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by

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FATIGUE CRACK PROPAGATION IN THIN SHEETS OF L73 UNDER CONSTANT STRAIN AMPLITUDE

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SUMMARY

This Report analyses data covering the growth of a crack in small thin sheets of aluminium alloy (L73) tested under constant strain amplitude. The results confirm that the crack propagation behaviour was determined by the stress intensity factor range ΔK, the critical stress intensity factor for fracture K_c, and the stress ratio R as in the more familiar case of a crack growing under constant load amplitude. In the constant strain case allowance must be made, in calculating the stress, for the fall off in load due to the diminishing axial stiffness of the specimen as the crack length increases.

A formula for calculating the axial stiffness of a centrally cracked sheet is derived in the Appendix.

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* Replaces RAE Technical Report 74042 - ARC 35433.

CONTENTS

Neg Nos. C11025-C11026

1 INTRODUCTION

Most of the theory and data so far published on the growth of fatigue cracks describe their behaviour under load controlled conditions. However the condition met with by a cracked element forming part of a complex structure will usually be somewhere between the condition described as load controlled and that described as strain controlled.

An example of this is provided by the skin of an aircraft pressure cabin. Suppose the skin suffers damage which starts a fatigue crack midway between two frames; initially, the skin at the site of damage is largely unconstrained by the frames and the crack grows in a load controlled condition. However, as the crack tip nears a frame, extension of the skin will be discouraged by the much greater stiffness of the frame and the crack will grow under increasingly strain controlled conditions. Another important example of loading in the strain controlled condition occurs in elements subjected to varying temperature whilst their ends are restrained.

In order to increase our knowledge of crack behaviour under constant strain amplitude it was decided to analyse data covering crack growth in a thin sheet specimen of L73 material which were amassed during an experiment to test the validity of using a cracked sheet to monitor fatigue damage[1]. The specimen during the test was mounted on an aluminium alloy spar in a manner such that the mean strain and the range of the alternating strain, experienced by the specimen, were held constant throughout the test.

The analysis shows that, provided allowance is made for the fall off in the load due to the diminishing stiffness of the specimen as the crack grows, the behaviour of the crack follows the same propagation law as governs a crack growing under constant load amplitude.

In the Appendix a formula is derived for the axial stiffness of a thin sheet with a central transverse crack.

2 EXPERIMENTAL ARRANGEMENT

2.1 The specimen

To appreciate the reasons for the configuration and method of testing of the specimen, it is important to realize that its design was dictated by the requirements of an experiment on the Fatigue Damage Indicator as already mentioned in the Introduction. A description of that experiment is the subject of another Report[1].

The specimens were thin sheet coupons in clad aluminium alloy, BS 2L73, whose nominal composition and specification are given in Table 1. The specimens were nominally identical; their dimensions are shown in Fig.1. A transverse slit 7.6mm long was made by spark erosion in the centre of the specimen and was increased in length by fatigue cracking to 12.7 mm before testing commenced. This pre-test cracking was done for all the specimens in a Haigh fatigue machine at a gross stress of 48.3 ± 34.5 MN/m^2; the stress was kept low to avoid leaving any significant residual stresses at the crack tips.

2.2 Mounting of specimen for testing

The specimen was attached to a spar of rectangular cross section as shown in Figs.1 and 2. It was intended that the attachment should ensure that the strain history in the specimen would be the same as occurred in the spar. For attachment purposes, the specimen was fitted with steel end pieces with terminal faces normal to the longitudinal axis. The connection was effected by bonding the ends of the specimen into slots in the end pieces by Araldite (Resin AV100 and Hardener HV100) and adding two 4.8mm diameter L69 rivets at each end to reinforce the bonding.

The spar was made from aluminium alloy, BS 2L65,whose nominal composition and specification are given in Table 2. The spar had attached to it brackets with projecting faces which were designed to receive the terminal faces of the end pieces of the specimen. The faces of the end pieces butted against those of the brackets and were held in position by axial screws. The manufacture of these items was closely controlled by making them in matching jigs.

The brackets were attached to the spar by bonding with an epoxy based adhesive, designated FM1000 by the manufacturers Cyanmid International, and then pinning with two stainless steel taper pins. Finally, to prevent rotation by flexure of the projecting limbs of the brackets which supported the specimen, steel clamping bars were fitted over the projections as seen in Fig.3.

Before fitting a specimen a small tensile load was applied to the spar so that the specimen could be eased on by hand. It should be noted that any residual strain in the specimen due to bad fit would affect the mean strain only and not the alternating strain. A dummy specimen was mounted on the opposite face of the spar to the operating specimen to avoid introducing bending stresses in the spar. The dummy was identical to a real specimen except that it had no central slit. No crack appeared in any of the dummy specimens throughout the tests and they played no part in the experiment beyond that mentioned above.

2.3 Method of measuring the strain in the specimen

The extension of the specimen when load was applied to the spar was measured by dial gauges, which were graduated in 0.0001 inch divisions; they were calibrated at the start of the experiment and found to conform to British Standard 2795: 1957. The gauges were attached to the arms of a rigid mounting 'tree' which was clamped tightly to the spar as shown in Figs.3 and 4.

The dial gauges were fitted so as to read axial movements of the inner faces of the end pieces both above and below the specimen surfaces, near each corner of the specimen - making eight measuring points per specimen. The axial extension was taken to be the sum of the means of the four measurements taken at each end.

It is worth mentioning here that two other methods were tried for measuring the extension, an inductive transducer and a strain-gauged arch made from a spring leaf which spanned the specimen between the end pieces. Neither, however, proved as trouble-free or consistent as the dial gauge method. Strain gauges on the specimen itself were not used because of the difficulty of calculating the total extension from discrete measurements in a strain field upset by the presence of a crack.

Before the fatigue testing of each specimen began loads corresponding to the fatigue loading cycle were applied statically to the spar and the resulting extensions of the specimen were measured. On each occasion the load was removed and the operation repeated a second time to measure the consistency of the method.

3 TESTS

3.1 The loads applied to the spar

Knowledge of the magnitude of the loads which were applied to the spar is not of prime importance for understanding the work recorded in this Report which is concerned with the behaviour of the crack in the specimen; the strains experienced by the specimen were measured independently as described in section 2.3. However, mention is made here of the loads on the spar to complete the picture of the experimental system, to show where the strains applied to the specimen originated and because the frequency and form of the strain history were the same for both specimen and spar.

The alternating load applied to the spar in all the tests was constant amplitude sinusoidal at a frequency of approximately 15 Hz. Four stress levels were applied namely ±15.3, ±24.5, ±36.8 and ±49.0 MN/m^2, each one superimposed on a mean stress of 85.8 MN/m^2. The magnitude of the load was measured and controlled by the standard equipment supplied with the fatigue machine which was a Schenck, Type PB 10/60.

3.2 The strains experienced by the specimen

The test strains experienced by each specimen are given in Table 3. The specimens have been batched in four groups, each group having been tested at a different nominal alternating strain. The difference between the strains as measured on the two static loadings applied to each specimen before fatigue testing, as mentioned in section 2.3, was always less than 0.00003.

The value, used in the calculations which follow in the next section, for the alternating strain in each batch was the average of the measured strains in the batch; the actual values varied very little from the average as can be seen in Table 3. The average values of the strains in the four batches were ±0.00023, ±0.00037, ±0.00051 and ±0.00067. The mean strain on all the specimens was nominally the same; for convenience a single average value, namely 0.00122, was used throughout the calculations.

Four tests, supplementary to those listed in Table 3, were done to check that the strain transmitted to the specimen did not change during fatigue cycling due to slippage at the joints. Three of the supplementary tests, designated A, B and C in Table 4, were done at different alternating strains using new specimens. The strain response of specimens A and B was unchanged by the fatigue cycling, but the response of specimen C dropped by about 8%. To investigate the unexpected fall off in strain of specimen C, a specimen was taken from batch 4, which had been fatigue tested at the same nominal strain as specimen C and the strain under static load was redetermined. The result is recorded in Table 4 and shows no difference in the strain measurements before and after fatigue cycling. It was assumed therefore that the fall off in strain in specimen C was an exception to the normal behaviour.

3.3 Measurement of crack growth

The length of the crack was measured at the beginning and at frequent intervals during the fatigue test by means of a travelling microscope mounted above the specimen. The appearance of the ends of the crack under the microscope was more clearly defined during dynamic loading than under static loading and all crack measurements were made without interruption of the fatigue test. At the time of each crack measurement, the number of load cycles was recorded. The test life of the specimen covered the period to grow the crack from 12.7 mm to 25.4 mm.

4 RESULTS

The results of the tests are shown in Fig.5 in which the total crack length (2a) is plotted against the number of cycles. An ICL 1907 computer was used to calculate the best-fit second degree polynominal curve through the data points for each specimen and to differentiate it to get the crack rate at each point. The computed rates have been plotted against the crack lengths (2a) in Fig.6.

4.1 Discussion of results and comparison with theory

The results were checked against a formula for crack propagation postulated by Forman, Kearney and Engle[2] which has shown excellent agreement with a wide range of test data. The formula is

$$\frac{d(2a)}{dN} = \frac{C(\Delta K)^n}{(1 - R)K_c - \Delta K}$$

in which R = ratio of minimum σ_∞ to maximum σ_∞ in a cycle

C = material constant

n = a numerical exponent (= 3 for the well-known aluminium alloys 7075-T6 and 2024-T3, Ref.2)

K_c = critical stress intensity factor for fracture of the material

ΔK = stress intensity factor range

where $\Delta K = \Delta\sigma_\infty \sqrt{\pi a}\beta$

and $\Delta\sigma_\infty$ = axial stress range away from the crack

a = half crack length

β = sheet finite-width correction factor

$$= \left[1 - \left(\frac{2a}{B}\right)^2\right]^{-\frac{1}{2}}$$ according to Dixon[3]

where B = width of sheet.

It was thought that the only difference between the effect of testing under constant load amplitude and constant strain amplitude should be that in the latter case the load falls off as the crack grows, due to the diminishing axial stiffness of the sheet. A formula for calculating a stiffness factor α , defined as the ratio of the axial stiffness of a centrally cracked sheet to that of an uncracked sheet has been derived and is given in the Appendix. Values of α and also the width correction factor β have been plotted against crack length in Fig.7. The factor α was used to calculate $\Delta\sigma_\infty$ from the equation

$$\Delta\sigma_\infty = (\Delta\varepsilon_\infty)E\alpha$$

where $\Delta\varepsilon_\infty$ = axial strain range away from the crack
E = Young's modulus
α = stiffness factor.

To determine the constants C and n applicable to this experiment, $\frac{d(2a)}{dN}\left[(1 - R)K_c - \Delta K\right]$ was plotted against ΔK on log-log scales in Fig.8. Four values of the expressions, corresponding to the four alternating strain conditions mentioned in section 3.2, have been plotted for each of the following crack lengths, 12.7, 14.0, 16.0, 18.0, 20.0, 22.0, 24.0 and 25.4 mm. The values used in the expression for $\frac{d(2a)}{dN}$ have been taken as the geometric means of each batch of curves plotted in Fig.6; the value of K_c , the critical stress intensity factor, applicable to L73 material (80 $MN/m^{3/2}$) has been taken from Ref.4. The points are seen to lie on a straight line whose equation is $\frac{d(2a)}{dN}\left[(1 - R)K_c - \Delta K\right] = 10^{-8}(\Delta K)^3$, giving values of 10^{-8} and 3 for C and n respectively. Finally, values of $\frac{d(2a)}{dN}$ have been calculated from this equation and plotted in Fig.6 superimposed on the results computed from the test data; the theoretical results lie within the scatter bands of the test results at all four strain levels.

It is worth noting that the effect of including the stiffness correction factor is quite significant, being a reduction in crack rate by a factor of about 2 at the longest crack length.

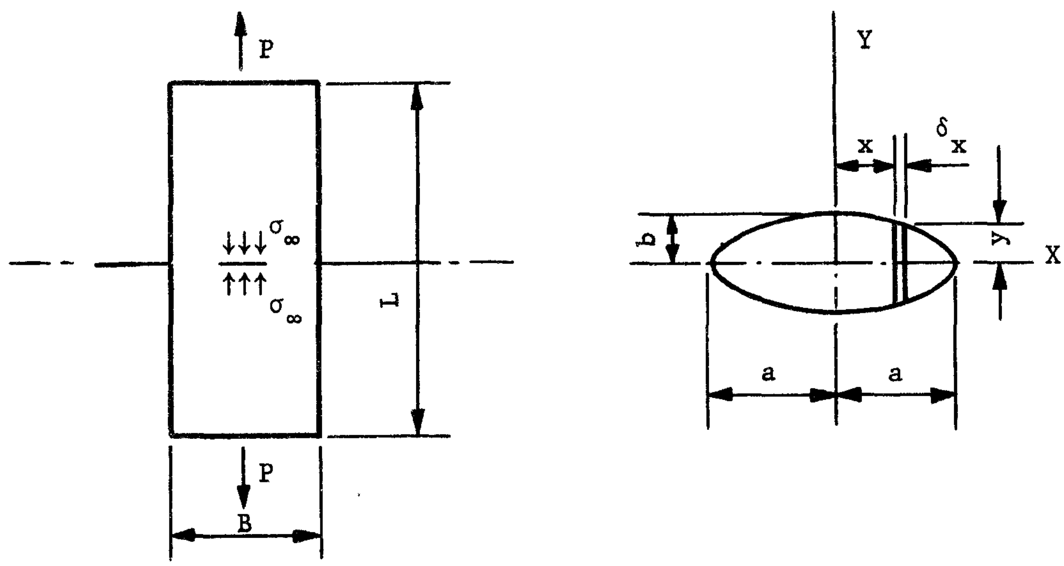
5 CONCLUDING REMARKS

The result of crack propagation tests on L73 material shows that the behaviour of a fatigue crack growing under constant strain amplitude is a function of the stress intensity factor range ΔK , the critical stress intensity factor for fracture K_c , and the stress ratio R as in the case of a crack growing under constant load amplitude. A general law which successfully predicts behaviour in the latter case can be used in the former case also, allowance being made for the fall off in load due to the diminishing axial stiffness as the crack length increases.

The practical significance of this result is that calculated rates of propagation of cracks in many structures will be excessive unless allowance is made for the reduction in load due to the fall-off in stiffness as the crack length increases. It follows that decisions based on crack rates which have been calculated without taking into account the stiffness factor may result in the scheduling of inspections at unnecessarily short intervals.

Appendix

THE AXIAL STIFFNESS OF A THIN SHEET WITH A CENTRAL TRANSVERSE CRACK



Consider the change in the strain energy of a thin sheet associated with the opening of a crack. Firstly, imagine the sheet under a static tensile load P , with a row of clamps positioned along the crack, keeping the crack closed. The load in each clamp is

$$\sigma_\infty \delta A$$

where σ_∞ is the gross stress in the Y direction away from the influence of the crack, and δA is the area of the clamp face $= (\delta x)t$

where t is the thickness of the sheet, assumed uniform, and is equal to the depth of the clamp face.

Secondly, imagine the clamps being released until the load in each one is zero, that is until the crack opens to its unrestrained shape. The work done by the movement of each clamp

$$= \tfrac{1}{2}\left[\sigma_\infty(\delta A)\right]2y$$

$$= \tfrac{1}{2}\left[\sigma_\infty t\delta x\right]2y$$

where y is half the crack opening.

Work done by all the clamps = release of strain energy associated with the opening of the crack

$$= U = \frac{\sigma_\infty t}{2}\sum_{x=-a}^{x=a} 2y\delta x$$

$$= \frac{\sigma_\infty t}{2}\ \text{(area of crack opening)} \quad .$$

Assume the opened area of the crack is an ellipse[5], then

$$U = \frac{\sigma_\infty t}{2}(\pi ab)$$

where b is the value of y at the centre of the crack opening.

It has been shown[6] for a thin sheet of infinite width that

$$b = \frac{2\sigma_\infty a}{E}$$

where E = Young's modulus.

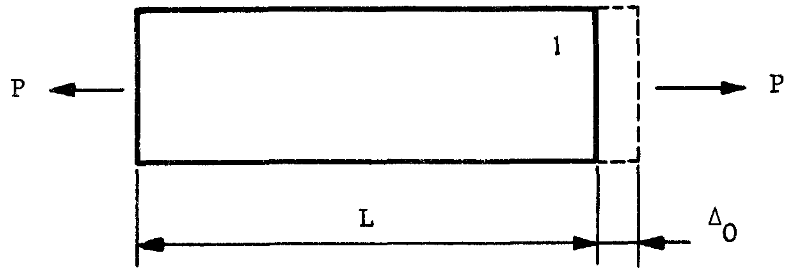
In the case of a sheet of finite width B, it is necessary to apply a correction factor to b, for which an equation will be given later. For now, this correction will be expressed as $f\left(\frac{2a}{B}\right)$ giving

$$b = \frac{2\sigma_\infty a}{E}\left[f\left(\frac{2a}{B}\right)\right]$$

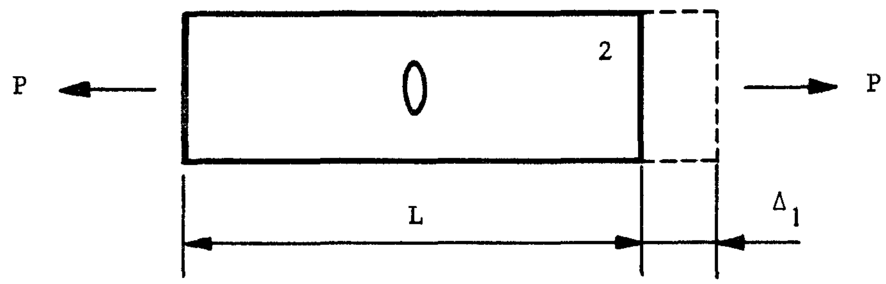
and

$$U = \frac{\pi\sigma_\infty^2 a^2 t}{E}\left[f\left(\frac{2a}{B}\right)\right] \quad .$$

Now consider the external work associated with the opening of the crack. Firstly, suppose that the sheet is uncracked and axially strained by load P



then, the external work done due to load $P = \frac{1}{2}P\Delta_0$ where Δ_0 is the extension of the uncracked sheet. Secondly, suppose that the sheet contains a crack which is free to open, and that it is strained by the same load, P



then, the external work done due to load $P = \frac{1}{2}P\Delta_1$ where Δ_1 is the extension of the sheet containing a crack. Therefore the external work associated with the opening of the crack is

$$\tfrac{1}{2}P(\Delta_1 - \Delta_0) \quad .$$

Equating the external work with the corresponding release of internal energy, U, gives

$$\tfrac{1}{2}P(\Delta_1 - \Delta_0) = \frac{\pi\sigma_\infty^2 a^2 t}{E}\left[f\left(\frac{2a}{B}\right)\right] \quad .$$

Let S_0 = the stiffness (i.e. the load to cause unit extension) of the uncracked sheet

and S_1 = the stiffness of the sheet with a crack.

Now,

$$\Delta_0 = \frac{P}{S_0}, \quad \Delta_1 = \frac{P}{S_1}, \quad P = \sigma_\infty Bt \quad \text{and} \quad S_0 = \frac{BtE}{L}$$

where L = length of unloaded sheet.

By substitution is obtained

$$\tfrac{1}{2}P^2\left(\frac{1}{S_1} - \frac{1}{S_0}\right) = \frac{\pi\sigma_\infty^2 a^2 t}{E}\left[f\left(\frac{2a}{B}\right)\right]$$

$$\tfrac{1}{2}\sigma_\infty^2 B^2 t^2\left(\frac{1}{S_1} - \frac{L}{BtE}\right) = \frac{\pi\sigma_\infty^2 a^2 t\left[f\left(\frac{2a}{B}\right)\right]}{E}$$

$$\frac{1}{S_1} = \frac{2\pi a^2\left[f\left(\frac{2a}{B}\right)\right]}{B^2 tE} + \frac{L}{BtE}$$

$$S_1 = \frac{B^2 tE}{2\pi a^2\left[f\left(\frac{2a}{B}\right)\right] + BL}$$

$$\frac{S_1}{S_0} = \frac{B^2 tE}{2\pi a^2\left[f\left(\frac{2a}{B}\right)\right] + BL}\,\frac{L}{BtE}$$

$$= \frac{BL}{2\pi a^2\left[f\left(\frac{2a}{B}\right)\right] + BL}$$

$$= \frac{1}{1 + \dfrac{2\pi a^2}{BL}\left[f\left(\frac{2a}{B}\right)\right]}\ .$$

To find a solution for $f\left(\frac{2a}{B}\right)$, the effect of finite width of the sheet, reference is made to Frost and Dugdale[7] and Dixon[3]. Frost and Dugdale carried out experiments on sheets containing a central slit. It was shown[3] that the expression $\left[1 - \left(\frac{2a}{B}\right)^2\right]^{-\frac{1}{2}}$ for defining the effect of finite width on the stress concentration at the tip of the slit was approximately valid as a correction for the effect of finite width on the opening at the centre of the slit. Substituting this solution for $f\left(\frac{2a}{B}\right)$ in the equation of $\frac{S_1}{S_0}$, gives

$$\frac{1}{1 + \frac{2\pi a^2}{BL}\left[1 - \left(\frac{2a}{B}\right)^2\right]^{-\frac{1}{2}}}$$

equals α, the ratio of the axial stiffness of a sheet with a central transverse crack to that of an uncracked sheet.

Table 1

SPECIFICATION BS 2L73 CLAD ALUMINIUM ALLOY SHEET, SOLUTION TREATED AND PRECIPITATION TREATED

Nominal chemical composition:

Element	Per cent by weight	
	Min	Max
Copper	3.8	4.8
Magnesium	0.55	0.85
Silicon	0.6	0.90
Iron	-	1.0
Manganese	0.4	1.2
Nickel	-	0.2
Zinc	-	0.2
Lead	-	0.05
Tin	-	0.05
Titanium and/or Chromium	-	0.3
Aluminium	-	The remainder

Minimum tensile properties:

0.1% proof stress	324 MN/m^2
Ultimate tensile strength	417 MN/m^2
Elongation	8%
E	72300 MN/m^2

Table 2

SPECIFICATION BS 2L65 ALUMINIUM ALLOY, SOLUTION TREATED AND PRECIPITATION TREATED

Nominal chemical composition:

Element	Per cent by weight	
	Min	Max
Copper	3.8	4.8
Magnesium	0.40	0.85
Silicon	0.6	0.90
Iron	-	1.0
Manganese	0.4	1.2
Nickel	-	0.2
Zinc	-	0.2
Lead	-	0.05
Tin	-	0.05
Titanium and/or Chromium	-	0.3
Aluminium	-	The remainder

Minimum tensile properties:

0.1% proof stress	402 MN/m^2
Ultimate tensile stress	463 MN/m^2
Elongation	8%
E	72300 MN/m^2

Table 3

TEST DATA

Specimen No.	Initial length of crack (mm)	* Measured extension of specimen Run 1 (inches)	* Measured extension of specimen Run 2 (inches)	Strain = (average measured extension) ÷ (nominal unstrained length)	Cycles to grow crack from initial length to 25.4 mm
Batch 1					
1	12.42	0.00502 ± 0.00093	0.00493 ± 0.00091	0.00124 ± 0.00023	186700
2	12.77	0.00492 ± 0.00090	0.00490 ± 0.00091	0.00123 ± 0.00023	159300
3	12.52	0.00497 ± 0.00097	0.00496 ± 0.00092	0.00124 ± 0.00024	159900
4	12.80	0.00497 ± 0.00089	0.00496 ± 0.00088	0.00124 ± 0.00022	181300
5	12.32	0.00481 ± 0.00092	0.00477 ± 0.00092	0.00120 ± 0.00023	172400
6	12.56	0.00503 ± 0.00095	0.00503 ± 0.00095	0.00126 ± 0.00024	172400
7	12.50	0.00499 ± 0.00098	0.00494 ± 0.00096	0.00124 ± 0.00024	156900
8	12.73	0.00466 ± 0.00085	0.00462 ± 0.00087	0.00116 ± 0.00022	174100
9	12.84	0.00526 ± 0.00097	0.00518 ± 0.00092	0.00131 ± 0.00024	208300
10	12.63	0.00491 ± 0.00089	0.00489 ± 0.00090	0.00123 ± 0.00023	150100
11	12.55	0.00473 ± 0.00086	0.00473 ± 0.00085	0.00119 ± 0.00022	124200
12	12.58	0.00492 ± 0.00088	0.00489 ± 0.00084	0.00123 ± 0.00022	140300
13	12.52	0.00502 ± 0.00095	0.00500 ± 0.00094	0.00125 ± 0.00024	177000
14	12.69	0.00500 ± 0.00093	0.00500 ± 0.00093	0.00125 ± 0.00023	154900
15	12.75	0.00531 ± 0.00098	0.00530 ± 0.00098	0.00133 ± 0.00024	209400
16	12.41	0.00502 ± 0.00090	0.00498 ± 0.00090	0.00125 ± 0.00023	168900
Batch 2					
1	12.33	0.00524 ± 0.00159	0.00521 ± 0.00154	0.00131 ± 0.00039	62200
2	12.34	0.00514 ± 0.00146	0.00517 ± 0.00145	0.00129 ± 0.00037	83500
3	12.78	0.00528 ± 0.00154	0.00524 ± 0.00154	0.00132 ± 0.00039	54800
4	12.66	0.00528 ± 0.00149	0.00521 ± 0.00151	0.00131 ± 0.00038	55400
5	12.66	0.00497 ± 0.00142	0.00490 ± 0.00139	0.00124 ± 0.00035	54000
6	12.41	0.00545 ± 0.00157	0.00549 ± 0.00156	0.00137 ± 0.00039	68300
7	12.98	0.00507 ± 0.00145	0.00508 ± 0.00146	0.00127 ± 0.00037	60900
8	12.59	0.00480 ± 0.00141	0.00482 ± 0.00141	0.00120 ± 0.00035	64300
9	12.42	0.00523 ± 0.00153	0.00523 ± 0.00153	0.00131 ± 0.00038	66100
Batch 3					
1	12.50	0.00470 ± 0.00206	0.00469 ± 0.00206	0.00118 ± 0.00052	35700
2	12.52	0.00449 ± 0.00203	0.00446 ± 0.00201	0.00112 ± 0.00051	20200
3	12.51	0.00483 ± 0.00210	0.00472 ± 0.00213	0.00119 ± 0.00053	24300
4	12.33	0.00453 ± 0.00202	0.00445 ± 0.00201	0.00112 ± 0.00051	23600
5	12.74	0.00468 ± 0.00207	0.00467 ± 0.00205	0.00117 ± 0.00052	28900
6	12.44	0.00464 ± 0.00200	0.00455 ± 0.00200	0.00115 ± 0.00050	29900
Batch 4					
1	12.55	0.00475 ± 0.00275	0.00484 ± 0.00276	0.00120 ± 0.00069	10500
2	12.49	0.00491 ± 0.00273	0.00499 ± 0.00273	0.00124 ± 0.00068	15400
3	12.51	0.00492 ± 0.00273	0.00501 ± 0.00274	0.00124 ± 0.00069	14600
4	12.80	0.00466 ± 0.00260	0.00469 ± 0.00259	0.00117 ± 0.00065	18400
5†	12.26	0.00460 ± 0.00251	0.00457 ± 0.00255	0.00115 ± 0.00063	19600

* The inch unit of the readings in Columns 3 and 4 was that used in the original measurements (1 inch = 25.4 mm)
† This specimen was subsequently statically strained after fatigue testing (see Table 4)

Table 4

SUPPLEMENTARY TEST DATA

Specimen	* Measured extension before fatigue testing Run 1 (inches)	* Measured extension before fatigue testing Run 2 (inches)	Strain = (average measured extension) ÷ (nominal unstrained length)	Number of strain cycles	* Measured extension after fatigue testing Run 1 (inches)	* Measured extension after fatigue testing Run 2 (inches)	Strain = (average measured extension) ÷ (nominal unstrained length)
A	0.00454 ± 0.00081	0.00451 ± 0.00084	0.00113 ± 0.00021	168000	0.00454 ± 0.00083	0.00448 ± 0.00082	0.00113 ± 0.00021
B	0.00484 ± 0.00144	0.00480 ± 0.00146	0.00120 ± 0.00036	63000	0.00478 ± 0.00144	0.00478 ± 0.00146	0.00119 ± 0.00036
C	0.00486 ± 0.00281	0.00481 ± 0.00281	0.00121 ± 0.00070	17000	0.00448 ± 0.00259	0.00448 ± 0.00256	0.00112 ± 0.00064
No.5 batch 4 (see Table3) †	0.00460 ± 0.00251	0.00457 ± 0.00255	0.00115 ± 0.00063	19600	0.00447 ± 0.00254	0.00452 ± 0.00255	0.00112 ± 0.00064

* The inch unit of the readings in columns 2, 3, 6 and 7 was that used in the original measurements (1 inch = 25.4 mm)

† This specimen was the same one as had been previously tested under designation number 5, batch 4 (see Table 3)

SYMBOLS

a	half crack length
b	half crack opening at centre of crack
B	sheet width
C	constant
E	Young's modulus
K	stress intensity factor
ΔK	stress intensity factor range (maximum K-minimum K in a cycle)
K_c	critical stress intensity factor for fracture
L	sheet length
n	numerical exponent
N	number of cycles
P	axial load applied to specimen
R	Ratio of minimum σ_∞ to maximum σ_∞ in a cycle
S_0	the stiffness of an uncracked sheet
S_1	the stiffness of a sheet with a crack
t	sheet thickness
y	half crack opening
α	axial stiffness factor defined as the ratio of the axial stiffness of a cracked sheet to that of an uncracked sheet
β	sheet finite width correction factor
Δ_0	extension of uncracked sheet
Δ_1	extension of sheet with a crack
ε_∞	axial strain applied to specimen measured outside the influence of the crack
$\Delta\varepsilon_\infty$	axial strain range (maximum ε_∞ - minimum ε_∞ in a cycle)
σ_∞	axial stress applied to specimen measured outside the influence of the crack
$\Delta\sigma_\infty$	axial stress range (maximum σ_∞ - minimum σ_∞ in a cycle)

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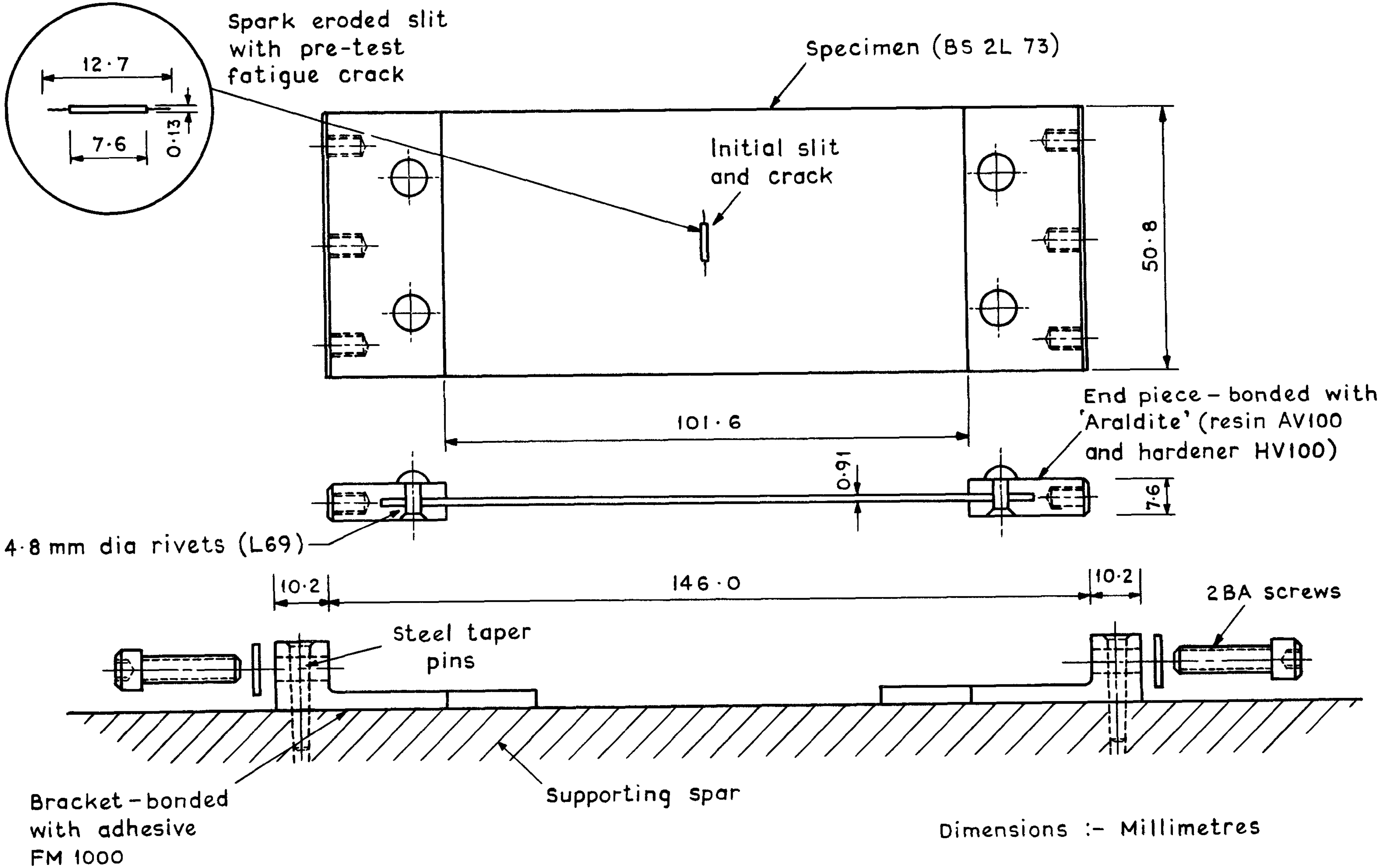

Fig. 1 Test specimen

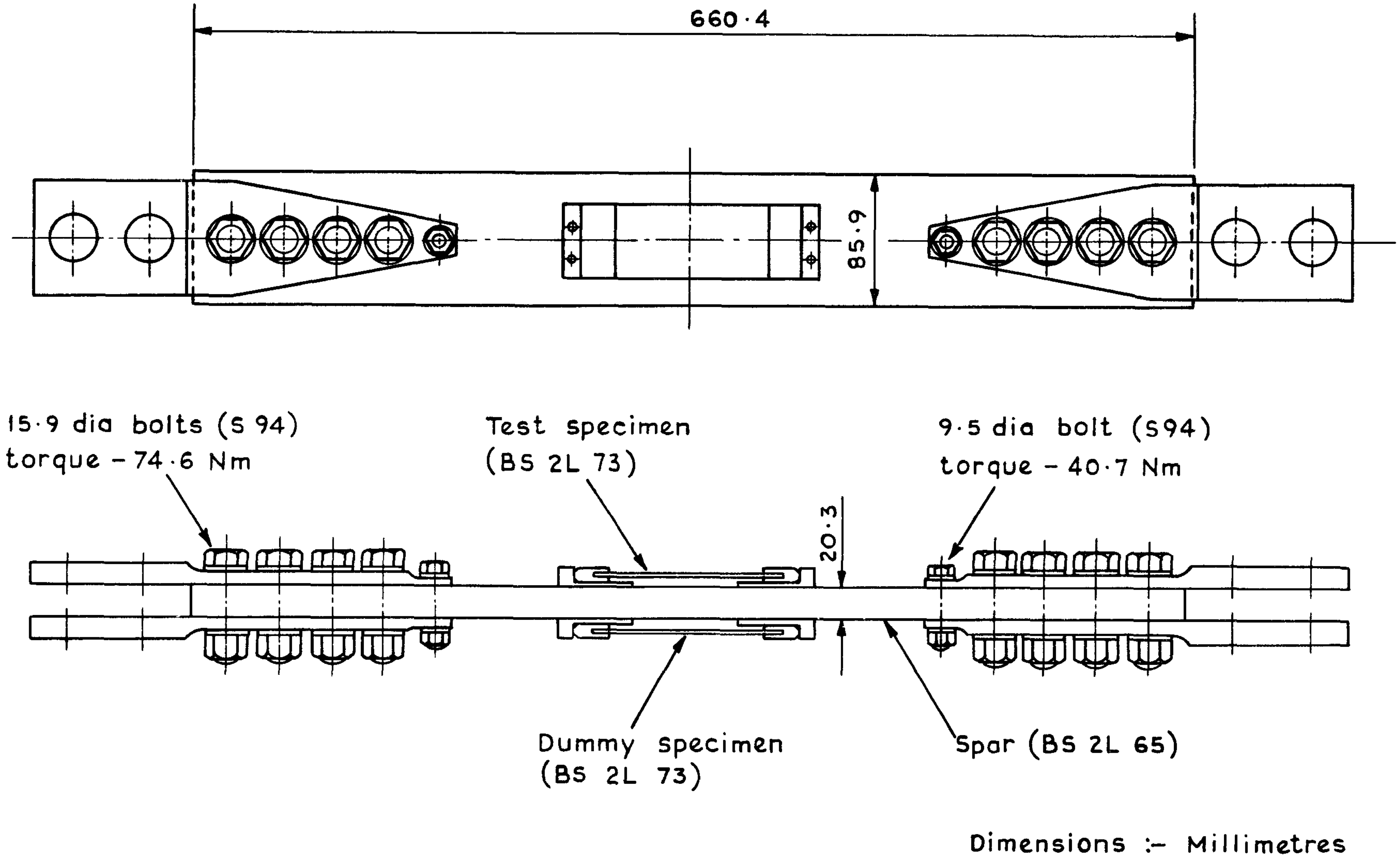

Fig. 2 Supporting spar with test specimen attached

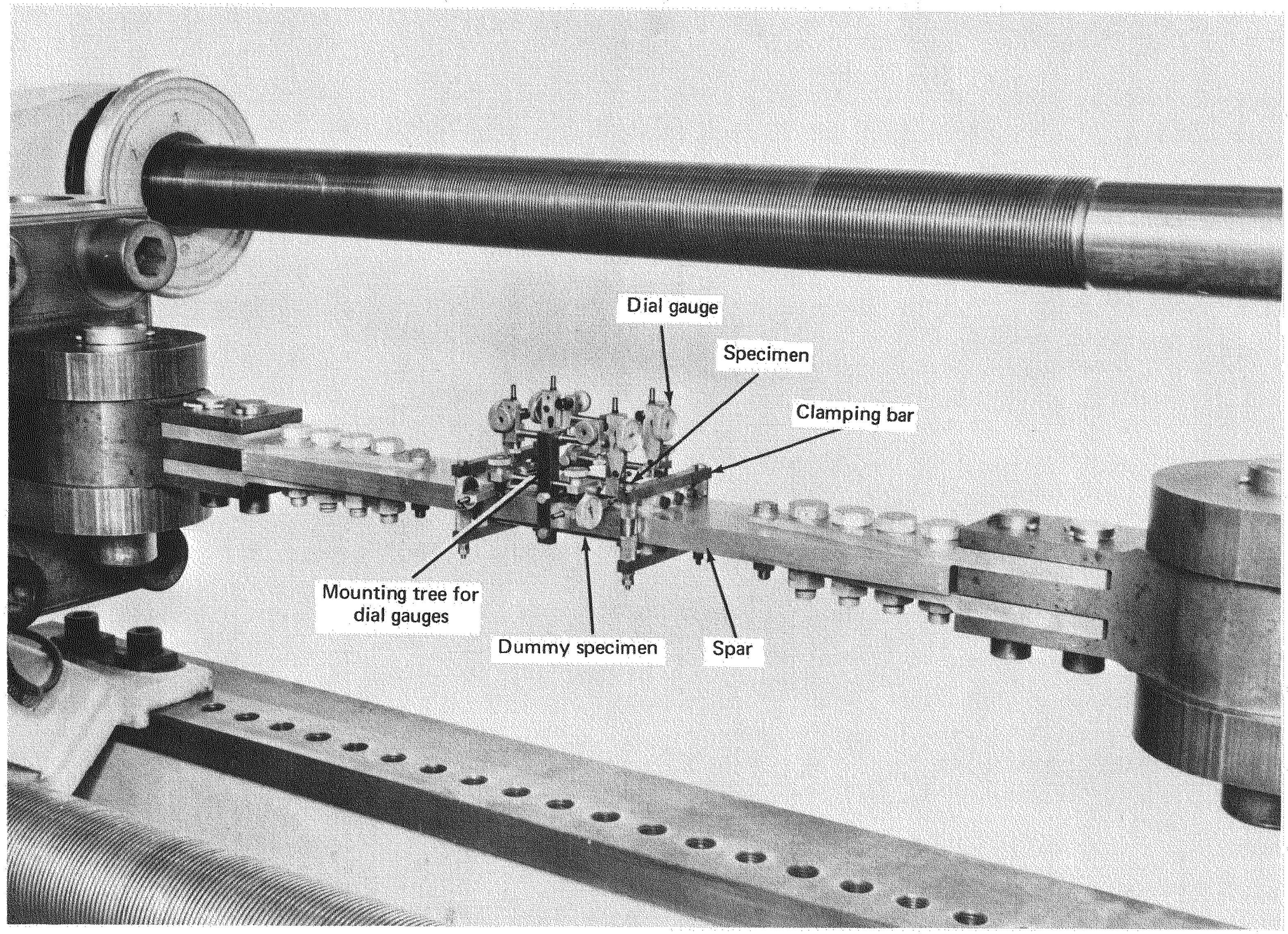

Fig.3 View of specimen in machine with dial gauges in position for measuring extensions

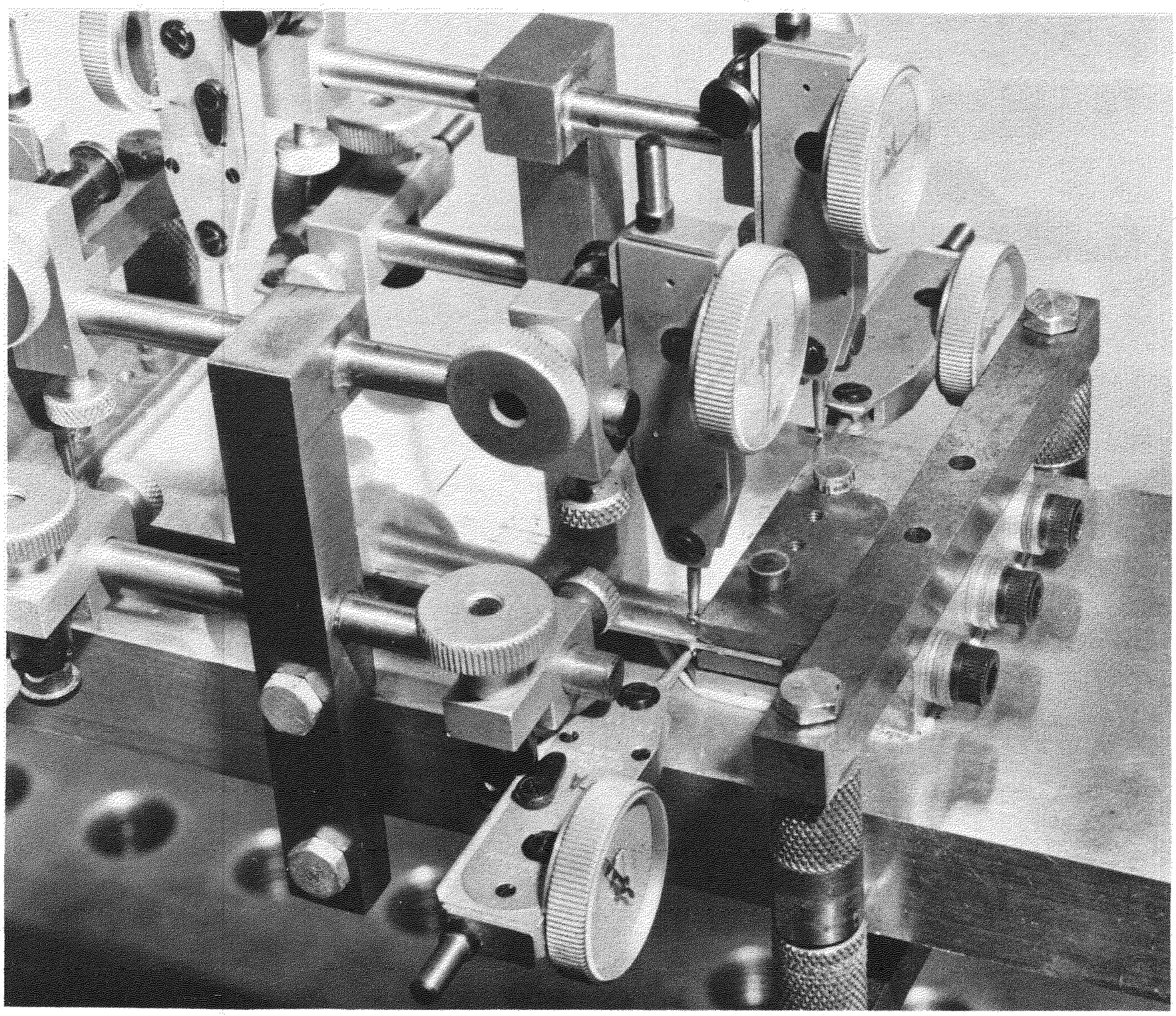

Fig.4 Close-up showing arrangement of dial gauges

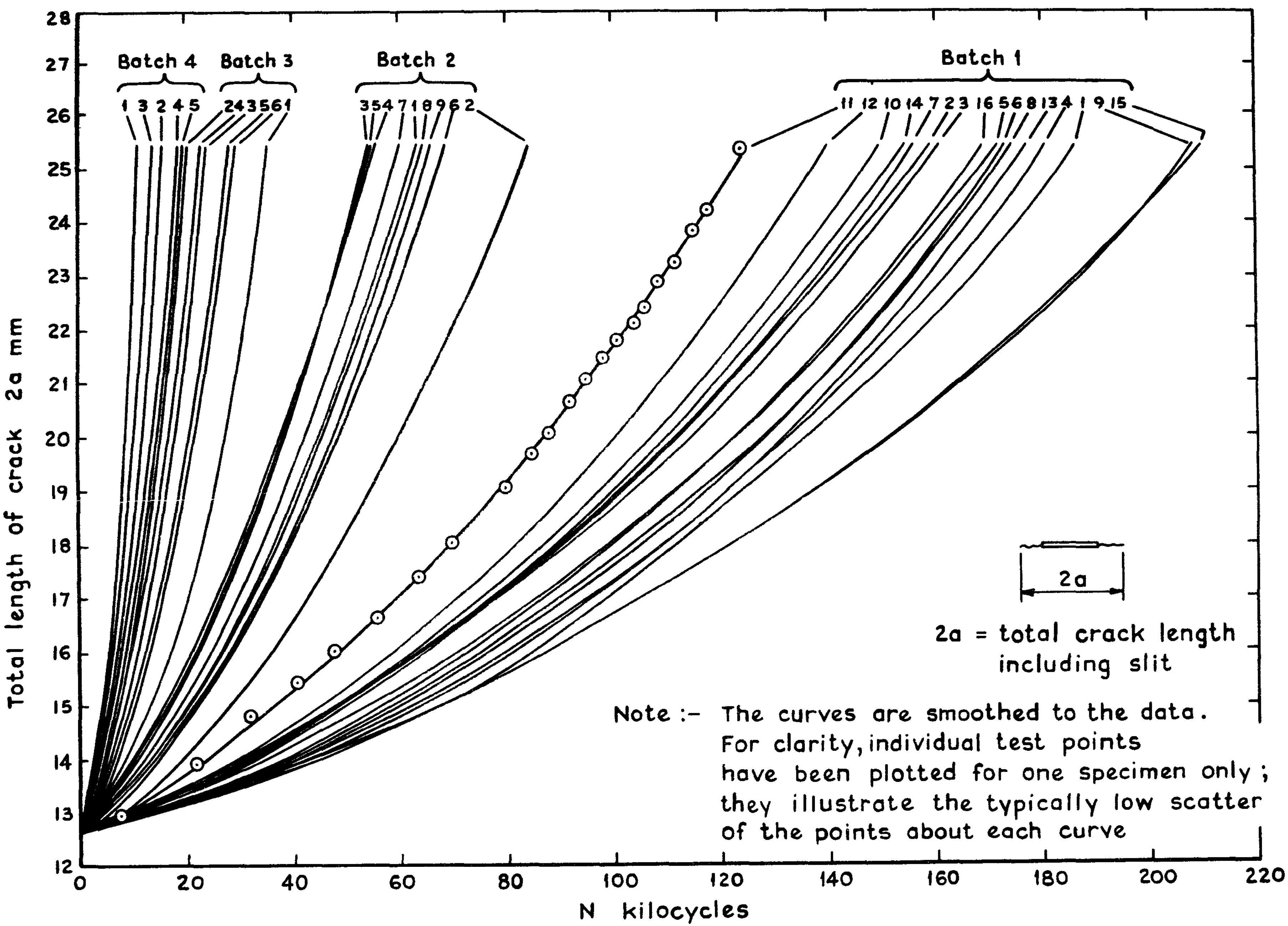

Fig.5 Crack length 2a v No of strain cycles N

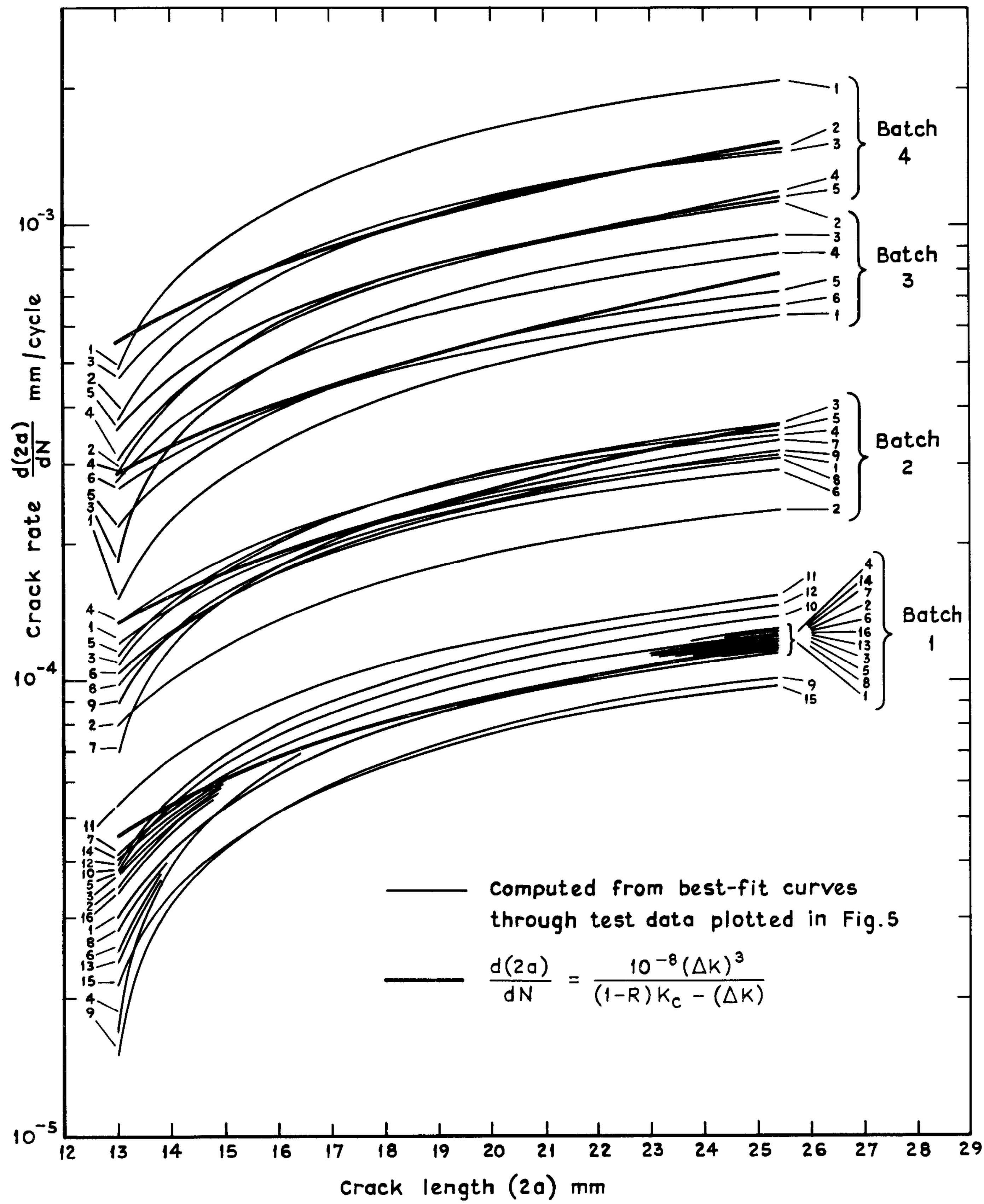

Fig.6 Comparison of crack rates computed from test data with rates calculated by theory

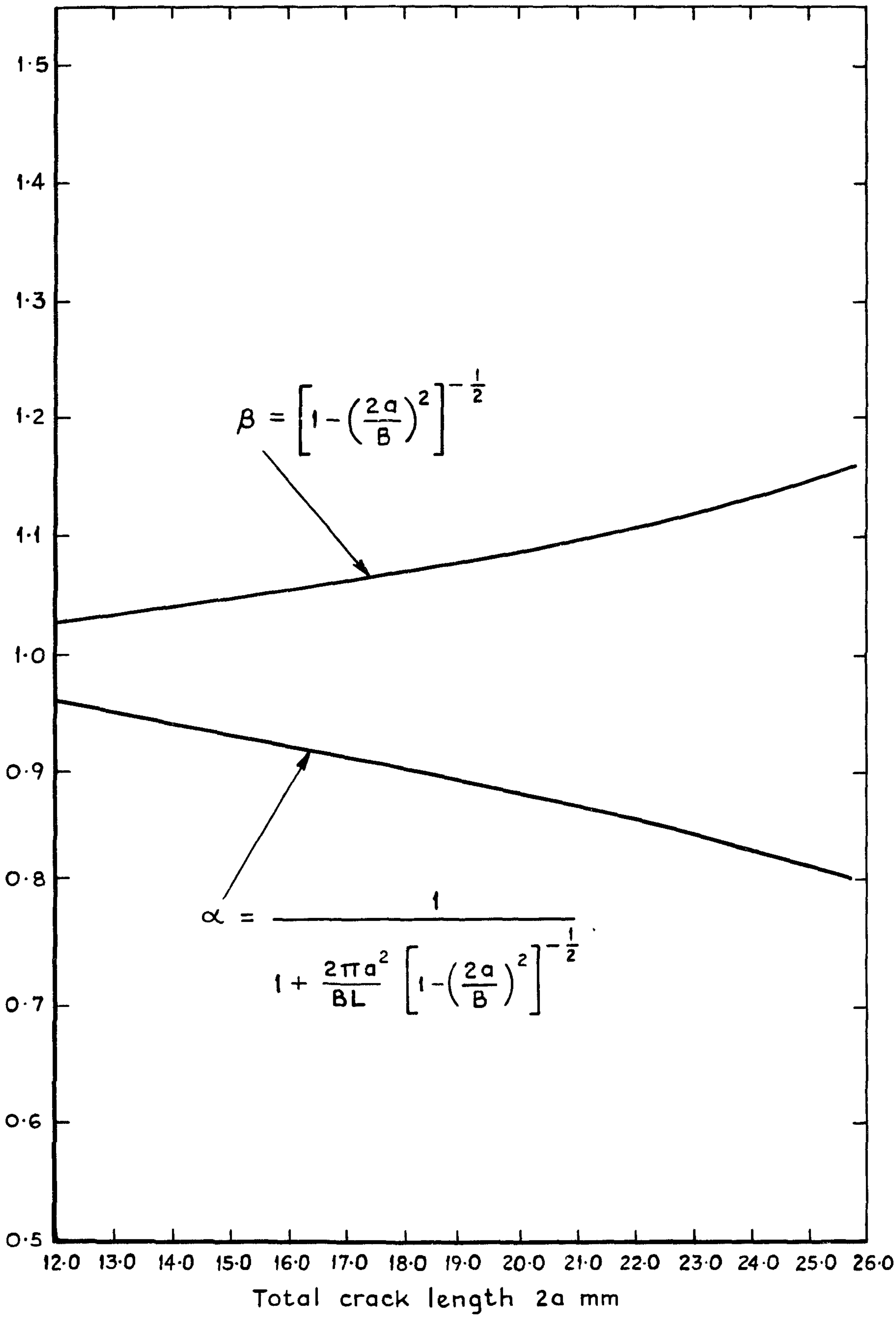

Fig. 7 Plot of stiffness factor α and width-correction factor β against crack length 2a for specimen used in this experiment

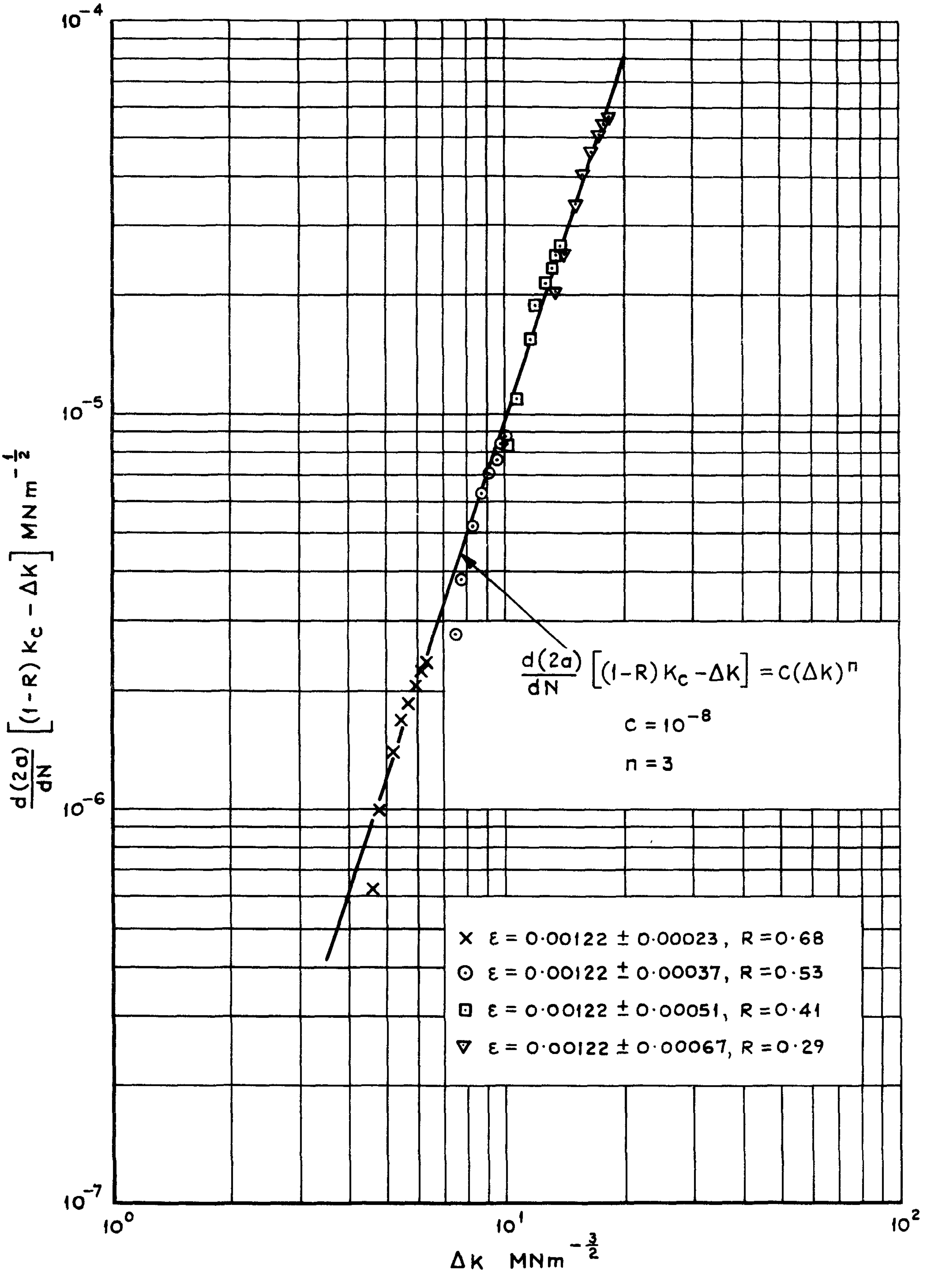

Fig. 8 Plot of $\frac{d(2a)}{dN}\left[(1-R)K_c - \Delta K\right]$ against ΔK to find C and n

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A formula for calculating the axial stiffness of a centrally cracked sheet is derived in the Appendix.

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