INVESTIGATION OF FATIGUE CRACK PROPAGATION IN 7475-T761 ALUMINUM ALLOY

V.A. Pastukhov, C.P.M. Pereira and H.J.C.Voorwald *

The experimental investigation of crack propagation in fine sheets from central cut under constant and variable amplitude cyclic loading is fulfilled. The essential influence of number of overload peaks on crack retardation effect is observed. The model developed in the framework of damage mechanics is applied to predict fatigue crack growth using material parameters obtained in elementary tests. The comparison of experimental and theoretical results shows good correspondence for constant amplitude loading and variable amplitude loading with prolonged overload blocks. The improvement of used model in the range of short overload blocks, where some overestimation of fatigue life is observed, is discussed.

INTRODUCTION

The prediction of fatigue life of structural elements operating under conditions of variable amplitude cyclic loading is the important applied problem of modern fracture mechanics. This problem is more complicated in the case of elements containing strong stress concentrators, when the failure occurs because of prolonged crack propagation process sensitive to history of loading. Some cycles with higher maximal load can reduce significantly crack growth rate at following stage, causing sometimes temporary or permanent crack arrest. The known theoretical models (Elber (1); Willenborg et al. (2); Wheeler (3); etc.) formulated in terms of crack closure or of effective stress intensity factor range relate this phenomenon to near crack tip residual stress field arising in plastically deformed region. These works played an important role in understanding and simulation of studied process and represent perfectly some available experimental data. However, the formulae relating crack growth rate directly to parameters of external load use some constants determined solely in crack propagation tests like in the case of well-known Paris-Erdogan equation for constant amplitude loading.

* FEG/UNESP, Guaratinguetá, SP, 12500-000, BRAZIL

The wide variety of variable amplitude loading programs reduces significantly the effectiveness of such approach for technical applications and demands more general criterion to predict crack behaviour under current loading conditions on the basis of previously known material parameters. The natural and promising way of development of reliable expert systems for crack growth prediction under complicated history of cyclic loading is given by local approach of fracture in the framework of damage mechanics analyzed by Lemaitre (4). This approach, formulated and successfully applied initially for high temperature creep problems, is adequate for any case of delayed structural failure caused by loading and/or environmental conditions. The modelling of subcritical crack propagation by tools of damage mechanics is based on two fundamentals: 1) analysis of local loading conditions in nett-section of cracked element; 2) criterion of crack growth formulated in terms of damage parameter with adequate kinetic equation relating its evolution to local loading history.

Since the growing crack is a strong stress concentrator approximating to fixed material points in nett-section, the applied damage equation should, at least, give a reliable prediction of fatigue life of smooth specimens in the area of high and increasing loads. Unfortunately, the kinetic equations derived from standard S/N curves give, generally, unacceptable overestimation in this area, because the traditional S/N approach is aimed at comparatively low stress levels and long fatigue life. The automated procedure was earlier developed in order to choose the optimal form of damage equation under current conditions and to determine the corresponding materials constants using available results of fatigue life tests (5). The results obtained for 2024-T3 aluminium alloy were used for simulation of crack growth under constant amplitude loading and showed a good correspondence with available experimental data (6). The aim of present work is to develop this approach on loading programs with overload peaks and blocks and to apply it for other structural material obtaining basic constants from tests of smooth elements and checking experimentally the predictions of crack behaviour.

MODEL OF CRACK PROPAGATION

Local Fracture Criterion

Local fracture criterion represents a condition of crack propagation. In terms of scalar damage parameter it's formulated as $\omega(a+d)=1$, were "d" is average grain size in material structure, "ω" is a damage parameter reflecting the reduction of material's lifetime under current loading conditions and not related to any partial micromechanism of fracture. At the start of loading $\omega=0$ and it's following evolution is described by differential equation

$$\frac{d\omega}{dN} = D(R)\left(\frac{G}{1-\omega}\right)^{k} \tag{1}$$

where "G" is determined dimensionless function of only one loading parameter (for example of maximal stress or of stress range); the constant "k" and the dimensionless function of stress ratio D(R) are materials parameters obtained from fatigue life tests of unnotched specimens; "N" is a number of load cycles.

Simulation of Crack Growth

The discrete crack growth with instant steps on length of average linear grain size is supposed. Thus, the nett-section is considered as a couple of finite elements operating in conditions of quasi-uniform loading. The number of cycles until failure of finite element closest to crack tip N_1 corresponds to fatigue life of smooth specimen tested under corresponding conditions. The reduction of fatigue life of rest elements during this period is calculated through integration of equation (1) from N=0 to $N=N_1$ using local value of stress function G. The number of cycles to next step N_2 is calculated through integration of equation (1) at second finite element from N_1 to N_2 using the local value of damage parameter calculated at first step as initial and critical value $\omega(N_2)=1$. Then, the damage evolution at rest finite elements is calculated and the procedure is continued until the failure of nett-section.

Stress State in Cracked Elements

For the application of formulated criterion and kinetic equation to simulation of crack growth process is necessary to describe the local evolution of two independent loading parameters: maximal stress of cycle σ_{max} and min/max stress ratio R. The ideal elastic-plastic behaviour of material is supposed. For the loading with constant amplitude and mean stress the local variation of necessary parameters was evaluated by Rice (7) using quasi-static analysis of stress distribution under maximal load and after partial unloading. The general analysis for loading programs including overloads is given by Matsuoka and Tanaka (8) and may be presented in analogous form of equations $\sigma_{max}=\sigma_{max}(a, r)$; $R=R(a, r)$, where "a" is a crack length and "r" is a distance from crack tip, for application in the developed procedure. These equations don't reflect the influence of finite width on stress distribution remote from crack tip, crack closure by residual stress at unloading and caused stress redistribution, however can be accepted as first approximation.

EXPERIMENTAL

Material and Specimens

The experimental program is fulfilled on sheets of aluminium alloy 7475-T761 (yield strength σ_{ys}=393 MPa; ultimate strength σ_{us}=462 MPa; modulus o elasticity E = 68900 MPa) widely used in aircraft industry. All specimens are cutted in longitudinal direction, have thickness 4.16 mm and gage length 300 mm. The unnotched specimens for fatigue life tests have width 20 mm. Fatigue crack growth is studied on center cracked elements of width 75 mm and initial crack length 2a=14 mm.

Loading Conditions

Al tests are fulfilled at loading frequency 50 Hz. For each of three positive values of minimal/maximal load ratio R (0.01; 0.3 and 0.6) the fatigue life corresponding to 4 different values of maximal stress was obtained. Two kinds of additional experiments (1st: with fixed load ratio and increasing mean stress; 2nd: with fixed maximal stress close to yielding strength and decreasing minimal stress) are aimed at testing of damage kinetic equation under conditions of approximating crack. The switch of loading regime is made at 1/4, 1/2 or 3/4 of critical number of cycles corresponding to initial regime.

In crack growth tests with constant amplitude of load ±3.15 KN are studied three values of mean stress: 9.45, 14.7 and 19.2 KN. First two regimes are used as reference in investigation of overload effect. The overload blocks are applied at crack length a = 10, 15 and 20 mm. For both cases are studied 4 numbers of cycles in overload block: 1, 10, 100 and 1000.

RESULTS AND DISCUSSION

Fatigue Damage Accumulation

The obtained S/N data were completed by available results for tension-compression cycles (load ratio R = -0.5; -1). Various forms of stress function G in damage kinetic equation were tested and the best correlation is given by fractional-linear function reflecting tendency of fatigue life to zero in the area of high maximal stress: $G = \Delta\sigma / \left(\sigma_{us} + \sigma_{ys} - \Delta\sigma\right)$ where $\Delta\sigma=\sigma_{max}(1-R)$ is stress range. The material parameters k and D(R) were determined using S/N data for loading regimes with constant amplitude and mean stress. The application of equation (1) with stress function G and these parameters to loading regimes with increasing maximal stress or increasing amplitude gives a reliable prediction of experimentally observed fatigue life.

Crack Growth and Effect of Overloads

The reliable predictions of crack growth rate and fatigue life under stable regimes of loading are obtained. Figure 1 represents the comparison of theoretical predictions (dotted lines) and experimental results (solid lines).

The observed effect of overloads strongly depends from overload / reference load ratio and from number of overload peaks. The experimental results for reference load 9.45±3.15 KN and overload 19.2±3.15 KN (maximal load ratio R_{ov}=1.77) are presented at figure 2 and for reference load 14.7±3.15 KN (the same overload; maximal load ratio R_{ov}=1.25) at figure 3. Curves number 1 correspond to 1 overload peak, 2 to 10, 3 to 100 and number 4 to 1000 cycles in overload blocks.

The theoretical prediction shows good correspondence to experimental results for 1000 overload peaks (figure 4, solid lines are experimental, dotted - theoretical). However, the model doesn't reflect the experimentally observed sensitivity to overload block size what leads to overestimation of retardation for single overload peaks and short blocks. This contradiction may be related to used quasi-static analysis of stress evolution. The retardation effect of overload is described by continuum damage model through reduced damage accumulation rate in plastically affected near crack tip zone, thus, the correct evaluation of its size and stress state is of most importance. The observed strong sensitivity to number of overload peaks in the range from 1 to 100 and the saturation of this effect from 100 to 1000 is a evidence of non-instant growth of plastically affected zone under cyclic loading. This phenomenon may be described on the basis of deep study of cyclic plasticity and incorporated into proposed model at further development, as well as improvement of stress approximations, taking account of equilibrium condotions at nett-stress and redistribution due to crack closure.

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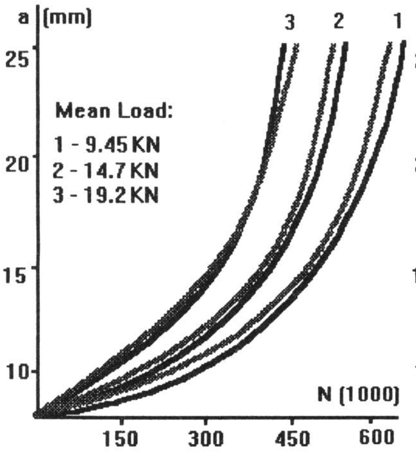

Figura 1. Crack growth under constant amplitude loading.

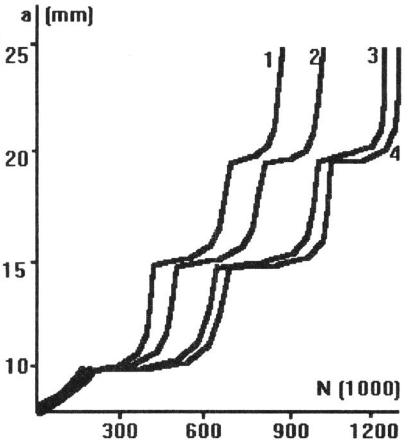

Figura 2. Crack growth retardation, overload ratio $R_{OV}=1.77$.

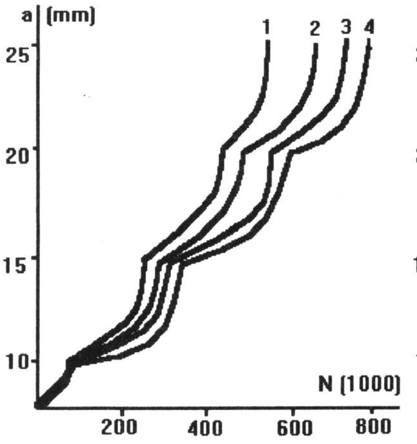

Figura 3. Crack growth retardation, overload ratio $R_{OV}=1.77$.

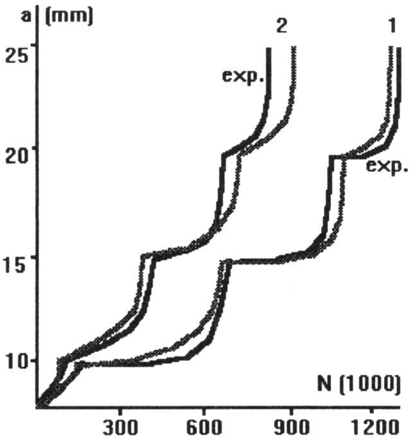

Figura 4. Retardation, reference load: 9.45±3.15KN (1); 14.7±3.15KN (2)