DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AERONAUTICAL ENGINEERING

Report VTH-203

THE EFFECT OF PRE-STRAIN ON FATIGUE CRACK GROWTH AND CRACK CLOSURE

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Abstract

A single pre-strain ($\varepsilon = 0.03$) applied to 2024-T3 material raised the static yield strength from 428 to 480 MN/m^2. The growth rate of a fatigue crack in the pre-strained material was about twice as large as in the material that was not pre-strained. A pre-strain followed by 1000 high, but still elastic pre-stress cycles did not further increase the growth rate. It was shown by COD measurements that crack closure occurred to a lesser extent in the pre-strained material as compared to the original material. The significance of the increased yield strength for fatigue crack growth is briefly discussed.

Notations

a	half length of crack
da/dN	crack growth rate per cycle
C	geometry correction factor
COD	crack opening displacement
ΔK	range of stress intensity factor ($=K_{max}-K_{min}$)
$\Delta K_{eff.}$	effective value of ΔK
R	stress ratio ($=S_{min}/S_{max}$)
r_p	plastic zone size
S	stress
ΔS	range of stress ($=S_{max}-S_{min}$)
$\Delta S_{eff.}$	effective value of ΔS ($=S_{max}-S_{op.}$)
$S_{op.}$	crack opening stress
w	semi width of specimen
ε	strain

Units: 1 MN/m^2 = 145.04 psi = 0.1020 kgf/mm^2

1 MN/m$^{3/2}$ = 910.05 psi$\sqrt{in}$ = 3.2246 kgf/mm$^{3/2}$

INTRODUCTION

In a recent publication Kang and Liu [1] made an interesting observation
on the effect of pre-strain cycles on fatigue crack growth in 2024-T351
aluminium alloy sheet material. If the maximum load of the pre-strain
cycle was above the static yield stress some thousands of pre-strain
cycles doubled the average crack propagation rate. In the discussion the
authors argued that the increased crack rate should be associated with
the exhaustion of cyclic ductility as caused by the pre-strain cycles.

Since the pre-strain cycles are raising the yield stress it is
thought that the plastic zone size should be smaller. As a result "crack
closure" as defined by Elber [2] should occur at a lower stress and the
effective stress cycle should be larger. In order to check this point the
tests as carried out by Kang and Liu were repeated to measure the occur-
rence of crack closure by a COD meter.

In view of the tension-tension type of the pre-strain cycles as
applied in [1] significant plastic deformation occurred in the first pre-
strain cycle only. In subsequent cycles the behaviour was almost fully
elastic. It is thought that one pre-strain cycle may then induce the same
crack growth acceleration as a thousand pre-strain cycles. For comparison
a few tests of the present program were carried out with just one pre-
strain cycle. In the discussion of the results brief comments on the
crack growth mechanism are presented.

TEST PROGRAM

The same type of specimen and the same material as used in [1] were
adopted to achieve a similar increase of the crack growth rate. The
dimensions as shown in Fig. 1 are practically the same as those given in
[1]. The pre-load cycle occurred between S_{max}=480 MN/m^2 (69700 psi) and
S_{min}=48 MN/m^2 (6970 psi) (R=0.1), again in approximate agreement with [1].
The value of σ_{max} is well beyond the static yield stress of 428 MN/m^2
(62100 psi) and the plastic strain in the first cycle was about 3
percent. Subsequent unloading and additional cycles were virtually

elastic (see Fig. 2).

After the pre-strain cycles a crack starter notch was applied consisting of a small hole (diameter 1 mm) and two small saw cuts (tip to tip 5 mm). Crack propagation tests were then carried out between S_{max}=138 MN/m^2 (20.000 psi) and S_{min}=13.8 MN/m^2 (2000 psi), the same values applied in [1]. The table below gives a survey of the tests.

Number of specimens	Number of pre-strain cycles	Crack closure measurements
4	none	2 specimens
2	1	1 specimen
3	1000	1 specimen

TEST RESULTS

The average crack propagation curves are shown in Fig. 3 while the individual growth rate data are given in Fig. 4. Both graphs confirm the result of Kang and Liu [1], i.e. the crack rate is approximately doubled by the pre-strain cycles. The graphs also confirm the present assumption that there is no difference between the effect of one pre-strain cycle and 1000 pre-strain cycles.

The crack closure measurements [3,4] were made on 4 specimens by a small COD meter with a gage length of 4 mm (see Fig. 5). The design of this COD meter was obtained from the German laboratory DFVLR in Porz-Wahn [2]. Crack closure measurements were made at three values of the crack length a = 7 mm, a = 10 mm, a = 15mm. The COD meter was clamped on the specimen by weak spiral springs. The location was about 2 mm behind the tip of the crack. The output of the COD meter and the load on the specimen were plotted on an X-Y recorder. Plots were made by varying the stress between σ_m and σ_{min} of the fatigue load cycle. The stress at which the crack was fully re-opened after (partial) closure, S_{op}, was determined from the transition between the nonlinear and the linear part of the X-Y plot (see Fig. 5). Such a deduction is subject to some personal judgement.

The accuracy cannot be considered to be very high. However, the same judgement applied to all tests. Consequently the results as compiled in Fig. 6 are showing a consistent and significant difference between the crack-opening stress for the pre-strained material and the material, that was not pre-strained. The effective stress range ($\Delta S_{eff.}$) is larger for the pre-strained material.

The crack growth rates have been plotted as a function of both ΔK and $\Delta K_{eff.}$ for the three values of "a" for which crack closure measurements were made.

$$\Delta K = C \quad \Delta S \sqrt{\pi a} \qquad (1)$$

$$\Delta K_{eff.} = C \quad \Delta S_{eff.} \quad \sqrt{\pi a} \qquad (2)$$

$$\text{with } C = \sqrt{\sec \frac{\pi a}{2w}} \qquad (3)$$

From the results as shown in Fig. 7 it can be seen that the difference between the two materials is considerably smaller if $\Delta K_{eff.}$ instead of ΔK is adopted as a basis for the comparison. (Actually Eq. (3) does not apply to the specimen shown in Fig. 1 in view of the waisted part of the specimen. However, a more correct geometry factor C would not have altered the relative positions of the curves in Fig. 7).
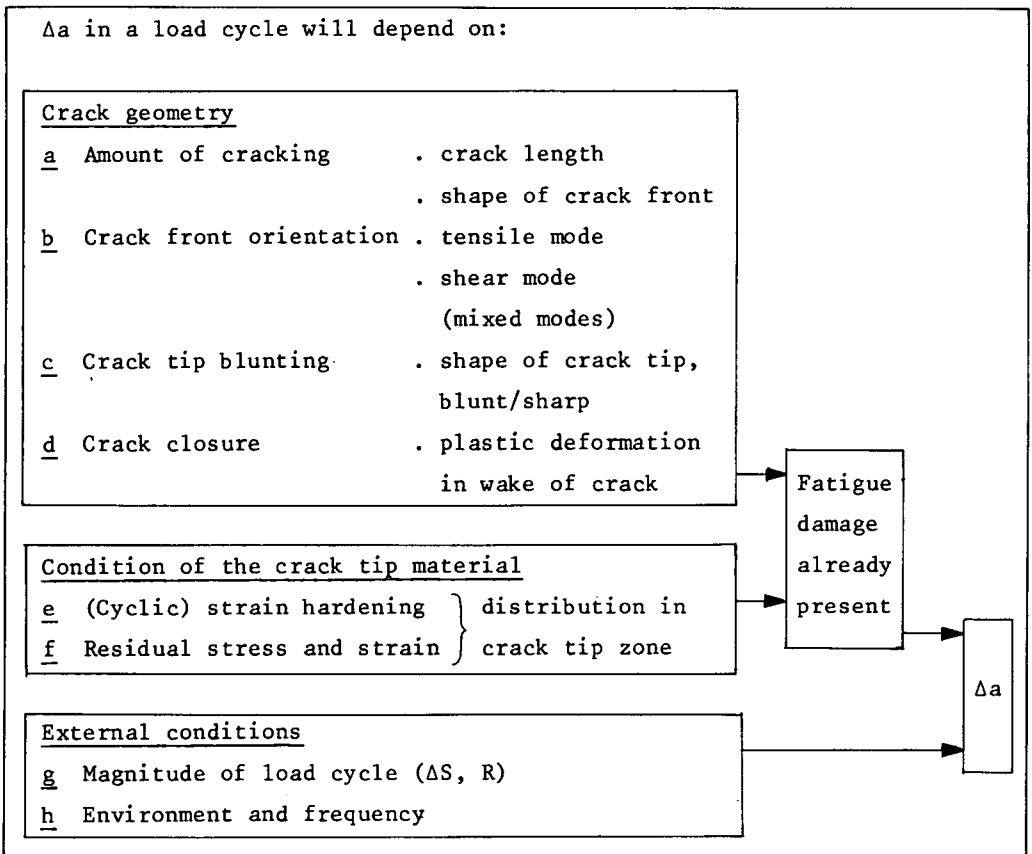
DISCUSSION

The COD measurements show that crack closure does occur. It occurs less in the pre-strained specimens as compared to the specimens that have not been pre-strained (Fig. 6). This observation was confirmed by the macroscopic appearances of the fracture surfaces. Black debris, indicative for cyclic metallic contact (fretting corrosion), could be observed on the original specimens, whereas it was not clearly visible on the pre-strained specimens.

In agreement with the crack closure observations the crack rate was faster in the pre-strained specimens. Still crack closure alone cannot

completely explain the differences between the two materials. One might conclude from a comparison between Fig. 7a and Fig. 7b that crack closure is responsible for about half the effect of prestraining on crack growth.

It was argued in [5,6] that the amount of crack extension in a load cycle is depending on the fatigue damage being present and the magnitude of the load cycle to be applied. In more detail the picture shown in the table below was presented.

Δa in a load cycle will depend on:

Crack geometry

a	Amount of cracking	. crack length
		. shape of crack front
b	Crack front orientation	. tensile mode
		. shear mode
		(mixed modes)
c	Crack tip blunting	. shape of crack tip,
		blunt/sharp
d	Crack closure	. plastic deformation
		in wake of crack

Condition of the crack tip material

| e | (Cyclic) strain hardening | } distribution in |
| f | Residual stress and strain | } crack tip zone |

External conditions

| g | Magnitude of load cycle (ΔS, R) |
| h | Environment and frequency |

Fatigue damage already present

Δa

The amount of cracking and the magnitude of the load cycle can be accounted for by ΔK (and R). Crack closure (aspect d) was already mentioned before as being part of the explanation by modifying ΔK to $\Delta K_{eff.}$. Probably the crack front orientation (b) did not play a significant

part in the present tests. Consequently crack tip blunting (c) and the condition of the material at the tip of the crack (e and f) should be considered for additional contributions. The tests have shown that the effect of one plastic prestrain cycle remained unchanged if more elastic pre-strain cycles followed. This suggests that the increase of yield strength from 428 MN/m^2 for the original material to 480 MN/m^2 for the prestrained material should be considered first. An obvious consequence of the higher yield strength of the prestrained material is a smaller "monotonic" plastic zone size (r_p). A first approximation is:

$$r_p = \frac{1}{D} \left(\frac{K_{max}}{\sigma_{yield}}\right)^2 \qquad (4)$$

with a constant D depending on the state of stress. The plastic zone size should then be about 20 percent smaller in the prestrained material. In view of the smaller plastic zones in the prestrained material less plastic deformation will be left in the wake of the crack. Consequently less crack closure should occur as it was observed.

The significance of the smaller plastic zone for crack tip blunting and the condition of the material in the plastic zone ahead of the crack is less obvious. It should be expected that a smaller plastic zone implies an increased tendency to a triaxial state of stress, smaller plastic deformations and consequently less crack tip blunting. It should also be expected that the tensile stress will be higher. Both arguments imply an apparently lower ductility, which was always associated with faster crack rates. An illustrative example was presented by Broek [7] who compared crack growth rates in 2024-T8 and 2024-T3 sheet material. The yield stresses were 454 and 365 MN/m^2 respectively. The crack rate in the former alloy for S_m = 68.6 and S_a = 63.7 MN/m^2 was about twice as fast as in the latter alloy.

Since fatigue crack growth is to be associated with cyclic plastic deformations in the plastic zone the monotonic plastic zone size should not be considered only. The reversed plastic zone is estimated to be one quarter of the monotonic plastic zone size [8]. However, since the

increased yield strength was obtained by plastic deformation it may be thought that the size of the reversed plastic zone will be approximately the same for the pre-strained material and the original material. Any further speculation on differences between the materials at the tips of the cracks is going to be rather difficult. It would require more information on the cyclic plastic deformations, the associated stress distributions (both as a function of number of cycles) and the fracture mechanism from which a failure criterion should be deduced. For the time being it should suffice to say that the increased yield strength as obtained by pre-straining the material has two interrelated consequences: The first one is that less plastic deformation is left in the wake of the crack, implying less crack closure and a higher effective stress intensity range at the tip of the crack. This should obvious enhance crack growth. The second one is the lower ductility by which higher stresse will be built up in the crack tip zone. This will give an additional contribution to enhanced crack growth.

CONCLUSIONS

1. Fatigue crack propagation tests (R=0.1) were carried out on 2024-T3 material, both on specimens that were prestrained in tension (ε=0.03) before applying a crack starter notch and on specimens that were not pre-strained. The crack growth rate in the former specimens was about twice as large as in the latter specimens. If the pre-strain (ε=0.03 and σ=480 MN/m^2) was followed by 1000 high pre-stress cycles between σ_{max}=480 and σ_{min}=48 the behaviour in these cycles was elastic and no further increase of the crack rate was observed in subsequent crack growth tests.

2. As a consequence of the pre-strain the yield strength was raised to 480 MN/m^2 (69700 psi) as compared to 428 MN/m^2 (62100 psi) for the original material. For fatigue crack growth the higher yield strength will induce smaller plastic zone sizes and consequently less crack closure. This was confirmed by COD measurements.

3. About half the difference between the crack rates in the pre-strained

specimens and the original ones can be explained by adopting the effective stress range derived from the crack-opening stress. This emphasizes that any fundamental fatigue crack growth study should include observations on crack closure.

4. It is suggested that the crack growth was also enhanced by the higher tensile stresses in the plastic zone ahead of the crack, which are due to the higher yield strength and the smaller plastic zone size.

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(1966)

[8] J.R. Rice, Mechanics of crack tip deformation and extension by fatigue
ASTM STP 415, 247 - 309 (1967).

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rolling direction
and loading direction

100

6

135

30

radius 75

3

location for crack
starter notch after
application of
pre-strain cycles
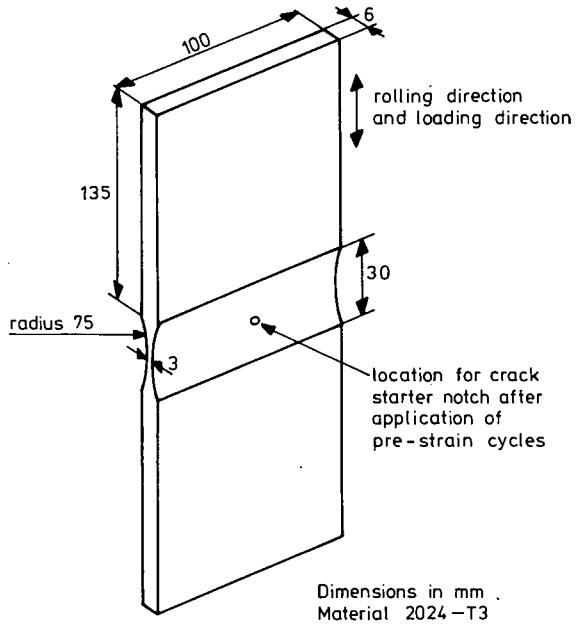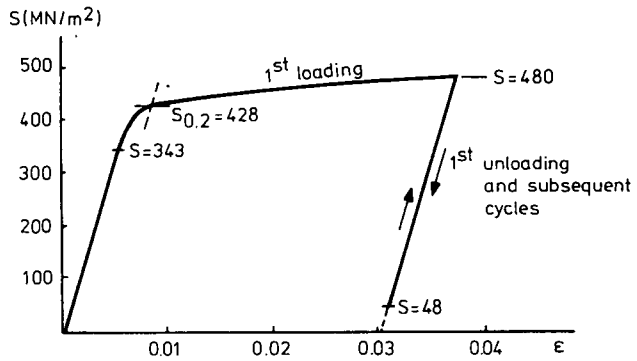
Dimensions in mm
Material 2024–T3

Fig.1: Dimensions of the specimens.

Fig.2: The pre-strain cycles.
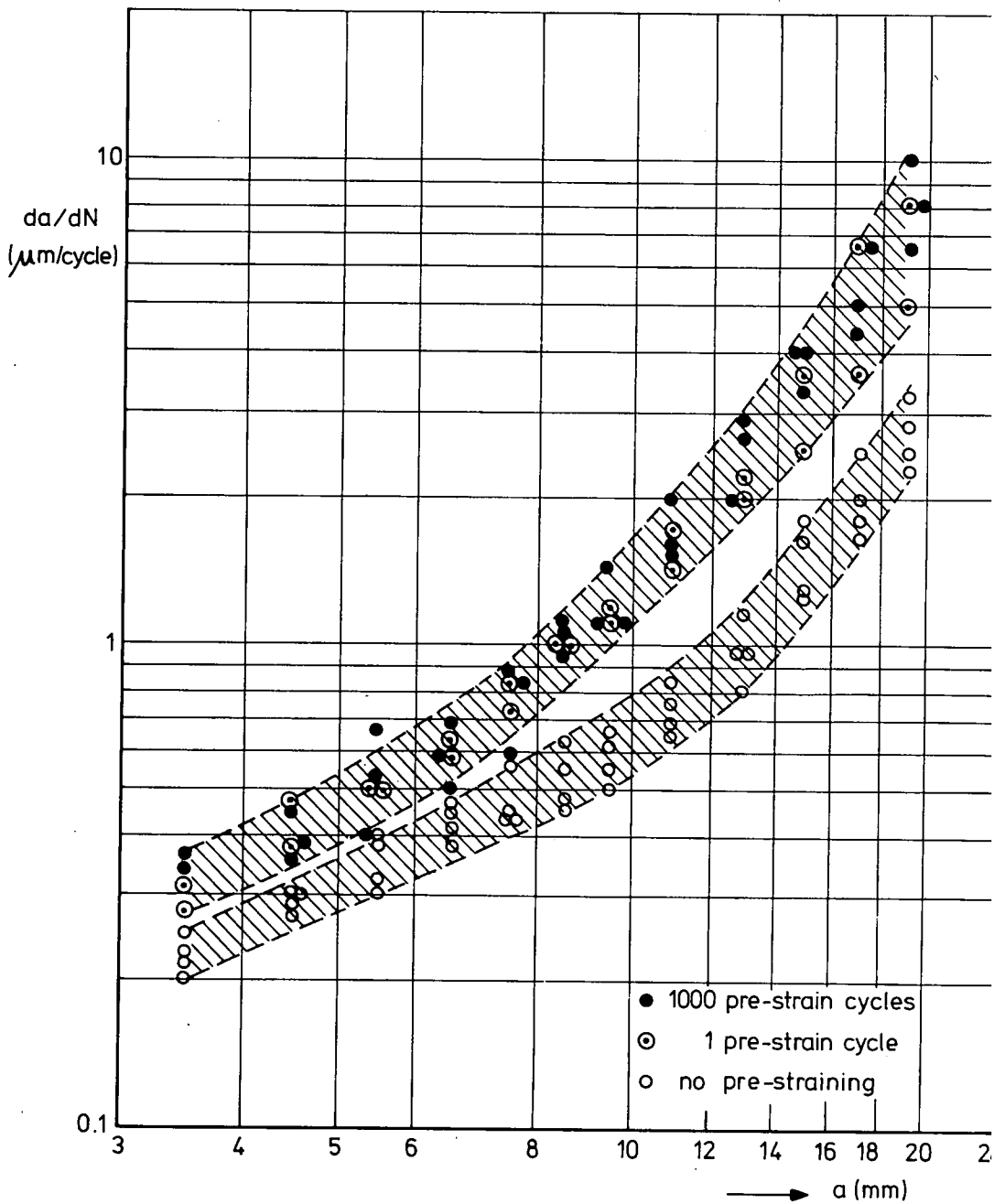
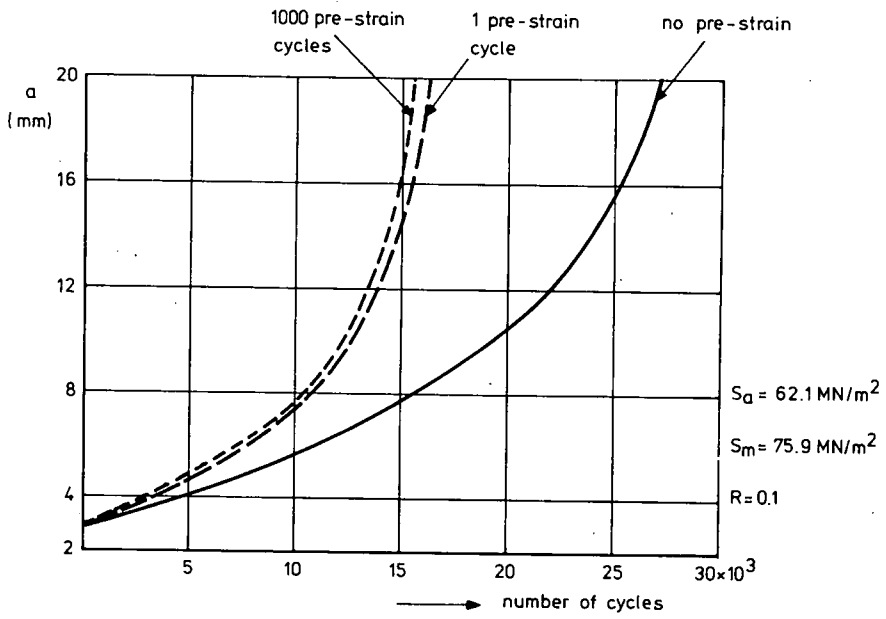Fig. 4:   The crack growth rate as a function of crack length.
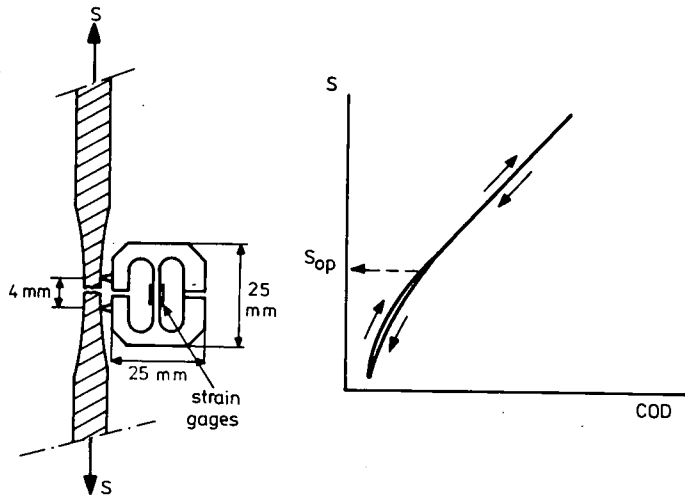
Fig. 3: The average crack propagation curves.

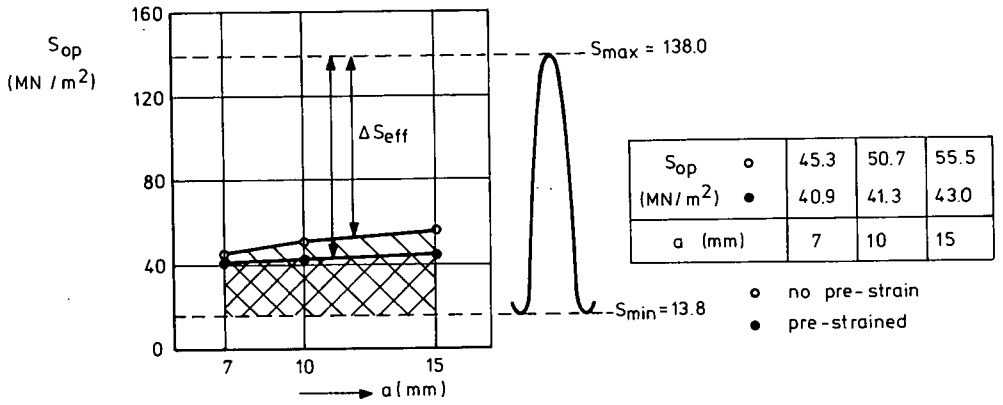Fig. 5: The COD−meter and a crack closure loop.

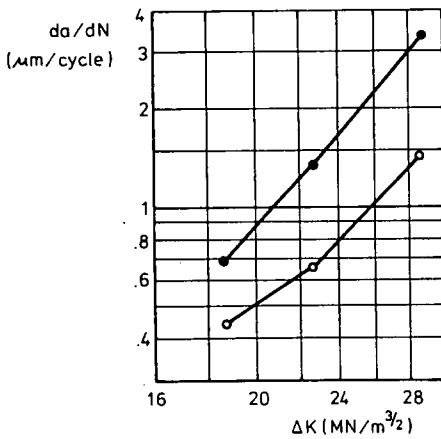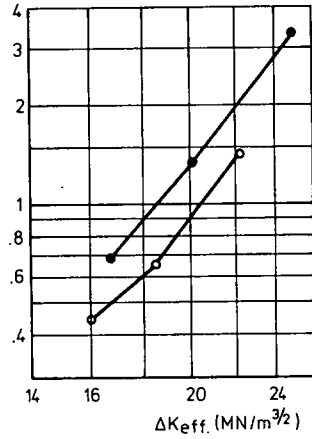Fig.6: The effect of pre-straining on the crack-opening stress.

Fig. 7a.

Fig. 7b.

● pre-strained material
○ not pre-strained

Fig. 7: The crack rate as a function of ΔK and ΔK$_{eff}$.