FATIGUE OF AN ALUMINUM ALLOY UNDER PREDOMINANTLY COMPRESSIVE LOADINGS

N.RANGANATHAN
Laboratoire de Mécanique et de Physique des Matériaux, E.R.A. - C.N.R.S. 863
E.N.S.M.A. , Site du Futuroscope , Chasseneuil du Poitou , B.P. 109, 86960 Futuroscope
CEDEX, France

ABSTRACT

This paper presents the results of an experimental study and modelling of the fatigue behavior of the high strength aluminum alloy 7075 T651 subjected to predominantly compressive loadings using test specimens with a stress concentration factor of 2.3. Constant amplitude loadings and a variable amplitide loading using an aircraft service spectrum are considered. The results of the constant amplitude loading permits the developpement of an analytical model to determine the evolution the local stresses and strains at the notch tip. This model is then used to estimate the evolution of the fatigue damage cycle by cycle for the variable amplitude loading studied. The life prediction to crack initiation are within 10 to 40 percent of the measured lives.

KEYWORDS

Fatigue, Compressive stresses, Notch effect, Crack initiation, Life prediction.

INTRODUCTION

Fatigue under predominantly compressive loadings has attracted little attention in the past as most structural components are subjected to predominantly tensile loadings. A limited number of studies concern the influence of a compressive underload on the crack iniation kinetics under tension-tension cycling (For exemple,Du Quesnay et al, 1992). It has been shown that the fatigue crack growth behavior of structural steels can be quite different under negative load ratios R (R is the ratio of the minimum to maximum loads in a fatigue cycle) when compared to positive R ratios (Tack and Beevers, 1990 and Mazur and Rudd, 1990). These studies have shown that the fatigue crack can remain open under compressive stresses and it has been suggested the crack closure concept can be used to descibe this behavior

In the case of the aircraft wing, the upper surface is subjected to tensile stresses when the aircraft is on ground and become compressive when its airborne. during the flight the stresses are purely compressive as shown in fig.1. Models to predict life to crack initiation have rarely been validated under loadings similar to the one shown in this figure.

In the present study, fatigue crack initiation at a notch with a stress concentration factor, K_t , of 2.3 are first experimentally measured under constant amplitude (CA) loadings for four load ratios, 0.1, -1, -3 and -5.3. The last mentioned load ratio represents the ratio between the mean stresses on the wing upper surface with the aircraft on ground and when it is airborne (see fig.1). Tests are then conducted using the variable amplitude (VA) spectrum covering a large life range from a few thousand flights to 500000 flghts.

The constants representing the material behavior at the notch tip are determined from low cycle fatigue and long life fatigue tests (Ranganathan et al, 1993).The local approach (Glinka 1985) is the applied to estimate the fatigue damage at the notch tip. Life predictions using the different hypothesis are compared and dicussed.

MATERIAL AND EXPERIMENTAL CONDITIONS

The nominal composition and the mechanical properties of the studied material are given in Tables 1a and 1b respectively. The alloy was heat treated to the peak aged condition.

Table 1a Nominal composition of the 7075 alloy

Element	Cu	Mg	Mn	Cr	Si	Fe	Ti	Zn	Al
Weight %	1.52	2.44	0.04	0.2	0.07	0.16	0.04	6.0	Remaining

Table 1b Mechanical properties of the alloy in the T651 condition

Young's Modulus (MPa)	Yield Strength (Mpa)	Ultimate Tensile strength (Mpa)	Elongation (%)
71000	527	590	11

The test specimen geometry is given in fig.2. The value of K_t for this geometry, estimated by finite element techniques is 2.3.

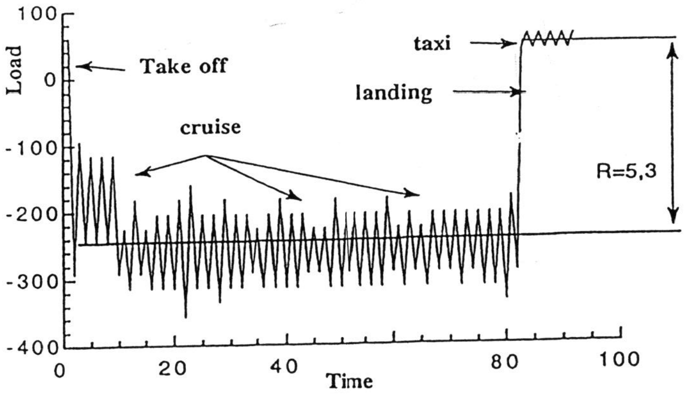

Fig.1 Typical flight

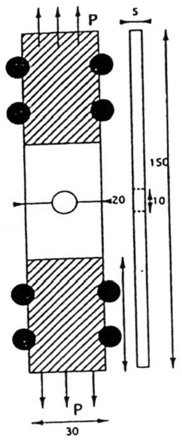

Fig. 2 Test specimen

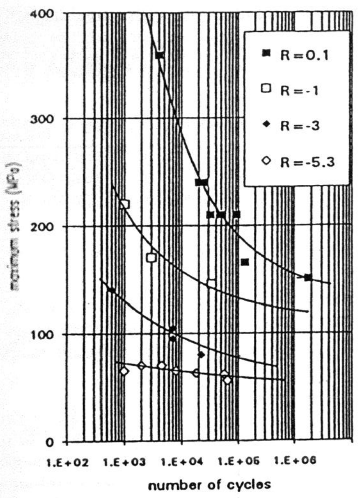

Fig3a Life to crack iniiation CA conditions

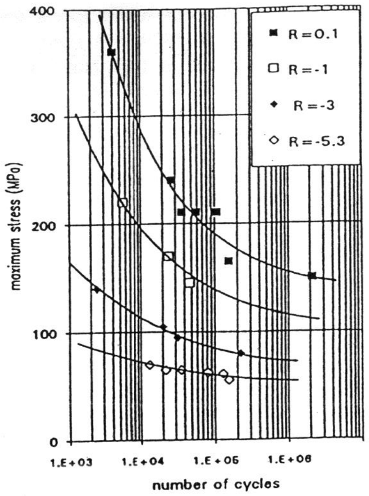

Fig.3b Life to failure CA conditions

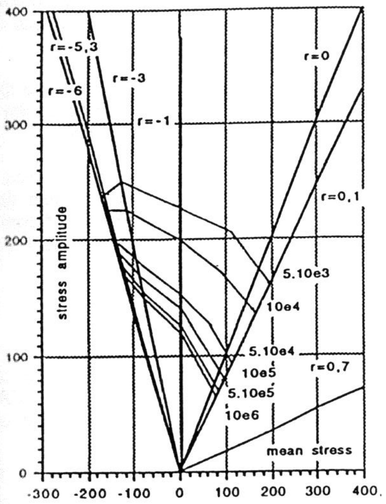

Fig. 4 Constant Life Diagrams

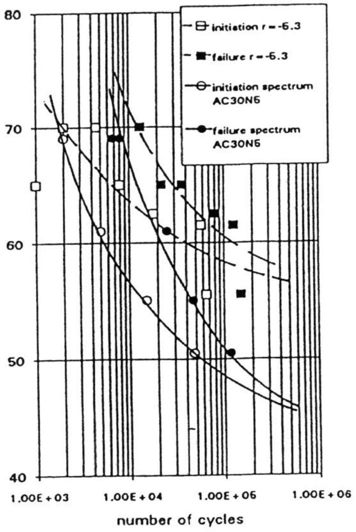

Fig. 5 Lives to initiation and failure under flight simulation loading

The specimens were attached with a special grip to a servo hyraulic machine with a load capacity of 10000 daN. Crack iniation was detected using an endoscope and the size of the crack detected was on the order of 100 µm.CA tests at four R ratios of 0.1, -1,-3 and 5.3 were conducted covering a life range of few thousand cycles to about 1 million cycles.

The VA loading consists of 1000 different flight configurations and 22054 cycles (a typical flight is given in fig.1). The testing was carried out using a computer to drive the signal input to the machine. The load levels were measured to assure that the applied loads were within 5% of the desired loads. Cracks were detected with the same experimental technique as for CA conditions.

EXPERMENTAL RESULTS.

The measured lives to crack iniation and final rupture are given in figs.3a and 3b respectively. these results are given in terms of the maximum stress in a cycle in order to distinguish easily between the different R ratios.

At R=0.1, typical concave shaped curves are obtained. The portion of life spent in the crack propogation stage is negligible in the range studied and represents about 20% of the total life. The concavity of the curves decrease for negative R ratios and this effect is more pronounced for higher negative R ratios. The curve at R=-5.3 is almost flat at this scale. Another important difference lies in the fact that the crack propogation stage becomes predominant at negative R ratios and at the longest life studied here and at R=-5.3, this stage represents about 80% of the total life. A similar result has been previously reported (Mazur and Rudd 1990))

Constant life diagrams are next shown in fig.4. While the constant life lines are almost linear at long lives, changes in curvature are observed at very short lies. This particular behavior at very short lives is attributed to local plasticity effects (Ranganathan et al, 1993). This result shows that the extension of a Goodman type relation to negative R ratios is not realistic and can lead to non conservative estimations.

The results for the VA tests are given in fig.5. The measured lives are given with respect to the maximum stress in the spectrum which occurs once per flight. In this figure the measured lives under CA conditions, at the most probable R ratio of -5.3 are also given for comparison.

For the VA tests life to initiation increases as the maximum stress decreases as for the CA tests. For comparable stress levels the number of flights to initiation or failure is higher than the number of cycles to initiaton or failure at CA conditions execpt for the lowest lives. It folows that one cannot neglect the effect of purely compressive cyles in a spectrum as has been suggested before (Hsu and McGee, 1980).

DISCUSSION

The first part of the discussion is centered around the developpement of an analytical model to take into account the material behavior under predominantly compressive loadings under CA conditions. The result of this analysis can then be incorporated into a model developped to estimate life to crack initiation under VA loading conditions.

Modelling Fatigue behavior under CA conditions

The effect of the load ratio is usually modelled by introducing a correction into the relationship between the stress amplitude and the life to failure (Morrow, 1965 and Smith, Watson and Topper 1969).The usual relationship betwwen the stress amplitude ($\Delta\sigma/2$) and life to failure (2Nf) is written in the form (for an R ratio of -1):

$$\Delta\sigma/2 = \sigma f'\ (2Nf)^{\wedge}b, \qquad 1$$

where $\sigma f'$ is the fatigue-strength coefficient and b, the Basquin's exponent
The correction for mean stress introduced by Morow is written in the form:

$$\Delta\sigma/2 = (\sigma f' - \sigma M)\ (2Nf)^{\wedge}b, \qquad 2$$

where σM is the mean stress .
Comparing equations 1 and 2 an equivalent stress amplitude that takes into account the mean stress effect can be defined using the following expression:

$$P_{\text{Morrow}} = (\Delta\sigma/2)eq = \Delta\sigma/2/(1-(\sigma M/\sigma f')) \qquad 3$$

The correction introduced by Smith Topper and watson (STW) also defines a an equivalent stress amplitude of the form given by,

$$P_{STW} = (\Delta\sigma/2)eq = (E\ \Delta\varepsilon t/2\ \sigma Max)^{\wedge}0.5, \qquad 4$$

where $\Delta\varepsilon t/2$ is the strain amplitude per cycle and σMax, the maximum stress in a cycle.

If either of these corrections are to be used in the case of negative R ratios all the data points relating the equivalent stress amplitude with respect to life to failure should fall in a single curve irrespective of the R ratio (positive and negative). This hypothsis is tested in figures 6a and 6b. It can be seen from fig. 6a that Morrow's correction seems to underestmate lives near the endurance limit while slightly overestimates the lives for 2Nf < 10^5 cycles.

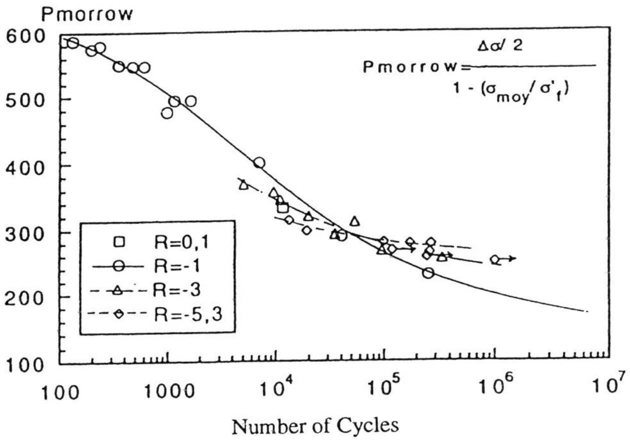

Fig.6a Morrow's Correction for Mean stress

The STW correction while giving reasonable estimations in the endurance limit range, leads to extremely conservative estimations at lower lives.This correction is modified in the following manner following a detailed analysis of the experimental results (Nicolas et al, 1993):

$$P^2_{STWm} = \{(\Delta\sigma/2)A + \sigma d\ B\}\ \Delta\varepsilon/2\ E, \qquad 5a$$

where σd is the endurance limit for R=-1 and A and B are constants given by

$A = (2 - R^2 + R)/(1-R)$, for R>0 and

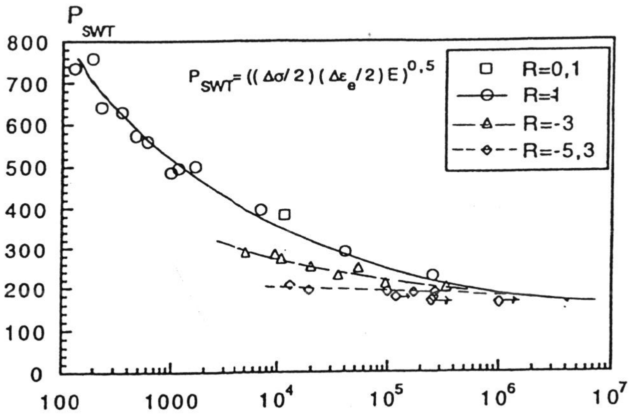

Fig.6b Smith Watson and Topper (STW) Correction

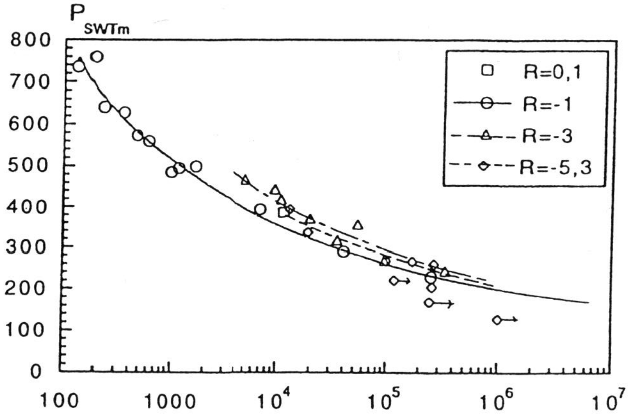

Fig.7 Modified STW Correction (STWm)

$A = (2 + R^2 + R)/(1-R)$, for R<0 and 5b

$B = (R2 + R)/\{2 (1-R)\}$ ^0.5 5c

The evolution of this parameter with respect to the measured lives for the different test conditions studied is shown in Fig.7 and it can be seen that this modfication leads to reasonable predictions throughout the life range studied and for all the R ratios.

Life predictions under VA coditions

Life prediction are made using the local stress approach which consists in determining the stresses and strains on an hypothetical low cycle fatigue specimen at the notch tip using the Glinka's energy based method (Glinka, 1985). The loading spectrum is first decomposed to closed cycles using the Rainflow analysis. A crack is considered to be initiated when this hypothetical specimen beakes as the fatigue damage (esitmated by Miner's rule) reaches the value of 1.

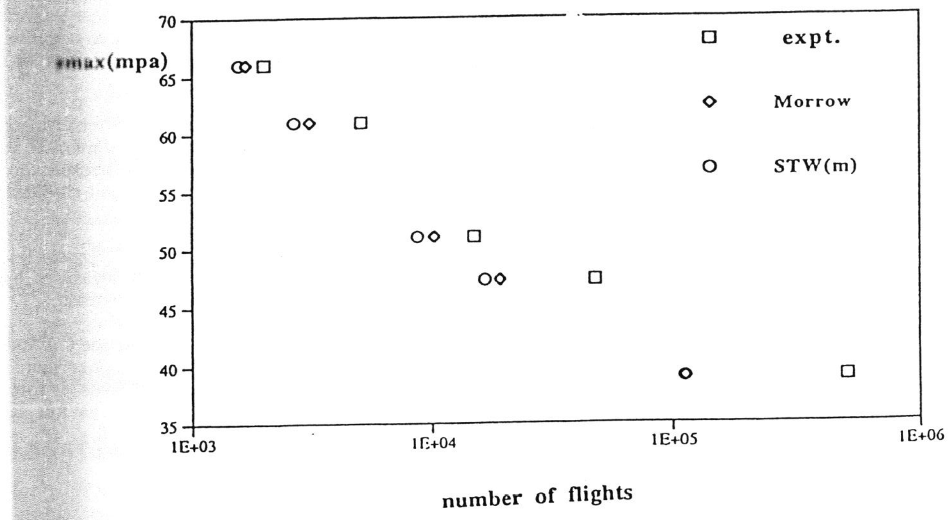

Fig.8 Comparison between measured and predicted lives to initiation

The estimated and predicted lives using Morrow's correction and the moditified STW correction are comared in fig.8. The estimations using Morrow's correction are slghtly higher than the ones using the second method. All the predictions are conservative and the diffference between the predictions and the measured values seem to increase at lower lives. The difference between the predictions and the experimental values can be partly attributed to the precison of the method used to detect the cracks (on the order of 100 µm in the present case). Probably if a more sensitive method were used to detect the cracks, the measured lives to crack initiation could have been lower, thus closer to the predictions.

CONCLUSIONS

This experimental study brings out the particularity of material behavior subjected to predominantly compressive loadings in fatigue.

Whereas for positive R ratios the crack propagation stage is quite negligeable with respect to the total life, this stage represents a significant portion of life under negative R ratios.

The modifications brought into the Smith, Watson and Topper model correctly takes into account the effect of negative R ratios.

Tests using an aircraft wing uppr suface loading spectrum (predominantly in compression) shows that one cannot neglect the damaging effect of fully negative cyles in fatigue.

Life predictions using the Glinka model and with the modified correction for mean stress effect and the Morrow's correction lead to comparable results and are within 10% to 40% of the experimentally measured lives.

The estimations are conservative for both the corrections.

REFERENCES

Du Quesnay , Topper, T.H., Yu, M.T. and Pompetzki, M.A. (1992), Int. J of fatigue, **14**, 45-50.

Glinka, G. (1985) ,Engng. Fract. Mech., **22**, 3, 485- 500.

Hsu, T.M. and McGee , W.M. (1980), ASTM STP 714, American Society for Testing and materials, Philadelphia , 79-92.

Mazur, C.J. and Rudd, J.L. (1990), AGARD repor R-767, NATO publications, 2-1 - 2-11.

Morrow, J.D. (1968) , Fatigue Design Handbook, Society of Automotive Engineers, Michigan, U.S.A

Ranganathan, N., Nicolas, C. and Lachaud, B. , (1993) Fatigue 93 confernece proceedings, Bailon and Dickson eds, **3**, 1545-1600.

Nicolas, C., Ranganathan, N, and Glinka, G (1993) in Sollicitation en service et comportement en fatigue, Société Française de Métallurgie, Paris, 268-279.

Smith K.N., Watson, P. and Topper T.H. (1969) A stress strain funda for the fatigue of metals, Report no.21, Solid Mechanics Division , University of Waterloo, Canada .

Tack AJ. and Beevers, C.J., (1990) Fatigue 90 conference proceedings, **2**, 1179-1185.