SMALL-CRACK GROWTH AND LIFE PREDICTION FOR LY12cz ALUMINUM CLAD ALLOY

X. R. WU and H. YU
Institute of Aeronautical Materials, Beijing 100095, China

ABSTRACT

Experimental and analytical studies were conducted on the initiation and early growth of naturally-occurring small fatigue cracks in the LY12cz Aluminum alloy. In the experimental program, the plastic replica method was used to monitor the small-crack at the root of a semi-circular notch. Pronounced small-crack effect was observed for this material, especially at the negative stress ratios. In the analytical program, a crack closure model was used to analyze the growth of small-cracks. Total fatigue life prediction was made solely based on crack growth starting from an assumed initial material defect. Reasonable agreement was found between measured and fatigue lives for most loading conditions. Plasticity effects on the predicted fatigue lives and crack growth rates were found very small.

KEY WORDS

Small-crack, fatigue, crack closure, life prediction.

INTRODUCTION

It is well known that the growth characteristics of small fatigue cracks are often very different from those of large cracks. Under the same stress intensity factor range ΔK, the growth rate da/dN, is usually higher for small-cracks than for large cracks. Small-cracks also grow at the ΔK-level below the threshold value ΔK_{th} determined from large cracks. Such behavior has been shown to be more pronounced in tests with compressive loads.

Many investigators have suggested and verified (Schijve, 1982, Taylor and Knott, 1981; Newman and Edwards, 1988; Newman and Wu, 1994), that crack closure was a major factor in causing some of the differences between the growth of small and large cracks. Newman et al (1988, 1994) have shown, on the basis of a crack-closure model, that a large part of the small-crack effect in aluminum alloys was caused by a small-crack emanating from an initial material defect, and the break down of LEFM concepts. The present approach is to apply the crack closure concept to both small- and large-crack growth.

TEST PROGRAM

Material and Specimen

The test program conducted on LY12cz clad alloy consisted of standard fatigue tests and small-crack tests on single-edge-notched-tension (SENT) specimens, and large-crack tests on the standard middle-crack tension (M(T), width 100mm) specimens. Both constant amplitude (R=0.5, 0, -1) and spectrum (Mini-TWIST) loadings were used.

The LY12cz clad sheet material is similar in chemical composition and tensile properties to 2024-T3 alloy. The clad sheet has a cladding layer 60-80μm (reduced to 40-60μm after chemical polishing) thick on each surface. The cladding, composed of mainly Al-Zn, is used to enhance corrosion resistance.

The SENT specimen, as shown in Fig. 1, is a rectangular sheet containing a semi-circular notch with a radius (*r*) of 3.2mm on one side of the specimen (*w*=50mm). The stress concentration factor is 3.15 based on gross section stress. Care was taken in machining the notch surface to minimize the residual stress, and chemical polishing was performed to deburr the edge of the notch, and to remove machining marks and a thin layer from the notch surface that might contain residual stress.

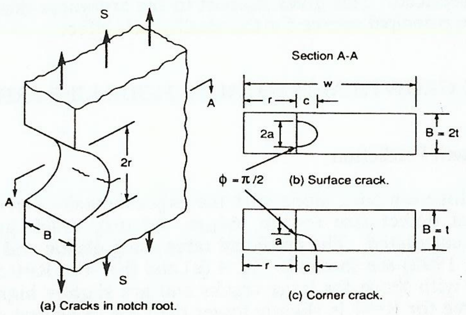


Fig. 1 SENT specimen for fatigue and small-crack test.

Test Procedure

Fatigue tests were conducted on SENT specimens. The purpose of this test is two fold: to obtain stress-life (*S-N*) curves for comparison with life prediction results, to determine stress levels for the small-crack tests. Crack growth was not monitored in fatigue tests.

Small-crack tests were very similar to the fatigue tests except that the crack initiation and growth history was monitored. The plastic-replica method was used to detect small-cracks at the notch root. This method has been found to be accurate down to the crack length of 10 μm. Replicas were taken at cyclic interval chosen so that at least 25 to 30 replicas were taken during each test.

The purpose of large-crack tests was to establish the crack growth baseline covering a wide range of crack growth rates from threshold to final failure. The constant amplitude da/dN-ΔK relation at different stress ratios were used to determine the da/dN-ΔK_{eff} relation, which was later used in the crack-closure model for life predictions.

ANALYSIS PROGRAM

Stress Intensity Factors for Corner Cracks

Accurate stress intensity factors for the particular crack geometry must be known for the crack growth data correlation. For the corner crack at the semi-circular notch in the SENT specimen subjected to remote uniform stress or displacement, the stress intensity factor has been determined by three-dimensional weight function (Zhao and Wu, 1990) and finite element method (Newman and Wu, 1994). The results are given by:

$$K = S\sqrt{\pi a / Q} \times F_{cn}(a/c, a/t, c/r, c/w, r/t, r/w, \varphi) \quad (1)$$

where Q is the shape factor and F_{cn} is the boundary correction factor for the corner crack. Highly accurate analytical F_{cn}-expressions have been developed (Newman and Wu, 1994), and these results were used in the present analysis.

Effect of Cladding on *K*-factors

In the LY12cz clad sheet, most cracks were initiated in the cladding layer and grew as corner cracks into the core material. The cladding layer (l) is a very weak material in comparison with the core material; its tensile strength is estimated to be about 50 MPa. In the tests, it was observed that the cladding layer always yielded and developed multiple cracks along the edge of the notch. Thus, as a first approximation, l was assumed to carry no load. A correction factor for the cladding on stress intensity factor was developed by taking the ratio of two stress intensity factor solutions for through-the-thickness cracks: uniform pressure applied over the (a), entire crack length, and (b), part of crack length with no pressure on the cladding layer (l). The later case was easily determined by the weight function method (Wu and Carlsson, 1991). The cladding correction factor reads

$$G_c = 0.4\sum_{i=1}^{5} \beta_i \left(1 - \ell / a\right)^{i-1/2} / (2i - 1) \quad (2)$$

The stress intensity factor for corner cracks in SENT specimen as given by Eq. (1) was further multiplied by G_c for the LY12cz clad sheet crack growth data correlation.

Crack Growth Model

A crack growth model (Newman, 1981) that accounts for crack closure effects was used to predict small- and large-crack growth rates and total fatigue lives for LY12cz clad alloy. The model is based on the Dugdale plastic-zone model but modified to leave plastically deformed material in the wake of the crack tip. The basic assumption in the growth model is the growth rate for any loading cycle lies on a single da/dN-ΔK_{eff} curve. It first calculates crack opening stress, and thereby ΔK_{eff} as a function of loading history. The ΔK_{eff} was then used to enter the da/dN-ΔK_{eff} baseline obtained from large crack tests to give the predicted crack growth rates for small-cracks.

A crack closure factor ratio (β_R) was introduced to account for the crack closure deference between the interior and free surface locations in the notch surface of the SENT specimen (Newman and Edwards, 1988), The expression used here is

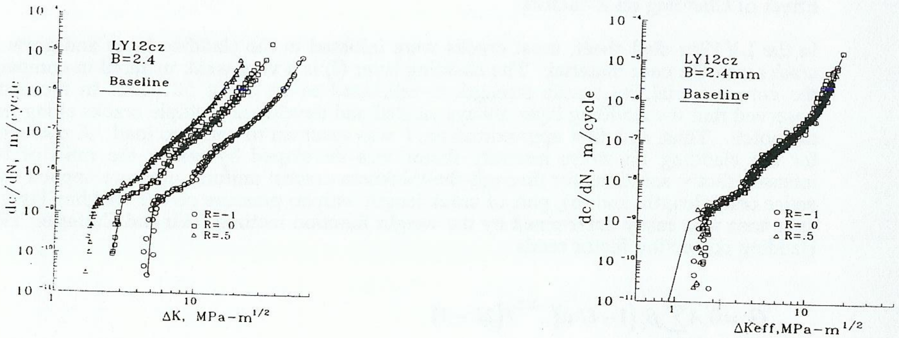
$$\beta_R = 0.9 + 0.2R^2 - 0.1R^4 \quad \text{for } R>0$$
$$\beta_R = 0.9 \quad \text{for } R<0 \quad (3)$$

The stress intensity factor range at a location where the crack front intersects the free surface was multiplied by β_R.

TEST RESULTS

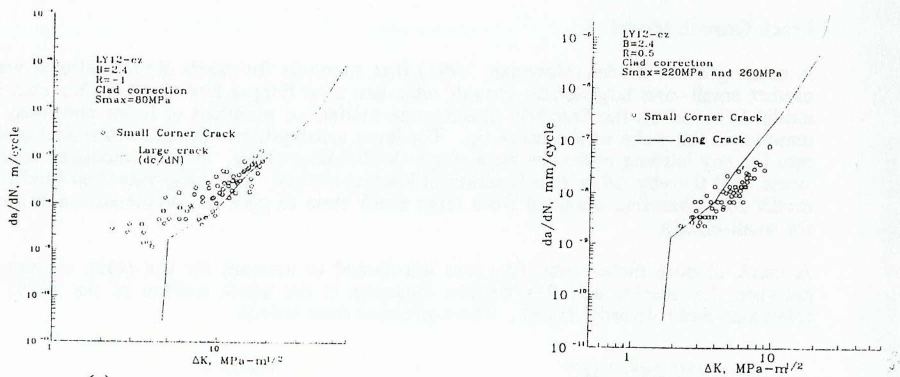
Large-Cracks

Large-crack growth rates from the tests are plotted in Fig. 2(a). On each data set, a visual best fit line was drawn through the data. These data were further used in establishing the da/dN-ΔK_{eff} relation for this material. In the calculations of ΔK_{eff} based on the closure model (Newman and Edwards, 1988), a constraint factor (α) of 1.1 was used for rates greater than 7.5E-07m/cycle and 1.73 for rates lower than 9E-08m/cycle. For the intermediate rates, α varied linearly with the logarithm of da/dN. The resulting da/dN-ΔK_{eff} relation is shown in Fig.2(b). The lower limit or small-crack threshold $(\Delta K_{eff})_{th}$ was an estimate on the basis of predicting the fatigue limit for constant amplitude loading.



(a) (b)

Fig. 2 Large-crack growth rates obtained from M(T) specimens.



(a) (b)

Fig. 3 Comparison of small- and large-crack growth rates.

Small-Cracks

In the LY12cz clad alloy, small-cracks were initiated mostly in the cladding layer as quarter elliptical corner cracks, and then penetrated in to the core material. It was found that a crack length of 64 μm (about the clad thickness) was observed before about 15 percent of the total fatigue life was consumed. Therefore, for engineering applications, it is reasonable to make life predictions solely based on crack growth from the material defect.

To eliminate the complication caused by multiple cracks produced mostly in tests at high stress levels, a non-interacting criterion (Newman and Wu, 1994) was adopted for screening out the data points which may have been affected by the neighboring cracks. Data scatter was greatly reduced by this procedure.

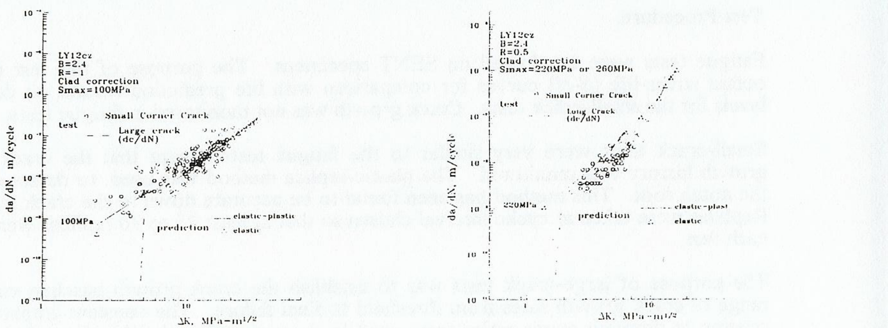
To account for the effect of the soft cladding layer on stress intensity factors, the cladding correction factor developed in the analysis program was used in the stress intensity range ΔK calculation.

Figure 3 shows two typical plots of small-crack growth at different stress ratios (-1 and 0.5). The large-crack growth curve is also plotted for comparisons. It is seen that small-cracks growth at higher rates than large-cracks, and this behavior is much more pronounced for negative R-values. At high positive R-value (0.5) , the difference between small- and large-cracks is greatly reduced. This gives support to the argument that the lack of crack closure for small-cracks is the principal source for the small-crack effect.

SMALL-CRACK GROWTH AND TOTAL FATIGUE LIFE PREDICTIONS

Small-Crack Growth Prediction

Using the crack closure model, along with the experimentally derived da/dN-ΔK_{eff} baseline and the initial material defect size (64μm, 64μm, 0.5μm), crack growth rates for any loading conditions can be calculated. The predicted rates using elastic and elastic-plastic stress intensity factors (Newman, 1992) are shown in Fig. 4 (a) and (b). For R=0.5, the predicted crack growth rates agreed well with those for large cracks and are slightly higher than the small-crack data. The predicted curve for R=-1 is slightly lower than the measured data of small-cracks. In both cases, plasticity effects on the predicted crack growth rates were very small.

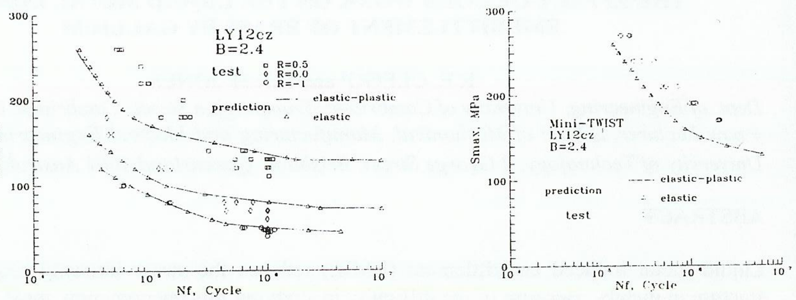


(a) (b)

Fig. 4 Predicted and experimental small-crack growth rates.

Total Fatigue Life Prediction

The crack closure model and the $da/dN\text{-}\Delta K_{eff}$ baseline were used to predict total fatigue lives based solely on crack growth starting from the initial material defect to the final failure. In this approach, a crack (the initial material defect - the cladding layer) was assumed to grow on the first load cycle. Comparisons are made with the standard fatigue test results (*S-N*) from SENT specimens.



(a) (b)

Fig. 5 Comparisons of predicted and experimental total fatigue life.

Experimental and predicted fatigue lives for constant-amplitude and Mini-TWIST spectrum loadings are shown in Fig.5(a) and (b). In general, the predicted total fatigue lives were in reasonable agreement with the measured data. It was also found that the plasticity effect on the total fatigue life prediction was rather small.

CONCLUSIONS

The present investigation leads to the following conclusions:

1. Small-crack mostly initiated from the cladding layer of LY12cz clad alloy, and grew as corner cracks. Most of the fatigue lives was spent in the crack propagation phase.

2. Small-crack effects were more pronounced in tests with negative stress ratios.

3. Small-crack growth rates and total fatigue lives can be predicted with reasonably good accuracy by using Newsman's plasticity-induced crack closure model and the $da/dN\text{-}\Delta K_{eff}$ baseline established from large-crack tests.

4. Plasticity effects on predicted crack growth and fatigue lives were small.

REFERENCES

Newman, J.C. Jr (1981), A crack-closure model for predicting fatigue crack growth under aircraft spectrum loading, *ASTM STP* **748**, 53-84.

Newman, J.C. Jr and Edwards, P.R. (1988), Short-crack growth behavior in an aluminum alloy. An AGARD Cooperative Test Program, *AGARD Report No.***732**

Newman, J.C. Jr. (1992), Fracture mechanics parameters for small fatigue cracks, Small Crack Test Methods, *ASTM STP* **1149**, 230-242

Newman, J.C. Jr. and Wu, X.R. (1994), Small-crack effects in high-strength aluminum alloys, A NASA/CAE Cooperative Program, *NASA RP* **1309**.

Schijve, J (1982), Difference between the growth of small and large fatigue cracks - the relation to threshold K-values, *Fatigue Thresholds*, Vol.II, 881-908

Taylor, D and Knott, J.F. (1981), Fatigue crack propagation behavior of short cracks - the effect of microstructure, *Fatigue Fract. Engng Mater. Struct.*, **4(2)**, 147-155

Wu, X.R. and Calsson, A.J. (1991), Weight Functions and Stress Intensity Factor Solutions, *Pergamon Press, Inc.*

Zhao, W and Wu, X.R. (1990), Stress Intensity Factor for Corner Cracks at a Semi-circular Notch Under Stress Gradients, *Fatigue Fract. Engng Mater. Struct.*, **13(4)**, 347-360