SOME CONSIDERATIONS ON DIFFERENT TEST TECHNIQUES FOR STRESS CORROSION/CORROSION FATIGUE

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ABSTRACT.- Slow Strain Rate Test technique has been examined from a fracture mechanics point of view, to compare results of stress Corrosion Tests obtained with different test techniques, under the hypothesys that the crack propagation mechanism is the same for monotonic and for cyclic loading, and that a simple superposition model can be used for the understanding of fatigue results. The tensile specimen has been treated as a single edge cracked panel under uniform remote tension; the total strain of the specimen far from the crack has been calculated and stress-strain curves for uncracked and for cracked specimens with different crack depth have been drawn.

This approach permits to evaluate more precisely both the nucleation time and the rate of growth of an SC crack. The obtained results have been applied to experimental data.

NOMENCLATURE

EAC=Environmentally Assisted Cracking

SSRT=Slow Strain Rate Test

CF=Corrosion Fatigue

SCC=Stress Corrosion Cracking

$\dot{\varepsilon}$=Strain Rate

ΔK=Stress Intensity Factor Range

da/dN=Cyclic Crack Growth Rate

KISCC=Minimum Stress Intensity Factor for Stress Corrosion Cracking

(da/dt)SCC= Crack Growth Rate Component due to Stress Corrosion Cracking.

INTRODUCTION

Under the name of "Environmentally Assisted Cracking" one can indicate a wide range of phenomena, characterized by the action of an aggressive environment coupled with an applied load. The effect of the two variables (load-environment) together is more detrimental than the sum of each of them, taken singularly. Environmentally Assisted Cracking is responsible for many failures in plants and structures.

To verify the sensitivity to EAC for a given material-environment couple, different test techniques can be used. They differ mainly with regard to the loading technique.

In particular, in this paper we will examine the Slow Strain Rate Test technique, to account for the presence of a crack in a tensile specimen, with the aim at obtaining a more precise estimate of crack growth rate to be compared with the value measured in Corrosion Fatigue tests. The work is made under the hypothesys that, for a given material in a given environment, the stress corrosion mechanism active is the same, provided that the stress- strain condition at the crack tip are favorable to the onset of the phenomenon.

For fatigue tests, a superposition model will be used, supposing that the stress corrosion effect is superimposed to a mechanical effect and that they are related by a simple superposition law.

Following this approach, the stress-strain curve for a tensile test has been calculated for an uncracked specimen, and for a cracked one. A comparison has been made between tests under load control and tests under strain control, which allows to explain some aspects of the results of crack growth rate measurements.

SSRT technique.

Slow Strain Rate Tests (SSRT) are widely used to determine the SCC susceptibility of alloys in aqueous environment.

For SSRT, the used specimen and test technique are similar to those used for tensile testing ; the specimen is tested in the aggressive environment; the load is applied under strain control, by straining the specimen at a fixed rate; this rate is usually very low, and it is recognised as an important parameter in SCC. Ductile fracture will occur when the strain rate is high. There exists a critical strain rate below which SCC occurs. In general, a decrease in the value of $\dot{\varepsilon}$ increases the severity of cracking, altough for some alloy systems there exists a lower-bound value for $\dot{\varepsilon}$ at which recovery of ductile properties starts to occur. The critical range of strain rates within which EAC occurs varies from one system to another.

From SSRT, information about crack growth rate are restricted to the evaluation of a mean value; the crack velocity is calculated as the ratio between the maximum crack length measured after the test, and the total test time. An incubation time is sometimes subtracted to the total, to account for the nucleation of the crack.

Corrosion fatigue.

The properties of a given material-environment couple with regard to corrosion fatigue are important to predict fatigue life of structural components. Materials and environments under study are often the same where SCC occurs.

To study the susceptibility to corrosion fatigue, tests are conducted on fracture mechanic specimens in aggressive environment. The practice of those tests is the object of an ASTM Standard(1). They are mainly conducted under load control, either by mantaining a costant load range (increasing ΔK tests), or by applying a constant stress intensity factor range during the complete test (to this pourpose, the load is slowly decreased as the crack grows).

The crack length is measured during these tests, optically or through remote tecniques such as compliance monitoring, potential drop and so on. As a consequence, the crack growth rate can be known with good approximation, not only due to the precision of the used technique, but also to the mathematical treatment of the data. The general shape of a fatigue crack growth rate curve in non-aggressive environment at constant load amplitude is well estabilished(2). The curves, da/dN vs ΔK in usual log-log plots, are of sigmoidal shape. A linear approximation is commonly used in the midrange. At low values of ΔK the growth approaches an apparent threshold. At high values of ΔK, an acceleration of growth is often noticed. While variables such as material and mean load influence the general behaviour, frequency appears to have no significant effect. When the environment is aggressive, an enhancement of crack growth rate is observed.

One of the main goal of research in EAC is to develop the capability of predicting, for design pourposes, the maximum crack growth rate that can be expected under a particular set of environmental conditions. A simple approach to this problem has been suggested by Wei and Landes (3) and by Vosikovsky (2), who have proposed a simple superposition model. Currently the following components are considered:

-A purely mechanical fatigue crack growth component

-A "true corrosion fatigue " component

-A "stress corrosion" component

as schematically shown in Fig.1.

This superposition model, which has received some criticism due to its simplicity(5), can anyway account for the effect of frequency in CF (6). It has been formulated as a consequence of the observed similarities between corrosion fatigue and SCC behaviour above KIscc. Those similarities have lead to the suggestion that the mechanism of corrosion fatigue crack growth is the same as that of crack growth under sustained and under monotonic load.

COMPARISON BETWEEN SSRT AND CF TECHNIQUES: THE CRACK GROWTH RATE VALUE.

The hypothesys that SCC, when observed in a given susceptible material environment couple, is due to the same mechanism with no regard to the used testing technique, is confirmed by the crack surface examination. On the other hand, crack growth rate values can be different of more than one order of magnitude when comparing fatigue results(7) or constant load results(8) with SSRT results(9). Moreover, SSRT data have shown that crack velocity increases with the applied strain rate(10), while for fatigue tests (using the superposition model) , the crack growth rate of the SCC component is usually constant, so as for constant load test.

To find the reason for this discrepancy, it is interesting to examine the differencies between the used test techniques. In particular, attention will be paid to the presence of a crack in a tensile specimen, tested under strain control.

When a specimen is tensile tested in a non aggressive environment, the fracture will be ductile and no cracks will form during the elastic part of the test. If the tensile test occurs in an aggressive environment, one or more cracks will form before the specimen is fully plastic. These cracks have an influence on the stress-strain curve.

A fracture mechanics approach has been used to draw a stress strain plot for a tensile specimen containing a crack. The specimen has been treated as a single edge cracked panel under remote uniform tension, and the strain has been calculated, following the EPRI approach, as the sum of four components (elastic opening for uncracked specimen, ductile opening for uncracked specimen, elastic opening for cracked specimen and ductile opening for cracked specimen). For further details of this calculation, see ref.11.

To apply this approach to an SSRT specimen, the theoretical stress-strain curve has been drawn for an uncracked specimen; the Ramberg-Ogswood coefficients have been calculated from an experimental set of data, obtained in a test where no environmental effect was observed. The curve and the data points from which the curve has beeen obtained, are shown in Fig. 2 . When the specimen contains a crack, the stress-strain curve is modified due to the increase of the specimen compliance. Since the specimen elongation corresponding to a given load is larger than that of the uncracked specimen, due to the contribution of the crack opening, in strain control one will experience, for a given applied deformation, a load which is lower as the crack length increases. The effect of the crack is shown in Fig.3, where a family of curves, corresponding to different crack length (1 to 6 mm) has been drawn (supposing that the crack propagates perpendicular to the edge of the specimen).

During a test, before the nucleation of a crack, the specimen will follow the stress-strain curve indicated in Fig.2; as the crack grows, the plot will pass from one curve to the other of the family in Fig. 3, depending on the crack depth. Since the test is made at constant strain rate, the strain increases linearly with time, so that it is possible to draw a time axis on the same plot; moreover, the hypothesys has been formulated that the SCC crack growth rate is constant; it is so possible to suppose that the passage from a curve to the following one happens in a constant range of time. As a consequence, when one know the nucleation time and the crack growth rate (supposed constant), one can draw the espected stress strain curve for specimens with only one crack; in Fig.4 such plots are shown, for two cases, with two different crack growth rate values, 10-4 mm/sec. and 10-5 mm/sec. The nucleation has been supposed to happen at the beginning of the test, and the applied strain rate to be equal to 10-6 sec-1.

If SSRT results are examined from this point of view, the following aspects can be evidenced qualitatively:

- Effects on load.

Under strain control, the growth of a crack causes a decrease of the load, while at the same time the increase of the applied strain causes an increase of the load. At the beginning of the test, the effect of the crack is small , but as the applied stress increases, the presence of a crack causes a marked unloading effect (Fig.3). Both processes (crack growth and applied strain) are depending on time with a constant rate. They are competitive, and a macroscopic decrease of the load can be observed when the unloading due to the crack exceeds the loading due to the applied strain.

2: Effects on crack growth rate.

The crack growth rate during an SSRT can be calculated by comparison of the stress-strain curve with the family drawn in Fig. 3. Using the time base, it is possible to calculate graphically the time spent for a growth of one unit of length. Supposing that a given stress-strain condition at the crack tip is necessary to mantain the crack growth, and that the unloading causes a decrease of crack velocity and sometime crack arrest, one can suppose that when crack velocity is high enough to produce unloading of the specimen, the crack growth can proceed by steps. When the crack growth mechanism is transgranular, the crack arrest will be indicated by a marking on the fracture surface, similar to those found by Hahn and Pugh (12). and corresponding to load pulsing.

3:Effects of strain rate.

As a consequence of the crack growth, a competition can start between the unloading due to crack growth and the loading due to the strain imposed to the specimen. Supposing that the crack growth rate is constant ((da/dt)SCC), as found in CF tests when applying the superposition model, since for SSRT the strain rate is constant too, the two processes are competitive, so that:

-it is possible to find a strain rate value below which the crack will proceed by steps, and the average crack growth rate will be lower than the real one.

-if $\dot{\varepsilon}$ is above this value, the crack will grow without stops.

As a conclusion, the approach here described gives the possibility of:

-obtaining an estimate of the crack growth rate which, at least for long cracks (high susceptibility to SC), is supposed to be comparable with the one measured with different test techniques;

-having a better understanding of the crack growth rate mechanisms;

-accounting for the effect of strain rate on SSRT results.

APPLICATION TO EXPERIMENTAL DATA

At CISE, experimental work is performed using both corrosion fatigue and SSRT techniques. The activity is underway since 1979, as a part of a main ENEL-DSR program on nuclear reactor safety. Tests have been made on A533B pressure vessel steel, and on sensitized AISI 304 in LWR environment. Results obtained up to now have shown the validity of the superposition model for CF on A533B Pressure Vessel Steel(13). Since a large amount of data obtained with SSRT technique are available, an effort has been made to correlate CF and SSRT results. A preliminary work has been done, with the aim at giving some experimental evidence to the approach described in this paper, on AISI 304 specimens.

It is well known that this material is susceptible to SCC in LWR environment, and that two different crack growth mechanisms can be evidenced, a transgranular one , and an intergranular one (due to sensitization). The two mechanisms are likely to be associated to different crack growth rates, as shown in literature(10).

In Fig. 5 the stress-strain curves of two specimens tested in the same environment are compared: the first one was treated at 600 C for 5 hours, while the second one for 50 hours. The different heat treatment caused a different sensitization; the fracture surface was completely ductile in the first case, while the second specimen showed about 40% of Intergranular fracture. The result of the ductile test has been used to calculate the stress-strain curve at different crack depth. The time based scale has been superimposed to the strain scale, and the curve for the sensitized specimen has been superimposed to the calculated family, so that the intersection of the experimental curve with each of the family could be used to have an estimate of the crack growth rate. In Fig. 6, an enlargement of a section of Fig.3 shows the family of curves corresponding to different crack depth, with superimposed the experimental data set. The enlargement corresponds to the rectangular region evidenced previously in Fig.3, and it has been made to allow a better estimate of the intersection points positions. The average crack growth rate, calculated as the ratio between the maximum crack length and the total test time is 1.5*E-5. From Fig. 6, the crack growth rate can be calculated for each millimeter of propagation; the obtained values are between $6.87\cdot10^{-5}$ and $7.38\cdot10^{-5}$, confirming that the SCC component rate is almost constant, as observed when applying the superposition model to corrosion fatigue data (7); the nucleation time is more difficult to be identified, due to the similarity between the curves corresponding to "no cracks" and "imm crack".

A couple of specimens where transgranular SCC was observed, have been examined with SEM. In this case, the crack propagation was about i mm maximum, starting on the complete specimen perimeter. Since a completely ductile curve has not been obtained, the stress strain plot was not calculated. It is interesting anyway to notice that the crack surface presents a similarity with the surface of a specimen tested under CF, as shown in Fig.7 (a) and (b), and that some arrest marks can be evidenced on the SSRT specimen surface. This morphology, very similar to what has been observed in correspondence of load pulsing (14), is likely to be associated to the discontinous crack growth, predicted by the fracture mechanics approach.

CONCLUSIONS

In this paper, SSRT technique has been examined considering the effect of crack growth on the compliance during the tensile test. This approach is quite new and it is likely to give the possibility of a better understanding of the complex interaction between the effects of mechanical loading and aggressive environment. The validity of the proposed method has been verified only partially by experimental data, since the aim of this paper is the suggestion of a different point of view, to be discussed and applied in the future.

This approach allows an estimate of the time required to increase the crack lenght of a given amount, and as a consequence to know the crack growth rate at different stages of a single test.

The comparison with experimental results proves that:

-it is possible to measure the crack growth rate in a simple way, which is likely to give results comparable with those obtained using different test techniques.

-the so calculated crack growth rate, for a sensitized AISI 304 specimen tested in LWR environment, is almost constant.

The described approach can account for the effect of the strain rate on the crack growth rate, and for the presence of arrest marks on the crack surface.

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Figure Titles.

Fig.1: The superposition model for corrosion fatigue.

Fig.2: Comparison of experimental data points with the calculated stress-strain curve.

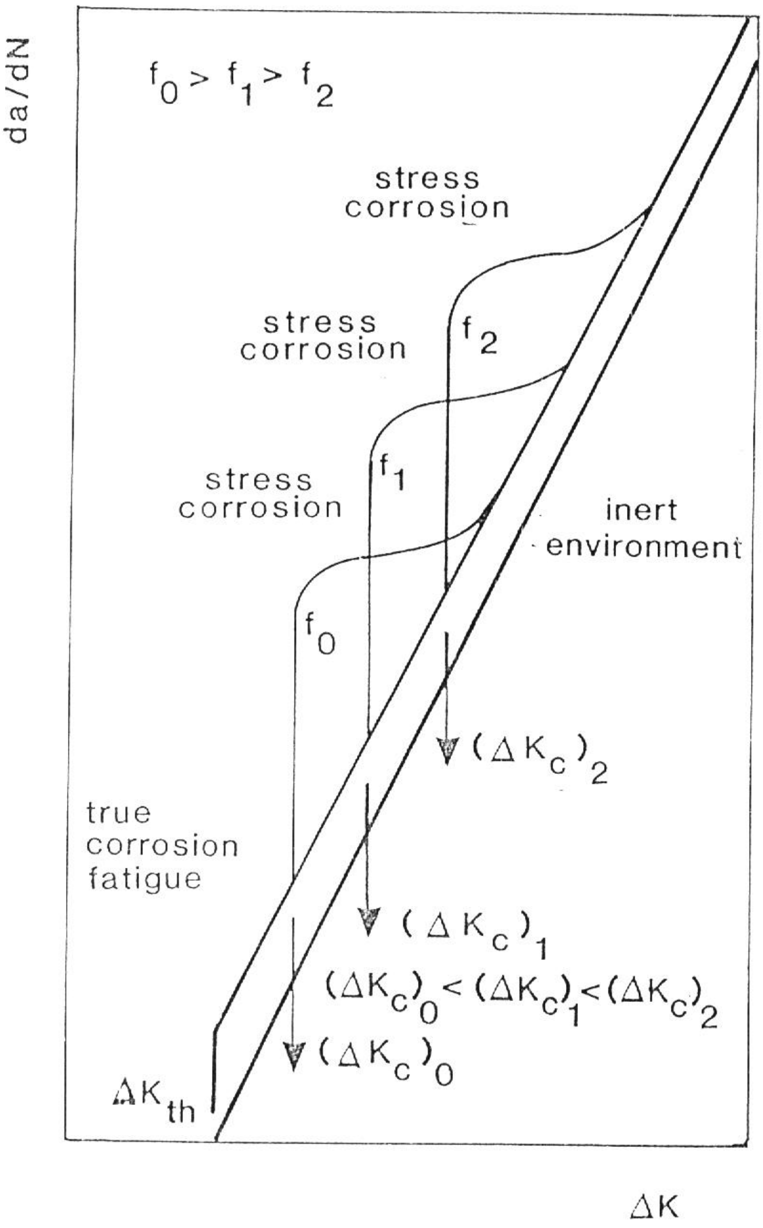
Fig.3: Stress -strain curves for crack depth varying form 1 to 6 mm.

Fig.4: Stress-strain curve for hypothetical SSRT results with constant (da/dt)SC value of 10-5 mm/sec. (a) and 10-4 mm/sec.(b).

Fig.5: Stress-strain curves from SSRT data at two different degrees of sensitization: (a) no sensitization, (b) high degree of sensitization.

Fig.6: Stress-strain curves at different crack depth calculated from the data shown in Fig.3 (enlargement of a section).

Fig.7: Comparison between the fracture surface of two AISI 304 specimens (transgranular fracture), tested under CF (a) and SSRT (b). Note the arrest mark, indicated by an arrow, in b.


da/dN
$f_0 > f_1 > f_2$
stress corrosion
stress corrosion
stress corrosion
f_2
f_1
f_0
inert environment
$(\Delta K_c)_2$
true corrosion fatigue
$(\Delta K_c)_1$
$(\Delta K_c)_0 < (\Delta K_c)_1 < (\Delta K_c)_2$
$(\Delta K_c)_0$
ΔK_{th}
ΔK

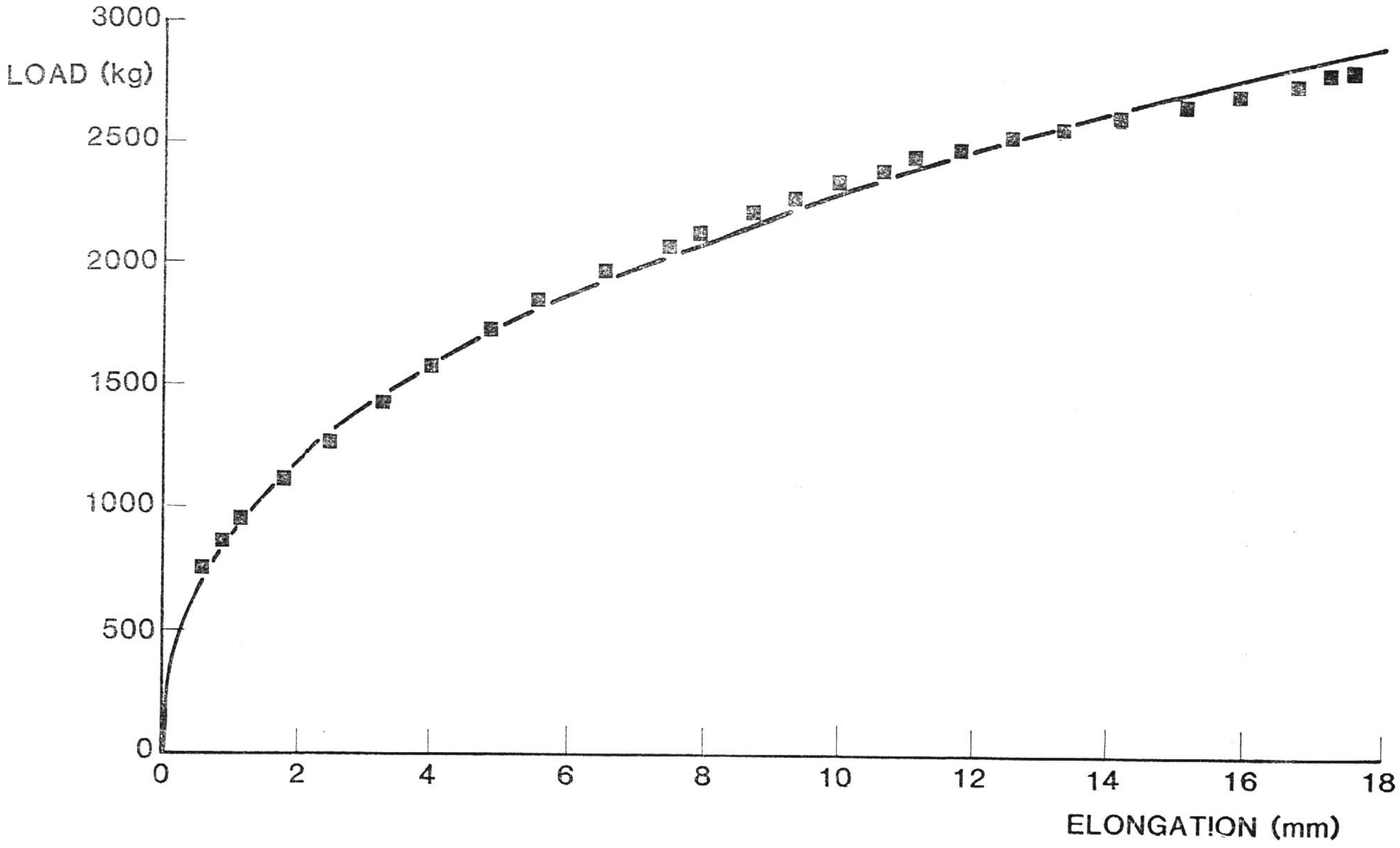

3000
LOAD (kg)
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
16
18
ELONGATION (mm)

Fig. 2

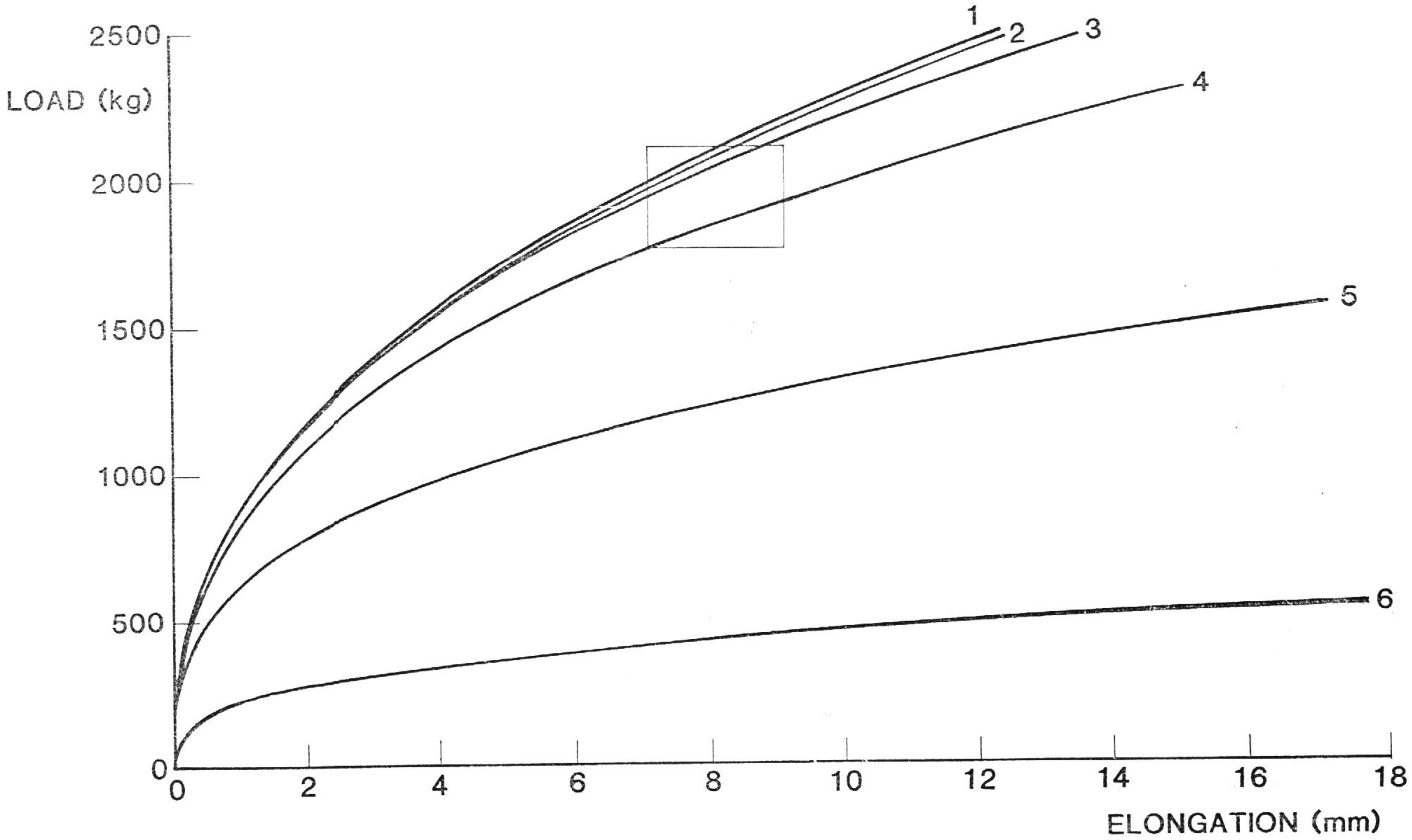

LOAD (kg)
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
16
18
ELONGATION (mm)
1
2
3
4
5
6

Fig. 3

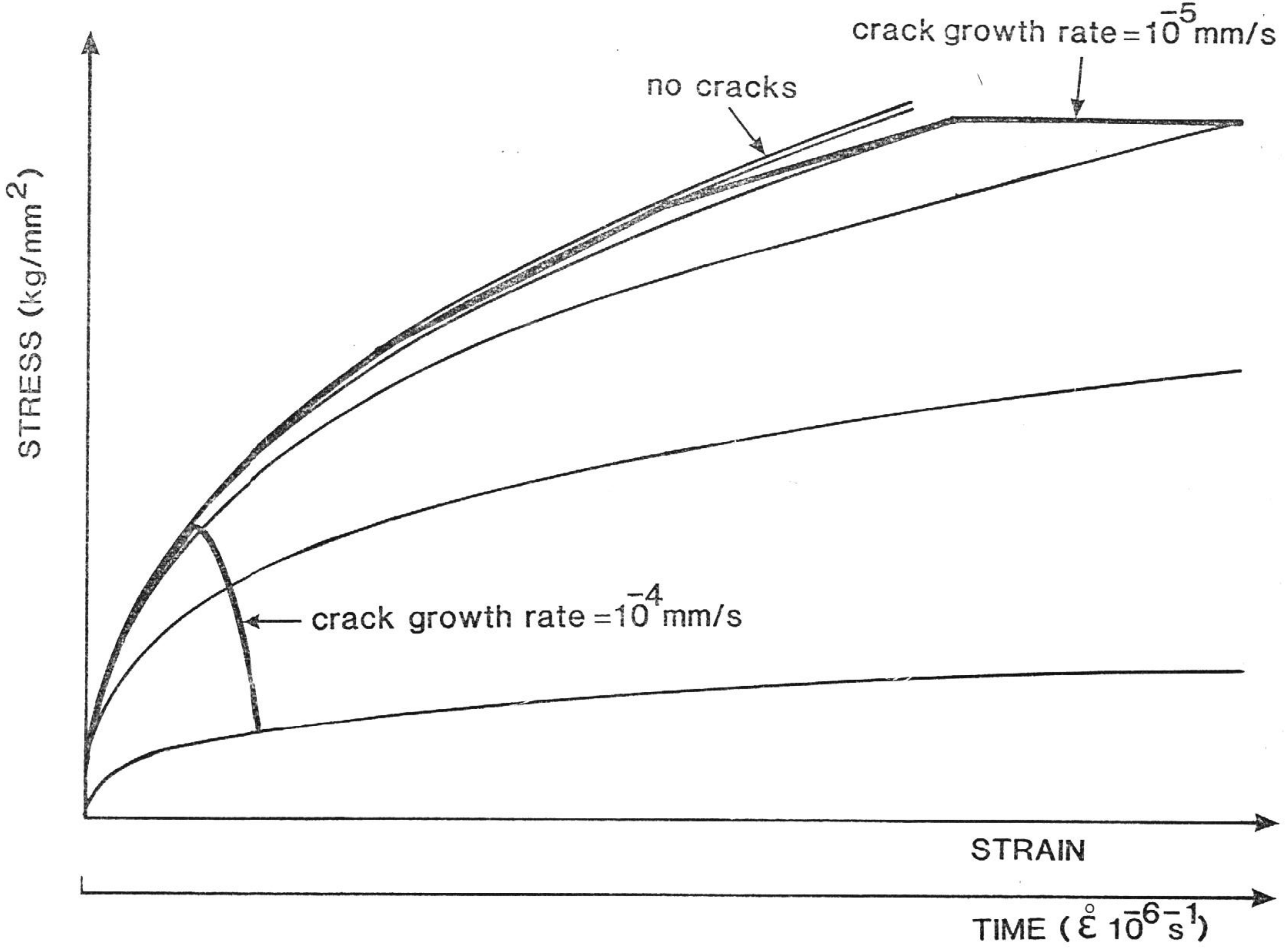

crack growth rate = 10^{-5} mm/s
no cracks
STRESS (kg/mm^2)
crack growth rate = 10^{-4} mm/s
STRAIN
TIME ($\mathring{\varepsilon}$ $10^{-6}s^{-1}$)

Fig. 4

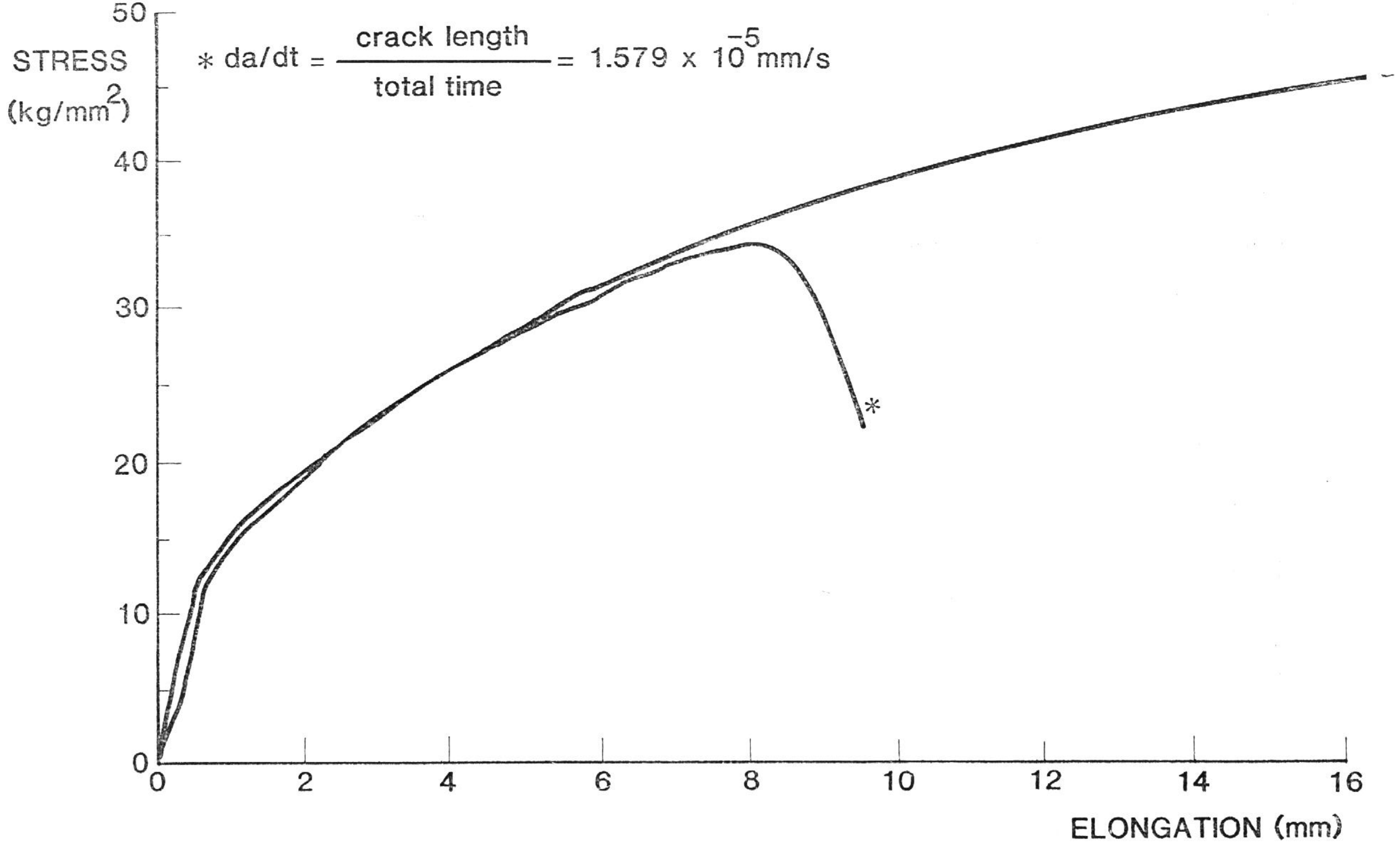

STRESS (kg/mm2)
50
40
30
20
10
0
* da/dt = crack length / total time = 1.579 x 10^-5 mm/s
*
0
2
4
6
8
10
12
14
16
ELONGATION (mm)

Fig. 5

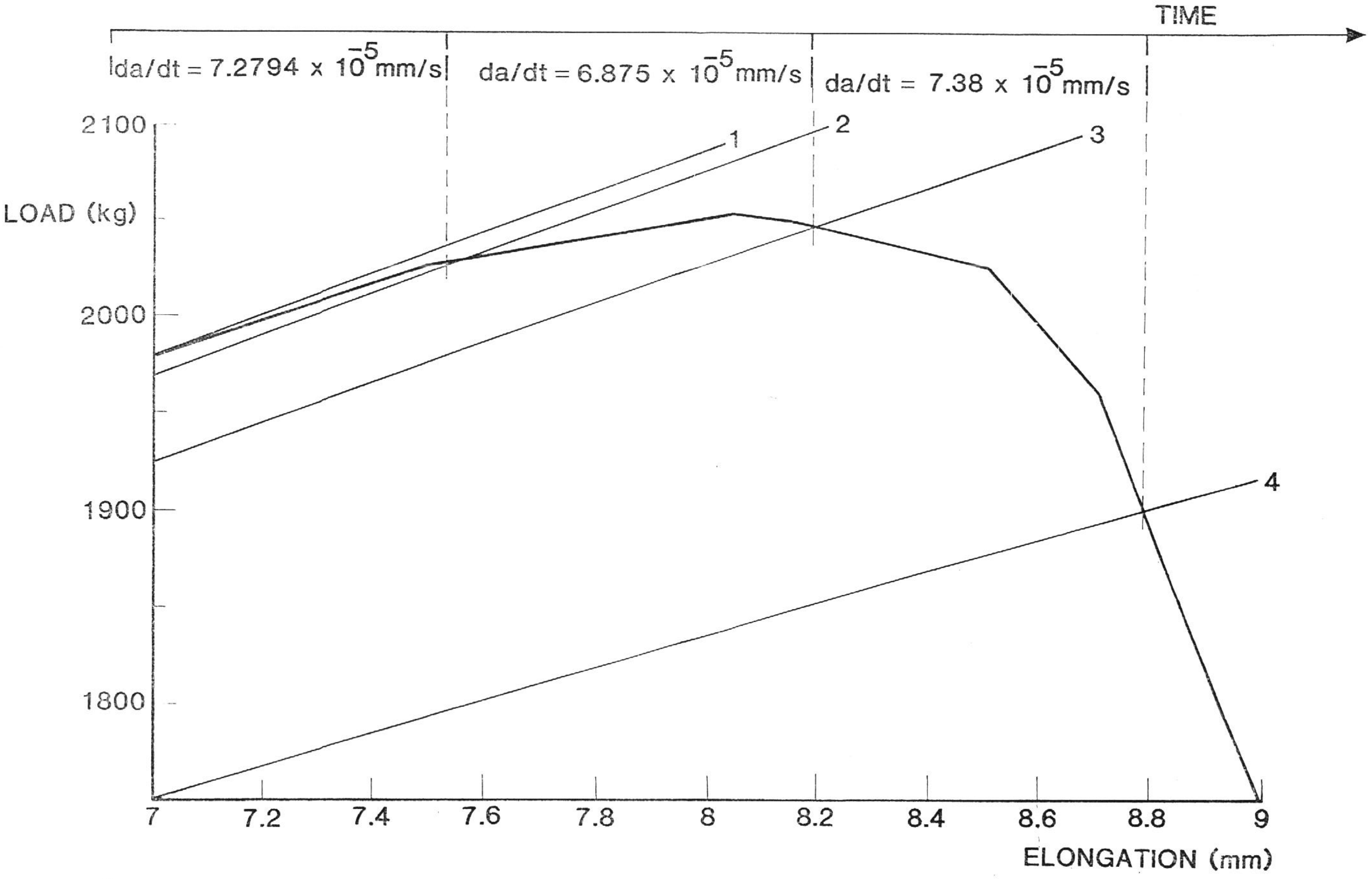

TIME
da/dt = 7.2794 x 10⁻⁵ mm/s
da/dt = 6.875 x 10⁻⁵ mm/s
da/dt = 7.38 x 10⁻⁵ mm/s
LOAD (kg)
2100
2000
1900
1800
1
2
3
4
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
8.8
9
ELONGATION (mm)

Fig. 6

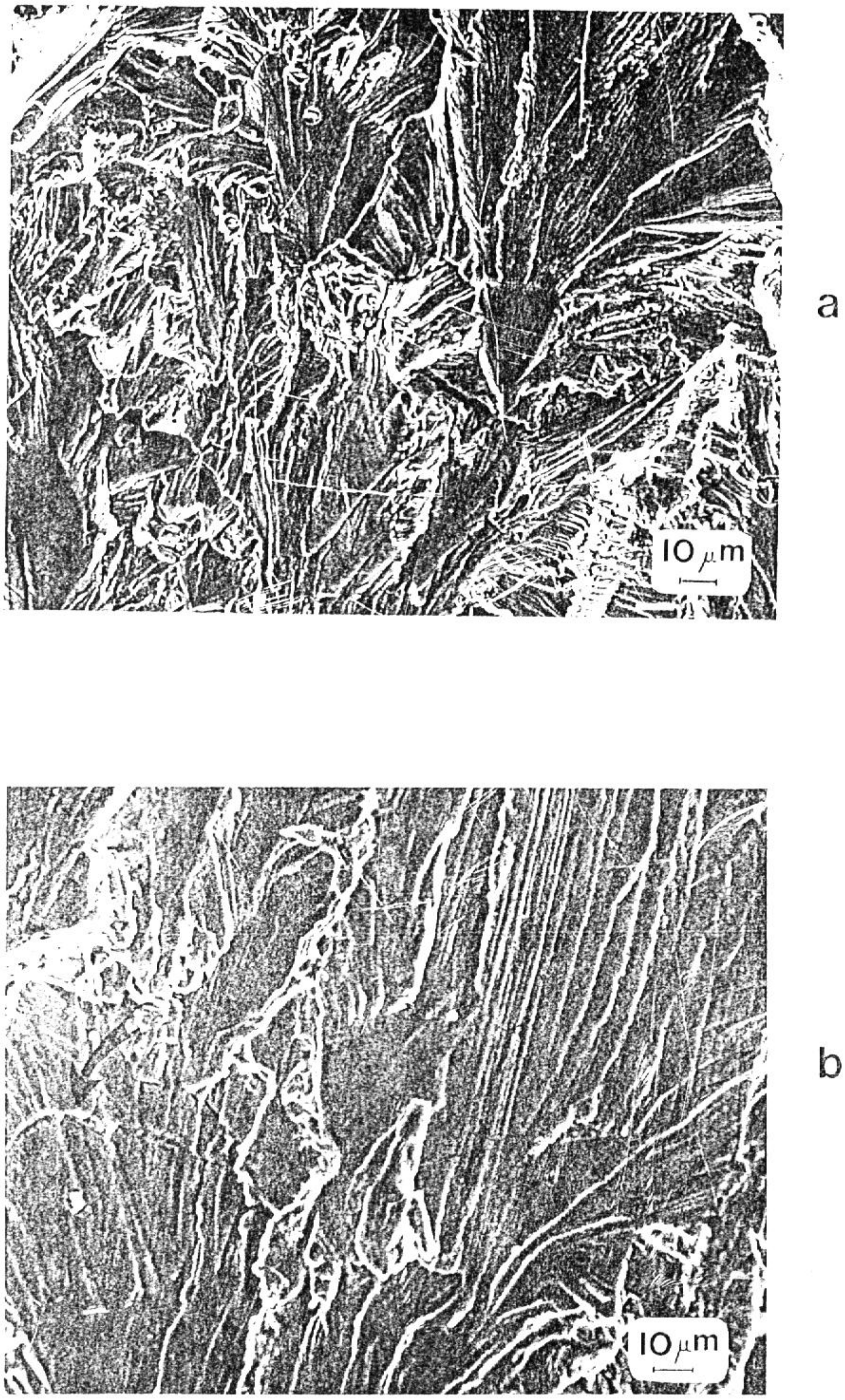


Fig. 7