where the effect of overloading at ORL=2.0 is low. The delay is very small and is of the order of 2300 cycles. At ORL=2.5 and ORL=2.6, the delay has increased considerably and so is respectively 20000 cycles and 35000 cycles. The delay due to a single load with variable overload ratio for 7175 T7651 Al-alloy was shown firstly at N= 29000 cycles. A second delay was shown at N= 90000 cycles when the delay is important comparatively the first delay. The retard cycles at ORL=2.0, 2.5 and 2.6 are respectively 4700, 12000 and 19000 cycles. The variation of the fatigue life for different Al-alloys studied for the same overload ratio is presented in Fig. 7. The results shown that 2024 T351 Al-alloy is sensitive to the effects of overload compared all Al-alloys of series 7000 which have the same sensitivity to overload. As against the 2219 T87 Al-alloy has a low sensitivity. A parameter that can overload affect fatigue cracking is the width of the block overload shown in Fig. 2c where the overload is characterized by a width “q”. The effect of the width of the block overload for ORL=2.0 of fatigue life of 2024 T351 Al-alloy is shown in Fig. 8. We note the spectrum shown in Fig. 2c, the lifetimes were decreased in bandwidth q=1000 and 5000 cycles compared to single overload (q=1) and band overload q=100 and constant amplitude loading. Applying such spectrum promotes to increase fatigue crack growth rate (Fig. 9).

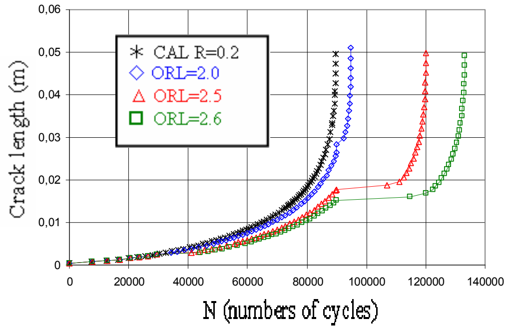

Fig. 5. Single overload effect on fatigue life of 7075 T7351 Al-alloy

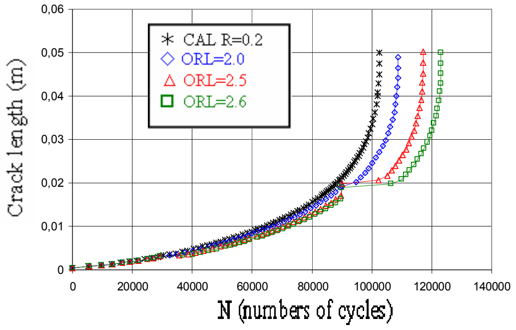

Fig. 6. Single overload effect on fatigue life of 7175 T7651 Al-alloy

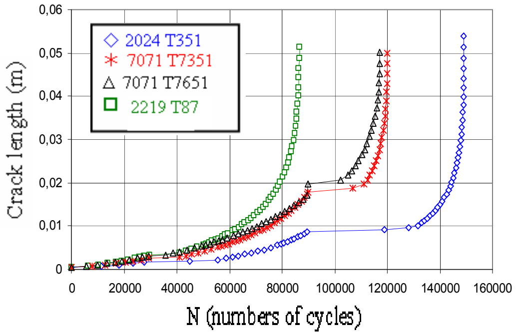

Fig. 7. Comparison in fatigue life of studied aged hardening Al-alloys at ORL=0.2 and R=2.

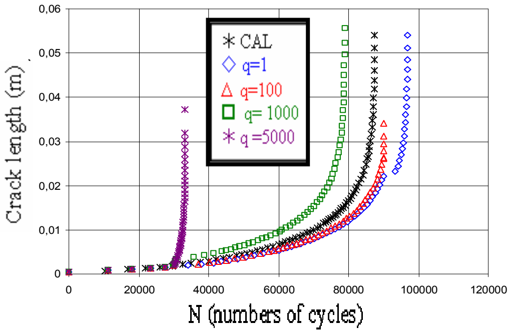

Fig. 8. Effect of overload band on fatigue life of 2024 T351 Al-alloy

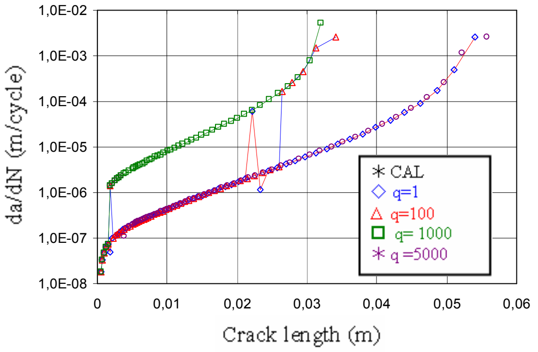

Fig. 9. Effect of band overload on fatigue crack growth rate of 2024T351 Al-alloy

Summary

The main points emerging from the effect of variable amplitude loading on fatigue crack growth can be summarized as follow:

* The effect of a single overload with different overload ratio showed that the increase in overload ratio increases the fatigue life and decrease the fatigue crack growth rate.
* Various types of delays occurred under application of a spectrum load only overload along the crack length.
* The fatigue life is affected by overload spectrum band where the increase in the overload band presents a detrimental effect on the fatigue life and fatigue crack growth rate.
* Al-alloy 2024 T351 have high sensitivity to overloads compared to 7000 Al-alloys series.
* Low sensitivity of overload was shown for 2219 T87 Al-alloy comparatively to previous materials.

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