CRACK EDGE INSTABILITY—A CRITERION FOR SAFE CRACK PROPAGATION LIMIT IN THIN SHEETS

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ABSTRACT

For the application of fail-safe design concept or the damage tolerance criterian to aerospace structural elements, it is desirable to have prior knowledge of the safe crack propagation limit, if any, under given amplitude of loading. In this paper an attempt has been made to identify the safe crack propagation limit for thin aluminium alloy (D16-ATV) sheets under constant amplitude fatigue loading, which happens to be the critical crack length associated with the onset of crack-edge instability. Attempt has also been made to predict the critical crack length based on experimental and semi-empirical analyses.

KEYWORDS

Macro-crack range; constant amplitude loading; fatigue crack growth; crack-edge instability; limit of stable crack growth; critical crack length.

INTRODUCTION

Aerospace structural elements employing monocoque or semi-monocoque construction often contain unavoidable crack-like defects. Under service loads the resulting cracks, in relatively thin stressed skins, can grow to catastrophic proportions unless otherwise detected and the crack growth arrested during routine inspection and maintenance. For the application of fail safe design concept or the damage tolerance criterion for such structural components, it would be useful to have reliable prior knowledge of the safe crack propagation limit, if any.

It is well known that the plane strain fracture toughness, K_{IC} is inapplicable to thin sheets (thickness less than 6.0 mm) as per ASTM specifications and, as such, the crack, length associated with K_{IC} of the material may not yield much useful information concerning the limit of stable crack growth in the macro-crack propagation range. The compressive stresses present along the free-edges of a long crack in a thin sheet under tension could cause the local buckling of the crack-edges and it has been shown by Forman (1965) and clarkson and Pietrusewicz

(1964) that the crack-edge instability influences the fracture toughness and fatique crack propagation under random loading respectively. Clarkson and Pietrusewicz (1964) have also observed that the point at which the crack-edge buckles is of significance from the point of view of rate of crack propagation.

In this paper results of a series of experiments on relatively thin aluminium alloy sheets have been presented and an attempt has been made to identify the significance of crack-edge instability on the fatigue crack propagation process and to develop an empirical relation by which it should be possible to predict, beforehand, the critical crack length for the onset of crack-edge instability under given constant amplitude loading.

EXPERIMENTAL ANALYSIS

The sheet material used in this investigation is an aluminium alloy, designated as D16-ATV (ALCLAD), which is commonly used for stressed skin of most Soviet-built aircrafts. The mechanical properties and approximate chemical composition of the material are listed in Table 1. The range of nominal thickness of sheets tested in these experiments varied from 0.8 mm to 2.0 mm .

TABLE 1 Mechanical Properties and Chemical Composition of Alclad Aluminium Alloy D16-ATV*

Ultimate strength, $S_{ult.}$ = 4.3146×10^{8} N m^{-2}

Yield strength (proportional limit), S_Y = 2.8437×10^{8} N m^{-2}

Elastic modulus, E = 6.9623×10^{10} N m^{-2}

Shear modulus, G = 2.6476×10^{10} N m^{-2}

Poisson's ratio, ν = 0.31

Material density = 2.78×10^{3} kg m^{-3}

Fracture toughness (for sheet thickness 2.0 mm)** = 69.4608×10^{6} N $m^{-3/2}$

Percentage chemical composition (D 16)

Cu : 3.8 - 4.9
Mg : 1.2 -1.
Mn : 0.9
Fe 0.5
Si : 0.5

Zn : 0.3
Ti : 0.1
Ni : 0.1
Al : Balance
Fe+Ni 0.5

Special treatments

A	Improvement in quality of alloy
T	Heat treated
V	Quality improvement after tempering and ageing

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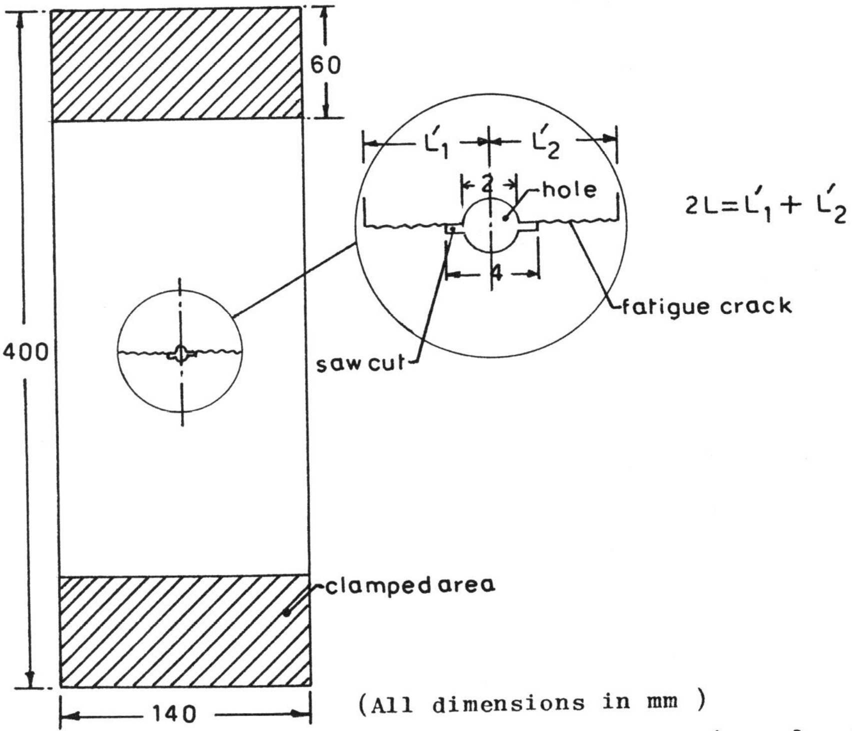
* Material specifications are as reported in Hand Book of Aviation Materials (1965)

** The information is based on personal communication; the experimentally determined value was, however, found to be somewhat lower than the quoted value.

Constant Amplitude Fatigue Test

Centre-cracked specimens of identical outside dimensions were made from sheet materials with different thicknesses. Figure 1 shows the dimensions of a typical specimen used in the constant amplitude fatigue test. It may be noted that the central concentrator was made first by drilling a hole 2 mm in diameter and then cutting with precision jig-saw blade 1 mm on either side. All the specimens were tested in a fatigue testing machine of the type GRM-1. The magnitude of the maximum stress, $_{max}$ was varied over a wide range, but keeping the average stress in the cross section well within the limit of yield stress.



(All dimensions in mm)

Fig. 1 Dimensions of centre-cracked specimen for fatigue test.

With a view to monitor the onset of local instability of the edges of crack, two sensitive strain gauges, of the type 2 PKB-20-200 X 5, were fixed back to back at the centre of one edge of crack with the axes of the strain gauges normal to the direction of loading. The two gauges were connected such that any bending of the crack-edge produced an electrical signal, which after proper amplification could be recorded in a six-channel photo-sensitive oscillograph. Accurate measurement of crack length in thin sheets was made with the help of a telemicroscope with a built-in vernier scale in the optical field. With this arrangement, it was possible to carry out dynamic crack length measurements upto an accuracy of 0.125 mm and within a time period of 10 seconds for both ends of crack. The frequency of loading was uniform at 400 cycles/minute for all specimens tested. Table 2 shows the details of the constant amplitude fatique test for four different nominal sheet thicknesses. It should be noted that atleast three specimens were tested corresponding to each case and the average values have been shown in Table 2.

TABLE 2 Constant Amplitude Fatigue Test Results*

Thickness T (mm)	$\sigma_{max} .10^{-7} (N\ m^{-2})$	R	$2\ L_{cr}$ (mm)	$L_1 = (\frac{N_{cr}}{N_f}) x100$	$L_2 = \frac{(N_f - N_{cr})}{N_{cr}}$ x 100
0.710	19.889	0.625	30.335	93.58	6.95
0.715	15.360	0.625	34.585	92.57	8.16
0.785	11.991	0.625	40.625	90.27	10.78
0.785	9.993	0.625	46.250	92.56	8.03
0.698	17.039	0.500	33.933	95.25	5.01
0.788	13.946	0.300	37.375	94.05	6.34
1.170	18.103	0.625	48.375	98.25	1.77
1.175	14.020	0.625	53.500	97.77	2.28
1.180	11.966	0.625	58.125	97.61	2.45
1.367	19.373	0.625	50.083	98.02	2.03
1.380	17.054	0.625	52.417	98.07	1.97
1.368	15.050	0.625	56.333	98.83	1.18
1.372	12.868	0.625	61.750	98.48	1.55
1.880	14.605	0.626	76.000	99.68	0.32
1.888	14.462	0.625	82.167	99.70	0.30
1.890	10.377	0.625	84.667	99.75	0.25

*Data show the average values for three specimens tested in each case.

For each specimen the number of cycles of loading necessary for the crack to grow from a reference length of 10 mm to the critical length for the onset of local buckling of crack-edges, N_{cr} was noted. The instant of the occurrence of crack-edge instability could be judged from the oscillograph record which showed a sharp rise in the signal level (i.e. deviation from mean position) at that instant. The corresponding critical crack length could be determined by synchronising the interval for the measurement of crack length with the time marker on the oscillograph record. The number of cycles needed for the crack to grow from the reference length to ultimate fracture, N_f was also noted. Since the time required for crack length measurement was about 10 seconds the accuracy for the number of cycles recorded was limited to within ± 30 cycles. Table 2 shows the ratio of stable crack growth period upto the onset of crack-edge instability to the total crack growth period upto fracture, defined as percentage useful life, L_1 and the ratio of residual crack growth period beyond the crack-edge instability to the stable crack growth period, defined as percentage residual life, L_2. It can be seen that for all the different maximum-stress levels, σ_{max}, stress ratios, $R = \sigma_{min}/\sigma_{max}$ and sheet thickness, T tested, the percentage useful life, L_1 is always greater than 90 and the percentage residual life, L_2 is almost negligible. This indicates the significance of crack-edge instability in the fatigue crack propagation process in thin sheets.

Determination of Critical Crack Length from Static Load Test

It is well known that the modified Southwell method can be applied for the determination of the local buckling load of a multiply-connected plate under tension. Carlson and co-workers (1970) and Parida (1976) have shown that the method of analysis is particularly suitable for thin sheets with cracks. The problem under consideration being of inverse nature, it was desirable to find the correlation between the tensile buckling load and the length of crack for geometrically similar specimens with different crack lengths.

For this series of tests sheet specimens of three different nominal thicknesses, and made of the same material, were prepared with identical outer dimensions. These specimens were fatigue-cracked under constant amplitude loading upto pre-determined lengths and then utilised for the local buckling tests under static loading. Care was taken to see that the maximum-stress level used for generation of fatigue cracks was well below the yeild stress of the material. Table 3 shows the results of the above test. The tensile buckling loads, P_{cr} were determined by use of the modified Southwell method, as described in the references cited above. The simple relationship that is used to correlate the critical half crack length, L_{cr} and the corresponding tensile stress, S for local buckling of the free-edges of crack, is given by

$$S = K \cdot E \; (T/L_{cr})^2 \qquad (1)$$

where K is a constant, depending upon the material properties and specimen geometry. From Table 3 it is noted that the average value of the constant, K_{av} varies appreciably for different nominal sheet thicknesses, thus necessiating experimental determination of its value for use in the empirical relation (1).

TABLE 3 Results of the Static Load Test

Thickness T (mm)	Crack length 2L (mm)	P_{cr} $.10^{-3}$(N)	S $.10^{-7}$(N m^{-2})	K	K_{av}*
0.705	30	19.328	19.583	1.273	1.285
0.720	35	14.895	14.777	1.254	
0.700	40	11.414	11.648	1.366	
0.720	45	9.786	9.709	1.362	
0.715	55	5.707	5.701	1.211	
0.710	60	5.452	5.485	1.407	
0.710	65	4.001	4.025	1.211	
0.780 **	30	23.632	21.642	1.150	
0.785 **	40	15.690	14.276	1.331	
1.190	50	27.123	16.281	1.032	1.129
1.185	55	24.309	14.653	1.133	
1.175	60	20.544	12.489	1.169	
1.170	65	17.474	10.668	1.182	
1.350	60	26.731	14.143	1.003	1.016
1.365	65	24.623	12.885	1.049	
1.360	70	19.926	10.465	0.996	
1.360	75	18.023	9.466	1.034	
1.375	80	15.817	8.216	1.000	

*K_{av} indicates the average value of the constant, K, obtained for sheets of given nominal thickness, but with different crack lengths.

** Sheets of a different batch of production.

TABLE 4 Comparison of Critical Crack Length

Thickness T (mm)	σ_{max} $.10^{-7}$(N m^{-2})	R	$2L_{cr(expt.)}$ (mm)	K_{av}	$2L_{cr(emp.)}$ (mm)	Percentage Error*
0.710	19.889	0.625	30.335	1.285	30.117	-0.71
0.715	15.360	0.625	34.585	1.285	34.512	-0.21
0.785	11.992	0.625	40.625	1.285	42.883	5.56
0.785	9.993	0.625	46.250	1.285	46.975	1.57
0.698	17.039	0.500	33.933	1.285	31.988	-5.45
0.788	13.946	0.300	37.375	1.285	39.917	6.80
1.170	18.103	0.625	48.375	1.129	48.760	0.80
1.175	14.020	0.625	53.500	1.129	55.644	4.00
1.180	11.966	0.625	58.125	1.129	60.486	4.06
1.367	19.373	0.625	50.083	1.016	52.243	4.31
1.380	17.053	0.625	52.417	1.016	56.211	7.24
1.368	15.050	0.625	56.333	1.016	59.315	5.29
1.372	12.868	0.625	61.750	1.016	64.334	4.18

* Computed with respect to $2L_{cr(expt.)}$

In Table 4 a comparison has been made between the critical crack length, $2L_{cr(expt.)}$, obtained from constant amplitude fatigue test and the critical crack length, $2L_{cr(emp.)}$, predicted by use of the empirical relation (1) in conjunction with the values of K_{av} from Table 3. It is to be noted that the magnitude of maximum stress in fatigue test is considered as equivalent to the critical stress, S in predicting the critical crack length for the onset of crack-edge instability. From Table 4 it is seen that the error involved in the above prediction is, in general, small. It may be mentioned here that the effect of crack-edge instability on the rate of crack propagation and fracture is under investigation.

CONCLUSIONS

For centre-cracked thin aluminium alloy sheets, under constant amplitude fatigue loading, the onset of crack-edge instability constitutes 90% or more of the total fatigue crack propagation life. The critical crack length associated with the onset of crack-edge instability, therefore, gives a conservative estimate of the stable crack growth range and may be considered as the safe crack propagation limit. It is possible to predict the critical crack length from the knowledge of the maximum stress magnitude and from the sample test on a few identical specimens under static loading.

Although the above conclusions are true for the case of constant amplitude fatigue loading, it appears possible to extend the concepts to other cases of fatigue crack propagation, invloving variable amplitude loading or spectrum loading, since the critical crack length is correlated to the magnitude of maximum tensile stress. However, in all cases the maximum stress should not exceed the elastic limit for the material inview of the restriction imposed by the empirical relation, used.

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