EFFECT OF BASELINE LOADING ON FATIGUE CRACK GROWTH RETARDATION DUE TO AN OVERLOAD

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The effects of a single tensile overload have been investigated on a 12NC6 heat treated steel. Generally, the fatigue crack growth retardation following a single tensile overload cycle is governed by the overload percentage ratio *OLR*.

But, the baseline loading parameters play an equivalent part. Indeed, these parameters are correlated to the plastic zones (monotonic and cyclic) : the crack length affected by overloading a_d is comparable to the difference between the monotonic overload and the baseline plastic zone sizes ω_{ol} - ω_{max}, and the crack length associated with the minimum crack growth rate a_{min} is proportional to the cyclic overload plastic zone size ω^c_{ol}.

INTRODUCTION

Many experimental studies have showed, since the seventies, that fatigue crack propagation rate (FCGR) is strongly dependent on loading history. Indeed, if the laws of Paris has described the fatigue crack propagation (FCP) under constant amplitude loading (CAL) relatively well, this is not satisfactory in the case of variable amplitude loading (VAL). Following a single overload cycle, the crack growth has revealed a delay. Many authors have tried to explain this phenomenon and showed that several causes are concerned : compression residual stresses into the overload plastic zone, crack blunting, crack closure and/or crack branching (1-7).

The subject of this work concerns the study of the influence of the different plastic zones size on the delay subsequent to a single overload cycle. The parameters allowing a variation of plastic zones size are the yield stress σ_Y and the following loading parameters : $\Delta K = K_{max} - K_{min}$, K_{max} and K_{ol}. An overload is distinguished by its magnitude

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over against the baseline loading magnitude. Many overload ratio definitions can be found in the literature (3). The most usual one is the ratio of the maximum loads $R_{ol} = K_{ol} / K_{max}$. In this case, this definition is not appropriate to characterize all the tests. The overload percentage $OLR = \left(\left(K_{ol} - K_{max}\right)/\Delta K\right) \times 100\%$ allows the comparison of all the loading conditions for this work. The ORL parameter is correlated with R_{ol} ratio by :

$$ORL = \left[\left(R_{ol} - 1\right)/\left(1 - R\right)\right] \times 100\% \qquad (1)$$

where $R = K_{min} / K_{max}$ is the baseline load ratio.

EXPERIMENTAL CONDITIONS

Material and specimens

Experiments were carried out on a 12NC6 steel. Its chemical composition (except carbon) was (% wt) : C 0.12, Ni 1.6, Cr 0.85, Al 0.76, Mn 0.6, Si 0.32, remainder Fe. Two heat treatments were completed :

- the specimens were austenitized at 880°C for one hour, then water quenched and tempered at 500°C (Heat Treatment called QT500),
- others specimens were austenitized at 880°C for one hour, then oven normalized (Heat Treatment called ON).

The yield stress σ_Y = 340 MPa, the elongation percentage A = 70 % for ON heat treatment and σ_Y = 930 MPa, A = 50 % for QT500 heat treatment.

The crack propagation specimens used for the fatigue crack propagation study were Compact Tension specimens (B = 15 mm and W = 80 mm). Their dimensions are in agreement with the ASTM E647-88a normalisation (8).

Loading conditions

Three series of tests by heat treatment were performed :

- serie 1 - R_{ol} = 1.5, 1.8, 2.0, 2.2, 2.5 with R = 0.1, ΔK = 19.8 MPa√m (ON)
  - R_{ol} = 1.5, 1.8, 2.0, 2.2, 2.5 with R = 0.1, ΔK = 21.6 MPa√m (QT500).
- serie 2 - R_{ol} = 1.5, 1.8, 2.0 with R = 0.33, 0.19, 0.1, respectively ΔK = 19.8 MPa√m (ON)
  - R_{ol} = 1.5, 1.8, 2.0, 2.2, 2.5 with R = 0.46, 0.35, 0.28, 0.21, 0.1, respectively ΔK = 21.6 MPa√m (QT500).
- serie 3 - R_{ol} = 2.5 with R = 0.05, 0.10, 0.15, 0.30, 0.50., K_{max} = 22 MPa√m (ON)
  - R_{ol} = 2.5 with R = 0.05, 0.10, 0.15, 0.30, 0.50., K_{max} = 24 MPa√m (QT500)

All the tests were organised in order to prevent overload interaction. So as to keep a constant FCGR $\left(da/dN\right)_{base}$ before the overload cycle, the SIF range ΔK was held at the same value during one test. The tests were carried out at room temperature and in air environment. The operating frequency was 30 Hz for the baseline loading, while, the overload frequency was 0.1 Hz.

RESULTS AND DISCUSSION

The study of the fatigue crack propagation curves after a single overload cycle showed different trends concerning the different delay parameters : the delay affected cycles number N_d and crack length a_d, the crack length associated with the minimum crack growth rate a_{min}, the severity of retardation ratio S_r. Moreover, the influence of the baseline loading and overload condition on the retardation parameters was investigated.

The delay affected cycles number N_d

All the tests show that the delay affected cycles number N_d are sensitive to an overload percentage *OLR* variation (Figure 1). Generally, when this ratio increases, the delay cycles number N_d also increases. But, this link is strongly dependent on heat treatment and probably on yield stress value. Indeed, for the ON heat treatment (σ_Y = 340 MPa), the N_d evolution versus the overload percentage *OLR* can be described by a power law function as :

$$N_d = C(OLR)^m \approx 17.7(OLR)^2 \quad (2)$$

In this relation, the parameter C has a number of cycles dimension.

On the other hand, in the case of QT500 heat treatment (σ_Y = 930 MPa), the increase in the delay affected number cycles N_d is not very significant. The overload is more beneficial for a low yield stress : $4 \leq N_{d(ON)} / N_{d(QT500)} \leq 7$ when the overload percentage *OLR* takes values between 60% and 140%.

The cycles delay ratio is defined as follows : $D_r = N_d / N_{CAL}$ where $a_d / (da/dN)_{base}$ represents the cycles number to propagate the crack over a length a_d under CAL. Its representation versus the overload ratio *OLR* is approximately a straight line covering all the tests of the two heat treatments (Figure 2). In this study, all the results lead to the following relation :

$$D_r = \frac{N_d}{N_{CAL}} = 2.22 \times 10^{-2}(OLR) \quad (3)$$

The D_r ratio is considered to be a parameter which best describes the overload effects because it gives a lifetime benefit. In this work, the lifetime is approximately doubled for 100 % of overload percentage *OLR*.

The delay affected crack length a_d

Many authors (6,7) have already revealed the correlation existing between the crack length affected by delay a_d and the overload plastic zone size ω_{ol}. The first set of tests meets this idea. Indeed, in this case, the ratio $a_d/(K_{ol} / \sigma_Y)^2$ is approximately constant for each heat treatment. Nevertheless, this work also shows a correlation between the crack length affected by delay a_d and the baseline maximum stress intensity factor K_{max}. When
$a_d/(K_{ol} / \sigma_Y)^2$ is calculated in the second series of tests, this ratio increases with the

overload ratio R_{ol}. So, when the baseline monotonic plastic zone size ω_{max} increases, then the crack length affected by delay a_d decreases. To sum up, the crack length affected by delay increases with :

- increasing overload monotonic plastic zone size ω_{ol},
- decreasing baseline monotonic plastic zone size ω_{max}.

Wheeler (1) has claimed that the delay affected crack length a_d can be compared to the length ω_{ol} - ω_{max}. This means that :

$$a_d = \alpha\left[\left(\frac{K_{ol}}{\sigma_Y}\right)^2 - \left(\frac{K_{max}}{\sigma_Y}\right)^2\right] = \alpha\left(\frac{K_{max}}{\sigma_Y}\right)^2\left[\left(\frac{K_{ol}}{K_{max}}\right)^2 - 1\right] = \alpha\left(\frac{K_{max}}{\sigma_Y}\right)^2\left[R_{ol}^2 - 1\right] \quad (4)$$

The representation of the experimental affected crack length $a_{d\,(exp)}$ versus the estimated affected crack length $a_{d\,(est)}$ calculated by relation (4) and Irwin's coefficient ($\alpha = 1/\pi$) is plotted on figure 3. This figure shows that the equation (4) associated with Irwin's coefficient α is a correct approximation of the delay affected crack length a_d.

The crack length associated with the minimum crack growth rate a_{min}

The crack length associated with the minimum crack growth rate a_{min} increases when increasing overload stress intensity factor K_{ol}, and/or decreasing minimum baseline stress intensity factor K_{min}. This crack length a_{min} changes with these two stress intensity factors in the same way as the cyclic overload plastic zone size ω_{ol}^c. The ratio of these two quantities is approximately constant.

$$\frac{a_{min}}{\left(\dfrac{K_{ol} - K_{min}}{2\sigma_Y}\right)^2} \approx 0.18 \quad (5)$$

This relation indicates that the α value of the cyclic overload plastic zone ω_{ol}^c is about 0.18. This value is not so far from $1/2\pi \approx 0.16$ used for plain strain plastic zone sizes calculation.

The severity of retardation ratio S_r

The severity of retardation ratio S_r is defined by the ratio of the minimum crack growth rate $(da/dN)_{min}$ after the overload cycle with the baseline crack growth rate $(da/dN)_{base}$. This parameter can well describe the relative evolution of the minimum crack growth rate $(da/dN)_{min}$. It is mainly influenced by the overload ratio *OLR*.

Figure 4 represents this evolution. When the overload percentage grows, then the severity ratio S_r falls rapidly. The minimum crack growth rate $(da/dN)_{min}$ strongly decreases for high overload percentage *OLR*. The severity ratio S_r tends towards zero if the overload percentage *OLR* comes to a critical value. In this case, the critical overload percentage is worth about 200% for the two conditions of heat treatment.

This paper showed how the baseline and overload plastic zone sizes can interact on delay. The calculation of these zone sizes allows the prediction of the a_d and a_{min} parameters. In the same way, the relation 2 allows the calculation of the benefit of the number of cycles after a single overload. In this case, the lifetime is doubled when the overload percentage is equal to 100 %.

SYMBOLS USED

ω^{c}_{ol} : Overload cyclic plastic zone $= \alpha\left(\left(K_{ol} - K_{min}\right)/2\sigma_{Y}\right)^{2}$

ω_{ol} : Overload monotonic plastic zone $= \alpha\left(K_{ol}/\sigma_{Y}\right)^{2}$

ω^{c}_{base} : Baseline cyclic plastic zone $= \alpha\left(\Delta K/2\sigma_{Y}\right)^{2}$

ω_{max} : Baseline monotonic plastic zone $= \alpha\left(K_{max}/\sigma_{Y}\right)^{2}$

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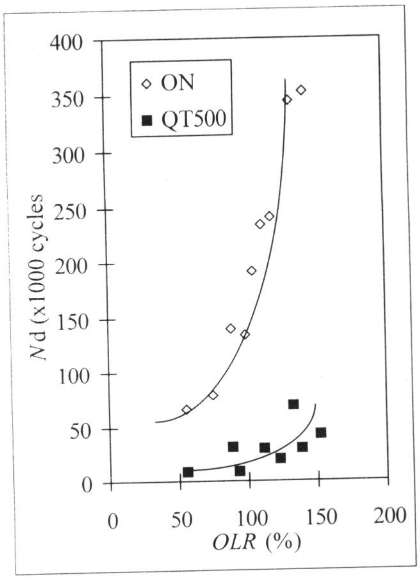

Figure 1 Influence of overload percentage *OLR* on the delay cycles number N_d.

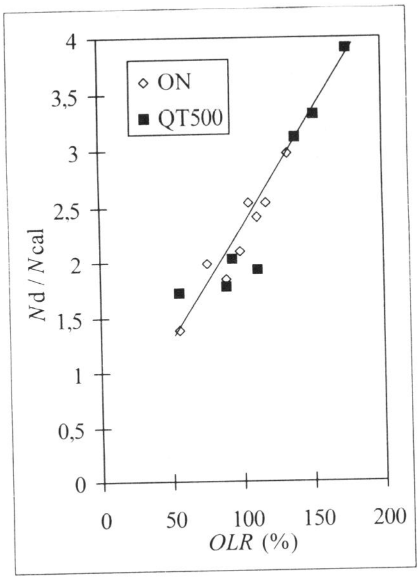

Figure 2 Influence of the overload percentage *OLR* on the delay ratio D_r.

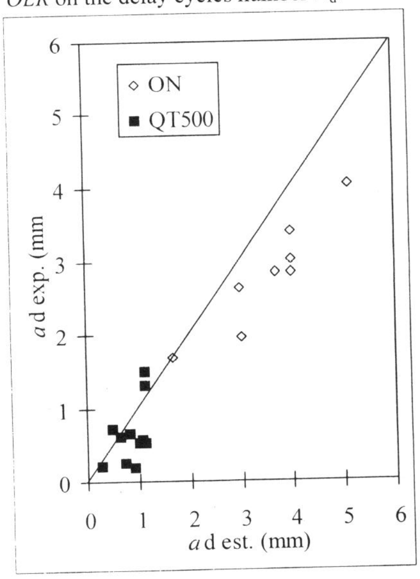

Figure 3 $a_{d\ (exp)}$ versus $a_{d\ (est)}$ calculated by relation (4).

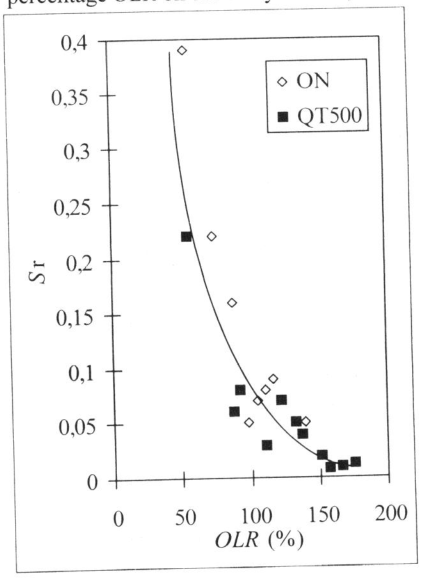

Figure 4 Evolution of the severity ratio S_r versus the overload percentage *OLR*.