EXPERIMENTAL PROCEDURE FOR FAST MEASUREMENT OF THRESHOLD IN FATIGUE CRACK PROPAGATION

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ABSTRACT

The fatigue crack propagation threshold ΔK_{th} is a material property, which is often not determined because its measurement requires a tedious test which normally requires 5 days or more of testing. The purpose of this paper is to propose a new faster method for its determination, based on a continuous decrease of the cyclic load with time. The proposed experimental procedure requires less than 1 day of testing. The tests was carried out employing linear and exponential functions of load reduction with time. After no cycles, Crack arrest is obtained for a certain ΔK_a. The extrapolation of the log ΔK_a versus log $N_a$curve to a large N_a (10^6 cycles) gave a good approximation of ΔK_{th} for 2024-T3 aluminium alloy.

KEYWORDS

Fatigue threshold-Aluminium 2024T3 - experimental procedure - Load decreasing.

INTRODUCTION

During the last ten years, the fatigue crack propagation threshold ΔK_{th}, has been a subject of increasing interest (J.P. Baïlon, J. Masounave, J.I. Dickson 1980). The number of studies performed on the threshold have been limited principally because of its very tedious measurement due to the extremely low crack propagation rates, da/dN $<10^{-7}$ mm/cycle. As well, measurements of ΔK_{th} on materials which are very sensitive to overloads require considerable caution during the classical load shedding procedure employed to approach ΔK_{th} (ASTM I978). In the present paper, a simple and relatively rapid method of determining ΔK_{th} is proposed, based on a continuous decrease of the load as a function of number of cycles, N, or time t. This method promises to reduce the time required to measure the threshold by a factor >5, while still maintaining reasonable accurancy compared to the traditional methods.

GENERAL APPROACH

The threshold can be defined as the value of ΔK for which the fatigue crack propagation rate tends to zero in the absence of any overloading effects. This definition is imprac tical, because it is too time-consuming to determine ΔK_{th} in this manner.

It is well known that, after an overload, the crack propagation rate can be reduced to a very low value comparable to that observed near ΔK_{th}. The value of ΔK for which the crack arrests after an overload can be called an apparent threshold, ΔK_a. The low propagation rate after an overload appears to be caused mainly by the compression residual stress left by the overload in the track tip region (T.C. Lindley 1980). In contrast, at the threshold, crack arrest occurs only as a result of the residual stresses developed in the plastic zone in the absence of any overloading effects.

The method, which appears to be the most efficient in order to arrive at ΔK_{th} rapidly, is a gradual reduction of load at each cycle. It is, however, assumed that even a small load reduction results in an overloading effect. In considering successive cycles, it is assumed that the overloading effect is partially additive and can lead to crack arrest. Two factors favour crack arrest by reducing the crack velocity. These are the amount of overload accumulation and that of load reduction. In contrast, because the crack continues to advance during load reduction, it relaxes the compressive stresses in the crack tip region. It is the net effect of these three factors which determine whether crack arrest occurs or not.

The proposed rapid method of determining ΔK_{th} is based on the fact that for each different rate of load reduction, from a given ΔK_o (the initial value of ΔK), a different value of the couple (ΔK_a, N_a) is obtained, where N_a is the number of cycles to crack arrest. Extrapolation of ΔK_a to a large number of cycles to crack arrest should yield the threshold value, ΔK_{th}.

It was decided to perform the load reduction as a function of the time, rather than, as proposed by Saxena and co-workers (1978) or by the ASTM (1978), as a function of the crack length. This choice was made principally because the crack length measurement is never precise and a load reduction procedure based on the variation of crack length would then be less continuous. It should be noted that in our proposed method there is no interaction between measure and control so that any error on the crack length does not affect the control of the load and thus avoids any accidental overload effect. It was also decided to test out both linearly and exponentially decreasing loadings. The former type, chosen for its simplicity, can be expressed as

$$\Delta P = \Delta P_o - QN \tag{1}$$

where ΔP is the load amplitude, ΔP_o the initial load amplitude and Q, the control parameter. Different values of the couple (N_a, ΔK_a) should result for the different values of Q chosen.

An exponentially decreasing loading procedure should be more adaptable to preventing overloading effects. Indeed, the plastic zone dimension R_p should be decreased with the time, in proportion to its instantaneous size

$$dRp/dN = Q'R_p \tag{2}$$

Solving equation (2) yield:

$$Rp = R_{p_o} \exp(-Q'N) \tag{3}$$

where R_{p_o} is the initial plastic zone dimension, Rp that after N cycles and Q' the control parameter.
By introducing the classical fracture mechanics relationships:

$$Rp = C\Delta K^2 \tag{4}$$

and

$$\Delta K = Y\Delta P/B\sqrt{W} \tag{5}$$

with Y the compliance function and B and W the usual specimen dimensions. Substituting equations (4) and (5) into equation (3) gives:

$$\Delta P = \frac{Yo}{Y} \Delta P_o \exp\left(-\frac{Q'N}{2}\right) \tag{6}$$

For combinations of a small increase of the crack length and a small crack length, Yo/Y can be assumed equal to one. For a constant K-DCB specimen this approximation is not required since Yo/Y ratio is equal to one for any crack length.
Equation (6) then becomes:

$$\Delta P = \Delta P_o \exp(-QN) \tag{7}$$

in order to attain crack arrest within a certain number of cycles an estimation of the value to employ can be obtained from a simple calculation based on the Paris crack growth relationship and equations 5 and 7.

EXPERIMENTAL PROCEDURES

Tests were carried out at room temperature and approximately 30% relative humidity on a 2024 - T351 aluminium alloy, (0.2% yield strength of 358 MPa, a tensile strength of 441 MPa and an elongation of 25%). The load ratio employed, R = Kmin/Kmax was 0.1; the frequency was 20 Hertz. Two specimen geometries were employed, a CT geometry (B = 12.7mm and W = 50.8mm) and a constant K DCB type geometry (B = 12.7 mm, w = 127 mm and $\theta = 20^o$). The latter geometry was tested both with and without side grooves in order to prevent the crack path deviation. K values for DCB specimen were obtained through a compliance calibration test. For the CT specimen, the compliance equation given in ASTM E-399-78 was employed.

The tests were carried out on an servohydraulic testing system, controlled by a minicomputer. This computerized testing system was able to continuously decrease the load following a chosen function and could also measure and record all variables (load, number of cycles, stroke, etc. The crack length was measured with a travelling optical microscope having a resolution of 0.01 mm.

RESULTS

STANDARD THRESHOLD MEASUREMENTS

Two sets of threshold measurements were carried out following the procedure recommended by the ASTM (1978) and the results are given in figure 1. The values of ΔK_{th} obtained were 4.7 and 4.2 MPa$\sqrt{m}$ employing the CT specimen geometry and the DCB geometry, respectively. This value is in a good agreement with litterature (Boisson 1977, Hudson 1969).

THRESHOLD MEASUREMENTS BY PROPOSED METHODS

Three sets of test were conducted to measure ΔK_{th} by the above proposed methods. The raw results are obtained as curves of crack length, "a", as a function of N, an example of which is given in Fig.2. Crack arrest is defined as shown in this figure with Na the number of elapsed cycles for wich the length of crack remains constant.

a) <u>CT specimen - linearly decreasing ΔP</u>

The results of tests on CT specimens employing a linearly decreasing ΔP (eq.1) are summarized in Table 1. The value of ΔK_a obtained in this manner were higher than the value of ΔK_{th}. The lowest value of Q which could be employed in this type of test to obtain crack arrest was $Q = 1.25 \times 10^{-4}$ (cycles $^{-1}$). Lower values of Q do not result in crack arrest because the increase in compliance caused by crack propagation becomes more important than the effect on ΔK of the decrease of ΔP. The net result is an increase rather than a decrease in ΔK.

b) CT specimen - exponentially decreasing ΔP

An exponentially decreasing ΔP procedure was employed, utilizing CT specimens, in order to attempt to reach the lowest possible values of ΔK_a and to study the influence of the parameters ΔK_o and Q (eq.7) on crack arrest. A few of the results are reported in table 2. The same limitations were observed as for the tests with linearly decreasing ΔP. For similar reasons, than in the previous paragraph, the minimum value of Q which gave crack arrest was 10^{-5} cycle $^{-1}$ (Fig.3).

c) DCB specimen - exponentially decreasing ΔP

The constant ΔK - DCB was then employed since it allows the exact application of equation. The results are plotted in figure 4. The dotted line was obtained by linear regression and the threshold value extrapolated to a value of Na of 10^6 cycles is 4.7- MPa$\sqrt{M}$.

DISCUSSION

As shown in table 1, for the linear shedding of ΔP, the value of ΔK_a can depend largely on ΔK_o and a. Also, it can be noticed that for the small values of ΔK_o, the crack propagates on a very short distance, wich implies lower precision on results (Na, ΔKa). For the same specimen, but with an exponentially decrease of load (table 2), the value of ΔK_a seems to be independant of the chosen value of a_o and ΔK_o in the chosen Q range. The threshold value obtained employing the DCB specimen and an exponential decreasing are in good agreement with the ΔK_{th} value determined by the accepted procedure.
These first results suggest two other methods for a more rapid determination of ΔK_{th}. Values of ΔK_a very close to ΔK_{th} were obtained within a relatively small number of cycles, employing an exponentially decreasing ΔP procedure with the CT geometry. It therefore appears that we could measure an approximate ΔK_{th} with only one test, if the correct value of Q is chosen. As indicated in the description of the general approach, a simple calculation can give us a first approximation of the value of Q to employ. If in the test employing this value, crack arrest results, a smaller value of Q can then be employed. The value of ΔK_a obtained immediately prior to the test with the value of Q that does not give crack arrest can be taken as the approximate value of ΔK_{th} within a few hours of testing.

The method employing a constant K-DCB specimen with an exponentially decreasing ΔP does not depend on a judicious choice of the value of Q. All values of Q lead to crack arrest. The results plotted if Fig.4 took approximately 15 hours of cycling (in total). The value of ΔK_{th} is taken for Na equal to 10^6 cycles.
We present here the first preliminary results of the proposed method. It is obvious that other tested should be carried out.

CONCLUSION

Two different experimental procedures have been used to find the fatigue crack propagation threshold value on an Aluminium 2024T3.
The first one was traditionnal and took us nearly 6 days.
The second one was by extrapolation of the results found by continuous decreasing of the applied load with an exponential function of the time (cycle number). On a constant K, DCB specimen this 2nd method took us around 15 h.

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TABLE 1 Linear shedding, CT specimens

Q	ao/w	ΔK_o (MPa$\sqrt{m}$)	N_a (cycles)	ΔK_a (MPa$\sqrt{m}$)	Δa (mm)
50 10^{-4}	0.22	8.7	15000	7.68	0.29
12.5 10^{-4}	0.42	8.7	94600	5.69	0.88
12.5 10^{-4}	0.16	8.7	no arrest		
12.5 10^{-4}	0.31	8.7	no arrest		
25 10^{-4}	0.47	8.7	66500	6.09	2.63
25 10^{-4}	0.20	8.7	74600	6.53	2.11
25 10^{-4}	0.28	7	28000	5.7	0.09
12.5 10^{-4}	0.38	6	19000	5.6	0.76

TABLE 2 Exponential shedding, CT specimens

Q	ao/w	ΔK_o (MPa$\sqrt{m}$)	N_a (cycles)	ΔK_a (MPa$\sqrt{m}$)
3 10^{-5}	0.32	10	61800	4.4
2 10^{-5}	0.38	10	95000	4.5
1 10^{-5}	0.46	10	no arrest	
2 10^{-5}	0.23	8	52400	4.9
2 10^{-5}	0.25	6.5	37700	4.5

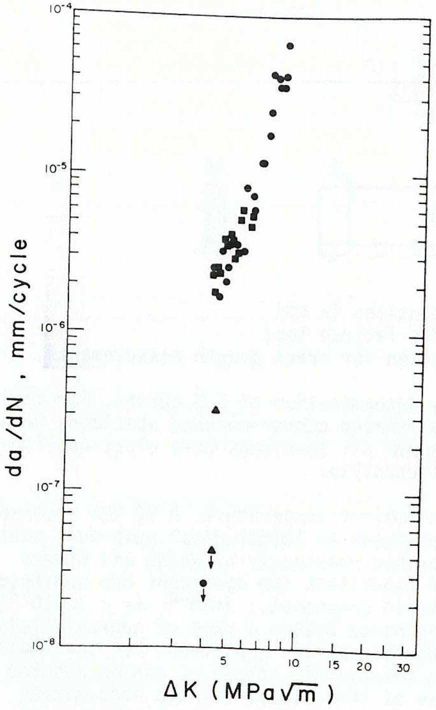

Fig.1 Fatigue crack propagation at low rate in Aluminium 2024 T3

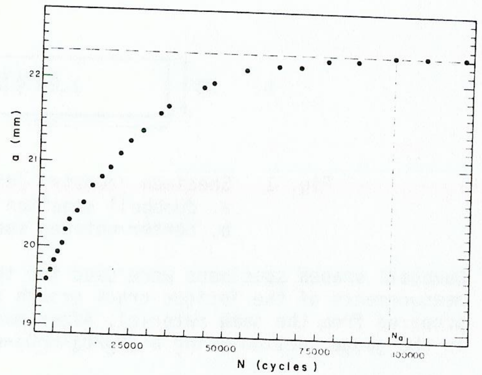

Fig.2 Crack growth during an exponential decrease of load

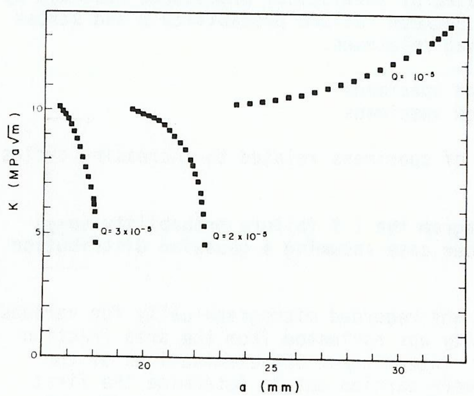

Fig.3 Effect of Q on an exponential decrease of load

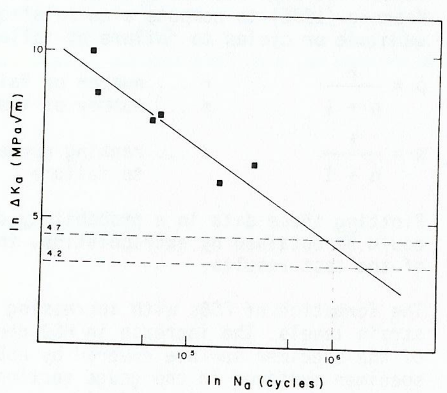

Fig.4 Threshold determination with exponential shedding of load on DCB specimen