BIDIRECTIONAL COUPLING OF A CRACKING TEST MACHINE TO A CALCULATOR

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ABSTRACT

This paper describes first a test machine of fatigue crack growth coupled to a calculator and then gives some results obtained with this equipment. The specimen is subjected to bending and the resonance frequency is utilized for the crack growth measurement. The described tests have been conducted on E 36 Z steel specimens with various variation laws of the stress intensity factor as a function of crack length. The test results show the influence of the ΔK gradient $d(\Delta K)/da$ on the crack growth rate and on the ΔK threshold.

KEY WORDS

Fatigue - crack propagation - threshold - E 36 Z steel - process control.

INTRODUCTION

The bidirectional coupling of a test machine of fatigue crack growth to a calculator and the use of an almost continuous means of measurement of the crack length allow to improve the test conditions at low crack growth rate and particularly to determine the crack growth threshold. The crack length estimate is affected by noise and shift; the growth rate estimate results from the derivation of this disturbed signal. Authors have endeavoured to solve these problems by using a simple test equipment including an electromagnetic resonant bending machine.

DESCRIPTION

The specimen, held vertically, is inserted by its lower end into a socket equipped with sensors allowing the bending moment measurement (Fig. 1). At the upper end, a horizontal arm is set up; it is subjected, parallely to the specimen axis, to the action of a mobile coil and of a spring and of a mass.

The control circuits of the machine include a self oscillation loop, a feedback control of the moment amplitude ΔM and a feedback control of the mean value of moment Mm (Fig. 2). This mean value is adjusted on the machine by means of a motorized screw. The phase shifter of the self oscillation loop is specified so that the operating frequency corresponds to the first resonance frequency of the system which depends upon the stiffness characteristic of the specimen during crack growth. For a determined material and a load ratio R, the operating period T depends only on the crack length a in a first approximation. A modelisation of the stiffness characteristic, together with an experimental calibration, allow the determination of law a(T) and if necessary the determination of the corrective terms due to secondary parameters among which the moment amplitude and the crack front curvature are the major parameters [1]. These secondary parameters are negligible in the crack growth rate estimate if they vary slowly and continuously.

The machine is connected to an HP 9815 calculator whose capacity and speed are sufficient for the achieved tests. Through DA converters, the machine receives from the calculator orders of the mean moment Mm and of the moment amplitude ΔM. Through a periodmeter and a counter, the machine yields back to the calculator the period T and the number of cycles N. The periodmeter operates by 100 cycles samples to limit the measurement noise.

MEASUREMENT UTILIZATION

Crack length estimate

The a(T) estimate is given by an approximation polynome of the calibration law. The noise on this estimate can be characterized by the peak to peak variation ε_a of the a estimate measured for 100 successive samples. The shift on this estimate can be characterized by the peak to peak variation δ_a on the mean value calculated on 100 successive samples. A stopped growth test of 48 hours gives the results:

$$\varepsilon_a = 4\text{x}10^{-3}\text{mm} \qquad \delta_a = 70\text{x}10^{-3}\text{mm}$$

These results can be compared to the one obtained by potential measurement [2]. Note that these results are obtained with a small size specimen.

In the case of close loop tests when ΔK must be a determined function of the length ΔK(a), the parasitic noise ε_M and the shift δ_M on the moment order ΔM must be also quantitatively evaluated. This ΔM order is calculated from the a estimate and from the imposed law ΔK(a) by the classical law K(M,a) [3]. It is also necessary to take into account the systematic error ρ_M due to the ρ_a error on the calibration law. The importance of these error terms is caused by the possible overload or underload effect altering the test particularly for a threshold measurement with a continuous ΔK decreasing. For example, in a programmed test designed to reach the threshold in the vicinity of a = 13.5 mm with a decreasing slope d(ΔK)/da = 1.5 MPa$\sqrt{m}$/mm, we yield when ΔK = 8 MPa$\sqrt{m}$:

$$\frac{1}{M}\varepsilon_M = \frac{1}{M}\frac{\partial M}{\partial a}\varepsilon_a = 1.4\text{x}10^{-3} \qquad \frac{1}{M}\delta_M = \frac{1}{M}\frac{\partial M}{\partial a}\delta_a = 2.5\text{x}10^{-2} \qquad \frac{1}{M}\rho_M = \frac{1}{M}\frac{\partial M}{\partial a}\rho_a = 3.6\text{x}10^{-2}$$

ε_M is negligible. The ρ_a effect can be corrected after the test as seen later. Among the error causes due to the machine and to the measurement means only δ_M can lead to an uncertainty on the yielded threshold value, uncertainty which can be evaluated.

Estimate of crack growth rate da/dN

Two estimate modes have been experimented:

Linear regression on a set of ΔN samples.

Let: $\quad a \text{ estimate} = b_o + b_1\frac{\Delta N}{2}$

where b_o and b_1 are linear regression coefficients in the least square sense, and are calculated on a set of ΔN data points (a_i, N_i). The da/dN estimate is da/dN = b_1. Calculation gives also the coefficient of determination r^2.

The number of samples necessary to obtain a minimum given coefficient of determination is related to ε_a and δ_a. It increases asymptotically when the crack growth rate decreases. Its variation should then be programmed during test. Figure 4 shows the minimum sample number necessary to get a given coefficient of determination versus crack growth rate da/dN. This diagram characterizes the rate measurement means. Slow shift is still the major responsible factor of the estimate degradation at low rate.

Finite difference on the filtered estimate of crack length a'_N. A rate estimate $(a'_{N+\Delta N} - a'_N)/\Delta N$ is taken. A first order numerical filter gives sufficient smoothing:

$$a'_{j+1} = \frac{\tau-1}{\tau}a'_j + \frac{1}{\tau}a_{j+1}$$

where a_{j+1} is the (j+1) rank length estimate, a'_j the length filtered estimate, and τ the filter constant. The choice of the τ constant and of the ΔN step results from a compromise between filtering quality and tracking error.

These two rate estimate means give neighbouring results.

PERFORMED TESTING

The specimen dimensions are given figure 3. Specimens have been longitudinally taken from a E 36 Z 15 mm thick steel plate. In the central part, the specimen is subjected to plane bending with a null shear force and with a non null but negligible normal force. Tests, performed with a load ratio R = 0.25 taking into account K calculation validity limits, lead to measurements which can be utilized between the length values a = 5 mm (frequency = 65 Hz) and a = 15 mm (60 Hz). The specimen dimensions result in a plane strain state in the central part of the specimen.

Threshold testing

A. Saxena [5] introduces a test procedure of continuous decrease and he suggests in his conclusion to perform tests with different d(ΔK)/da access slopes at the threshold. Consequently several ΔK decrease laws have been used, all of them programmed in order to reach the threshold at almost the same length a = 14 mm, with slopes lying between 0.6 and 20 MPa$\sqrt{m}$/mm. These laws are presented in figure 5 with the corresponding variation of the r_y radius of the monotonous plastic area calculated with plane strain hypothesis [4] .

Curve I is in accordance with the decreasing mode proposed by Saxena for quite difference test conditions.

Curve II represents a parabolic law. It results from a moment stepping procedure smoothing; this procedure is defined by

$$K_j/K_{j-1} = 0.8$$

$$a_{j+1} - a_j = (3/\pi)(K_j/\sigma_y)^2$$

where K_j and a_j are respectively the K maximum value and the crack length in the end of j rank step [6] . Figure 7 shows the obtained decrease law. This law gives a constant gradient dr_y/da. Curves III, IV, V and VII represent parabolic laws obtained by modifying the h parameter which characterizes the decrease slope.

Law VI, arbitrarily rectilinear, corresponds to an intermediate decrease mode. Curve VIII which is linear to $\Delta K = 9$ presents later an exponential decrease mode close to the one of curve I.

Figure 6 represents the [da/dN](ΔK) variations obtained according to figure 5 procedures each specimen on both figures being attributed the same Roman numeral and the same symbol. Rate estimates inferior to 3×10^{-8} mm/cycle have been considered as insignificant and have no been plotted. Testing was stopped when a drop of the coefficient of determination r^2 for an $N = 2\times10^6$ sampling occured. This drop takes place between 10^{-7} and 10^{-8} mm/cycle.

The ΔK threshold value obtained is corrected after testing to compensate the error due to the neglected parameters in the calibration law a(T). To get this correction, the ΔM amplitude at the end of testing must be noted, the crack length after sawing the ligament must be measured accurately and the corresponding ΔK must be calculated. The order of magnitude of the ΔK threshold value is not contradictory to the one currently given in technical litterature.

Although the approach slopes vary in a ratio of 30 and although the steepest of the slopes are inacceptable considering the radius of monotonous plastic area, the differences we get are not significant. They could be explained by the difficulty of taking into account the crack front curvature.

Reversibility tests of the law [da/dN](ΔK)

In our tests, we take a decreasing slope of $\Delta K(a)$ chosen arbitrarily rectilinear, continuously followed by an increasing slope. Figure 9 shows the the used $\Delta K(a)$ laws. The approach slope is varied as well as the ΔK value corresponding to a slope change. Results are given in figure 8 . In any case, to the slope change corresponds a rate increase which appears on the diagram as a discontinuity. Furthermore the coefficient of determination r^2 increases noticeably after the slope change.

CONCLUSION

Crack growth tests with ΔK continuous variation and particularly threshold tests can be made on little size test pieces and the machine which is described in this paper is a simplified test means in comparison with equipements described formerly [5, 7] .

In our test conditions, ΔK variation rate has no influence upon the obtained threshold. Comparing with the duration of the continuous decrease procedure proposed by A. Saxena, we think it possible, in conditions which have to be determined and after verification with others materials, to reduce even more the test duration for the threshold determination.

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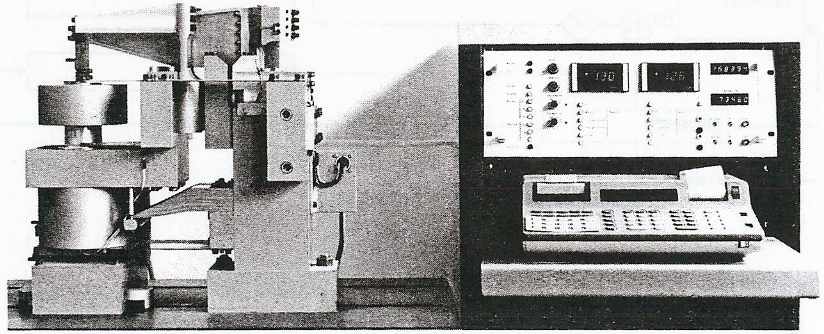
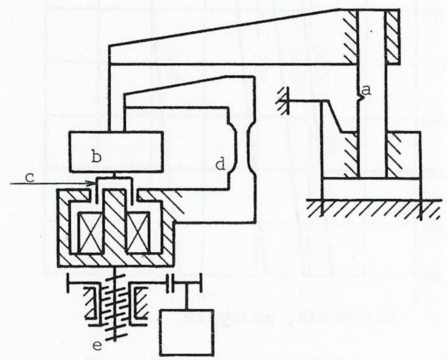




(a) Specimen
(b) Mass
(c) Coil
(d) Spring
(e) Screw

Fig. 1. Crack growth bending machine

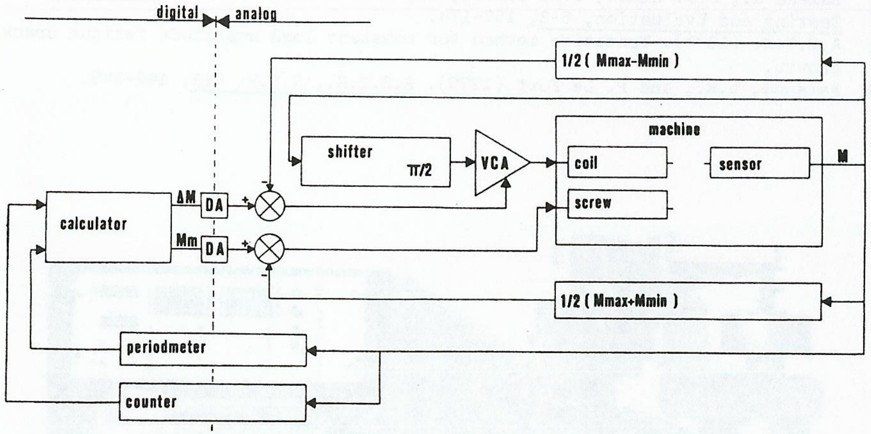


Fig. 2. Control circuits.

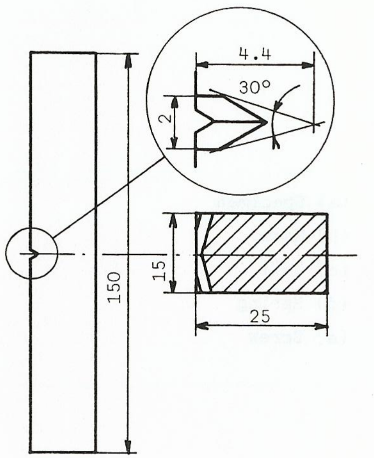


Fig. 3. Specimen dimensions, mm.

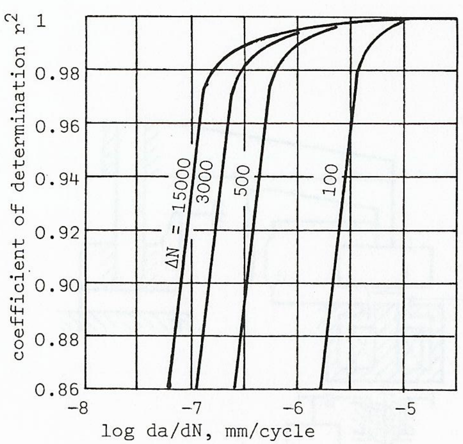


Fig. 4. Minimum sample number ΔN

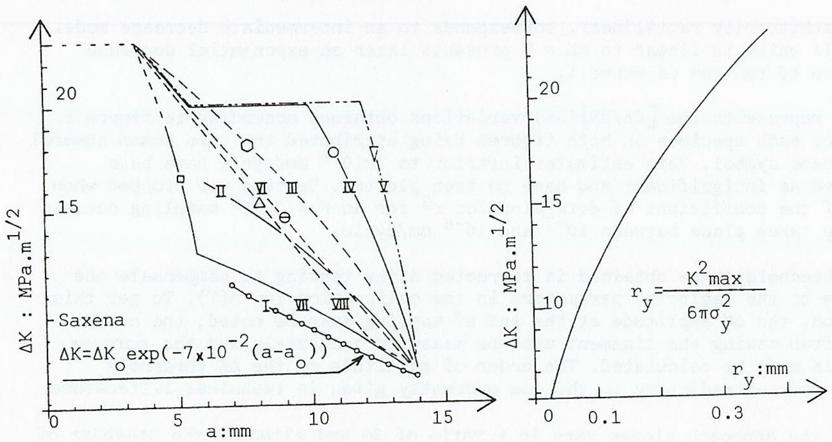


Fig. 5. $\Delta K(a)$ decrease law .

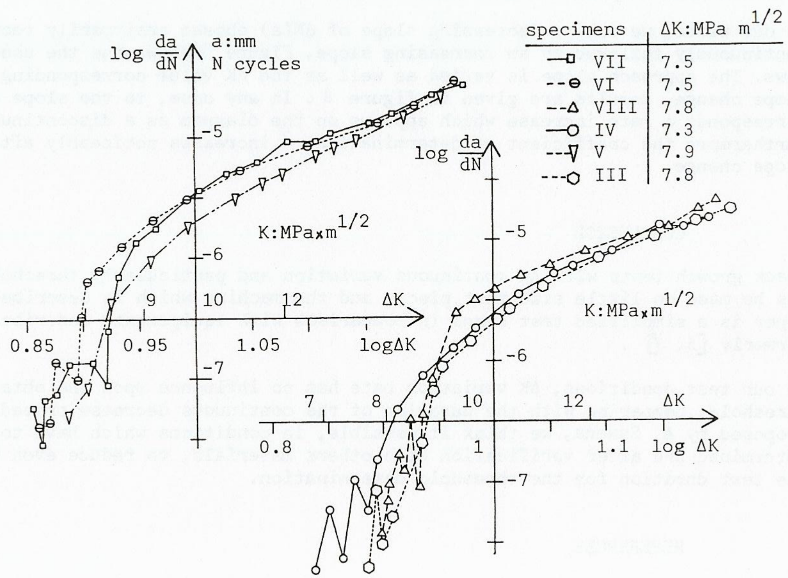
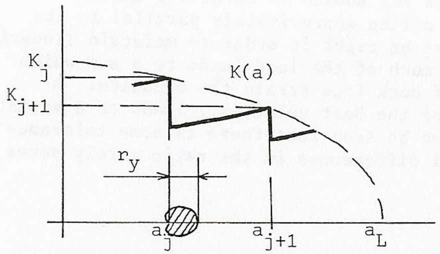


Fig. 6. Threshold tests.
The table shows ΔK threshold values.



$$a_{j+1} = a_j + bK_j^2 \quad \text{where } b = 3/\pi\sigma_y^2$$

$$a_n = a_o + bK_o^2 \sum_{1}^{n} c^{2n-2}$$

$$K_n = c^n K_o \quad \text{where } c = 0.8$$

$$\Delta K(a) = h(a_L - a)^{1/2}$$

$$\text{where } h = (1-R)\sigma_y \sqrt{0.12\,\pi}$$

Fig. 7.. Parabolic decrease law .

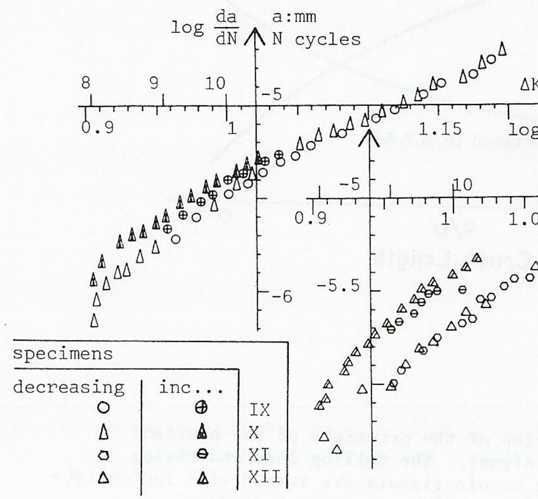


Fig. 8. Reversibility test results

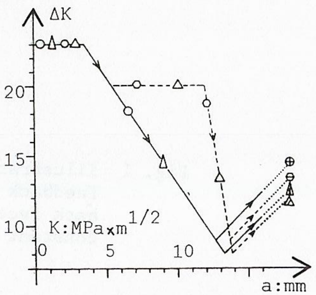


Fig.9. ΔK(a) laws of reversibility tests