

DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AEROSPACE ENGINEERING

Report LR-239

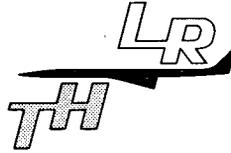
**SOME NOTES ON THE INFLUENCE OF RESIDUAL
STRESSES ON STRESS CORROSION CRACK GROWTH
AND COMPLIANCE MEASUREMENTS OF A
SENSITIZED ALUMINIUM 7075 ALLOY**

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H. F. de Jong

DELFT - THE NETHERLANDS

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ABSTRACT

Stress corrosion tests were performed on DCB specimens of an Aluminium 7075 alloy, which had received a sensitizing heat treatment. The stress corrosion tests showed that in the specimens high residual stresses were present. Compliance measurements proved that these stresses were caused by the sensitizing heat treatment.

NOTATIONS

a	cracklength (mm)
a_i	initial cracklength (mm)
B	specimen width (mm)
E	modulus of elasticity (kgf/mm^2)
H	height of specimen (mm)
K_I	stress intensity factor for mode I ($\text{kgf}/\text{mm}^{\frac{3}{2}}$)
K_{I_i}	initial stress intensity factor for mode I ($\text{kgf}/\text{mm}^{\frac{3}{2}}$)
P	force (kgf)
P_{op}	force at which the crack opens (kgf)
V_c	crackopening at the loadline (mm)
V_m	measured crackopening (mm)

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1. INTRODUCTION

Stress corrosion tests were performed on an aluminium alloy of the 7075 type. Originally the goal of the experiments was to investigate the influence of the applied stress (or K_{I_1} -value) on the crack growth rate in a 3% NaCl-solution. The specimens were of the DCB-type (fig. 1). The heat treatment of the alloy in the as received condition was T7351. This heat treatment is developed to improve the stress corrosion resistance. In this condition the material is less suitable for stress corrosion experiments. A sensitizing heat treatment (TX) was given to the specimens after machining. This heat treatment consisted of:

- (1) solution treatment: 1 hour at 482°C,
- (2) quenching in cold water (0 - 4°C), the specimens were immersed in the vertical position,
- (3) ageing at 121°C for 24 hours (Ref. 1).

All specimens were heat treated simultaneously. The specimens, with either a static precrack or a fatigue precrack were stressed to various K_{I_1} -values (i = initial value). Stress corrosion testing occurred in an aerated 3% NaCl-solution. Due to exceptional circumstances the specimens were not looked after for a period of 4 months, so crack growth rates were not measured. After this period two of the specimens had failed completely, and the others showed crack lengths ranging from 50 to 90 millimeters (as far as visible on the specimen sides). The two parts of the two failed specimens showed a considerable bending. This fact indicated that there were considerable residual stresses in the specimens, probably due to the reheat treatment. This phenomenon is already described by Hyatt (ref. 2).

To investigate this, compliance measurements were carried out on specimens in the as received condition (T7351) as well as in the reheat treated condition (TX). It was shown that the specimen in the TX-condition had considerable residual stresses. Both the stress corrosion experiments and the compliance measurements are discussed in more detail in the following chapter.

2. EXPERIMENTAL

2.1. STRESS CORROSION TESTS

The D.C.B. specimens were loaded by tightening the bolts until the desired crack-opening was reached (fig. 2). Because the crack-opening is not measured at the loadline, a correction is necessary. The crack-opening at the loadline for the specimens used in this investigation, can be calculated by using the formula:

$$V_c = V_m \cdot \frac{a}{a + 21} \quad \text{ref. 3} \quad (1)$$

where V_c = crack-opening at the loadline (mm)

V_m = measured crack-opening (mm)

a = crack-length (mm)

The formula used for calculating the K_{I_i} -values is:

$$K_{I_i} = \frac{E \cdot V_c}{H} \cdot \left[\frac{3.46 + 2.38 \left(\frac{H}{a}\right)}{7.97 \left(\frac{a}{H}\right)^2 + 16.48 \left(\frac{a}{H}\right) + 11.32} \right] \quad \text{ref. 4} \quad (2)$$

where E = modulus of elasticity (N/mm^2)

H = height of the specimen (mm) see fig. 1.

The K_{I_i} -values are given in table 1.

The steel bolts and the knife-edges for the COD-meter are protected against the influence of the corrosive medium by dipping this part of the specimens in molten paraffin wax.

The specimens were placed in a 3% NaCl solution saturated with air. The pH of the solution was between pH = 6 and pH = 7. The solution was refreshed every week.

2.2. COMPLIANCE MEASUREMENTS ON SPECIMENS WITH SAW CUT

Compliance measurements were made on two specimens. One specimen was in the as received condition (T7351) and the other specimen had received the TX heat treatment. The compliance C of a specimen can be determined by measuring the crack-opening V at the loadline of the specimen at a certain load P as a function of the crack-length a .

The crack-opening was measured with a clip-in displacement gage of the type described in ref. 5. After each measurement the crack-length was increased some millimeters by sawing with a jewelers saw. The width of the saw cut was approximately 0.3 mm. Formula (1) was used to calculate the crack-opening at the loadline.

3. RESULTS

3.1. STRESS CORROSION TESTS

After 4 months the specimens were removed and examined for stress corrosion cracks. Two of the specimens had failed completely and the other 5 specimens were cracked over a length varying from 50 to 92 millimeters, as far as visible on the specimen sides (see table 2). The two parts of the specimens that had failed completely showed considerable bending (fig. 3). It was clear that the last few millimeters of the fracture were not due to stress corrosion, but were caused by mechanical failure (fig. 4).

The other specimens were dried and stored for about 1 month. After this period one of this specimens had also failed completely, while the crack-length of the other specimens had increased by 6 - 15 millimeters, measured at the specimen sides (table 2). Again the parts of the failed specimen showed considerable bending.

There was a remarkable difference in fracture surface appearance between the part of the crack grown in the NaCl environment and the part of the crack that had grown in the air environment. The first part was dark and rather rough, whereas the other part was bright and relatively smooth (fig. 5 en 6).

The remaining specimens were loaded until mechanical fracture occurred. All specimens showed the same difference in fracture appearance (fig. 7). The crack-fronts were extremely curved: the crack-length in the middle of the specimens was about 20 - 30 millimeters longer than the crack-length visible at the specimen sides (fig. 5, 7 and 8). So K_I -calculations based on the crack-length measured at the specimen sides are highly inaccurate.

All observations made it clear that significant residual stresses were present in all specimens.

3.2. COMPLIANCE MEASUREMENTS

The compliance measurements for the T7351 specimen showed the usual linear relation between load and crack opening for all crack-lengths. However, the TX-specimen showed a quite different behaviour. Until a crack-length of about 35 millimeters the relation between the load P and the crack-opening V_m was exactly the same as for the T7351 specimen. For longer crack-lengths the registered P - V_m relation could be divided into two parts (see fig. 9):

- a: in the first part the crack is not fully open, the slope of the P - V_m registration is comparable to the slope for a crack-length of about 18 millimeters. The P - V_m relation is not exactly linear but the deviation is small (see fig. 9),
- b: in the second part of the registration the crack is opened at a certain load (called P_{opening}) and a normal linear P - V_m relation is obtained. The value of P_{op} increases with increasing crack-length, until a maximum value of 476 N is reached at a cracklength of about 71 millimeters. For longer crack-lengths P_{op} decreases with increasing crack-length (table 3).

The specimen failed at a crack-length of 130 millimeters at a load of 56.4 kgf. At that crack-length the value of P_{op} had decreased to 30.2 kgf.

The compliance measurements proved that the residual stresses were due to the TX heat treatment. The compliances of the specimens are given in fig. 10. It was possible to reduce the compliance of the specimen with residual stresses into the compliance of the specimen without residual stresses. Therefore the second part of the P - V_m registration is lengthened to the V_m -axis. The point of intersection is the new point from where the corrected V_m -value for a given load P is measured (fig. 11). In table 4 this corrected V_m -values are given. The corrected compliance of the specimen with residual stresses is exactly equal to the compliance of the specimen without residual stresses, as can be seen in fig. 10.

In this figure also the theoretical compliance of a specimen with a

crack-width of zero is given. Formula (2) is used to calculate the compliance. It can be seen that the finite width of the saw cuts of the actual specimens (about 0.3 mm) has only a minor influence on this compliance.

4. DISCUSSION OF THE RESULTS

The TX heat treatment is applied to increase the stress corrosion susceptibility by changing the micro-structure of the alloy. A major disadvantage of such a reheat treatment is that introduces significant residual stresses, which also will affect the stress corrosion behaviour. Consequently it is not possible then to investigate the influence of the change of the micro-structure alone.

The method advised by Hyatt in his already mentioned report (ref. 2) to eliminate the residual stresses by plastically deforming the DCB specimen blanks after quenching is only possible if a tensile machine with the required capacity is available.

The extremely curved crack-fronts shows that the highest residual stresses are in the centre of the specimens. Due to this curved crack-fronts a measurement of the crack-length by visual means is meaningless. Even if a part of the specimen (from the faces that are perpendicular to the crack plane) are removed by machining (as is done by Hyatt), the curvature would still be unacceptable in this case for an accurate crack-length measurement

A better method is used in an investigation that is carried out at this moment. By this method blanks with a size of appr. 14 x 17 cm are heat treated. After the heat treatment the blanks are machined to a size of appr. 12 x 15 cm. The specimens are made from this machined blank. So those parts of the blanks where a stress gradient in the horizontal plane existed are removed and the crack-fronts are almost straight.

In a stress corrosion test on a DCB-specimen with a fixed crack-opening at the load line the crack-length can still be determined by measuring the crack-opening at another location on the specimen. The location on top of the specimen (see fig. 1) is very useful for this purpose, also because it need not be immersed during the stress corrosion test. In eq. (1) it means that V_m is measured while V_c is a constant. The value of a can then be calculated. Unfortunately this method can not be used if residual stresses of the kind described in the foregoing chapters are present.

No reasonable explanation could be made for the fact that no influence of residual stresses was measured until a crack-length of 35 mm. For the specimen geometry as used in this investigation residual stresses should be expected for crack-lengths of about 12 to 15 mm and longer. It is possible that the fact that the specimens were immersed in the quenching bath in the vertical position with the top of the specimens upside had some influence on the quenching rate. After quenching the temperature of the bath had raised from 3°C to 10°C.

5. CONCLUSIONS

- 1) Stress corrosion tests and compliance measurement have shown that cold quenching of DCB specimens introduces considerable residual stresses.
- 2) If the influence of a change in the micro-structure of the material due to a heat treatment is studied, it is necessary to eliminate these residual stresses (p.e. by plastically deforming after quenching).
- 3) It is possible to reduce the compliance of a specimen with residual stresses into the compliance of a stress free specimen.
- 4) Compliance measurements on DCB specimens with thin saw cuts were in good agreement with a formula in the literature, derived for infinite crack-width.

6. ACKNOWLEDGEMENT

The author would like to thank prof. J. Schijve for his useful remarks during preparation of this report.

7. REFERENCES

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Specimen	Initial crack-length a_0 (mm)	V_{measured} (mm)	$V_{\text{corrected}}$ (mm)	K_{Ii} ($\text{kgf}/\text{mm}^{\frac{3}{2}}$)
18	28	1.320	0.754	61.8
19	34	1.716	1.061	63.1
21	28	1.320	0.754	61.8
22	30	1.716	1.009	73.8
23	29	1.320	0.765	59.2
54	25	1.320	0.717	70.5
117	28	1.320	0.754	61.8

Table 1: Initial cracklength and K_{Ii} -values.

Specimen	Crack-length after 4 months (mm)	K_I after 4 months ($\text{kgf}/\text{mm}^{\frac{3}{2}}$)	Crack-length after 5 months (mm)	K_I after 5 months ($\text{kgf}/\text{mm}^{\frac{3}{2}}$)
18	50	23.1	57	18.3
19	72	16.9	78	14.6
21	73	11.7	80	9.9
22	failed	--	failed	--
23	70	12.8	85	8.8
54	failed	--	failed	--
117	92	7.6	failed	--

Table 2: Crack-length and K_I value after stress corrosion tests.

No.	Length of saw cut (mm)	P_{opening} (kgf)
1	---	0
2	chevron	0
3	18.0	0
4	23.5	0
5	28.0	0
6	31.5	0
7	35.0	0
8	40.0	18
9	42.5	26
10	45.0	33
11	48.0	38
12	50.0	40
13	54.0	45
14	58.0	47.5
15	62.5	48.5
16	66.0	48.5
17	71.0	48.5
18	77.0	47
19	83.0	45.5
20	87.0	42.5
21	90.5	42.5
22	96.0	42.5
23	100.0	41.25
24	105.0	40.5
25	110.5	38.6
26	116.0	37.5
27	120.5	36.5
28	126.0	34.8
29	130.0	30.2

Table 3: Value of P_{opening} as a function of the crack-length.

No.	Length of saw cut (mm)	V_{measured} (mm) (P = 60 kg)	Corrected V_m (mm) (P = 60 kg)	V_c (mm)	$V_c/P \cdot 10^3$ (mm/kgf)
1	---	---	---	---	---
2	chevron	---	---	---	---
3	18.0	0.084	0.084	0.039	0.65
4	23.5	0.135	0.135	0.071	1.18
5	28.0	0.242	0.242	0.138	2.30
6	31.5	0.326	0.326	0.196	3.26
7	35.0	0.363	0.363	0.227	3.78
8	40.0	0.357	0.488	0.320	5.33
9	42.5	0.363	0.588	0.393	6.56
10	45.0	0.334	0.650	0.443	7.38
11	48.0	0.316	0.759	0.528	8.80
12	50.0	0.334	0.855	0.602	10.03
13	54.0	0.315	1.043	0.751	12.52
14	58.0	0.311	1.215	0.892	14.86
15	62.5	0.338	1.477	1.106	18.43
16	66.0	0.383	1.661	1.260	21.00
17	71.0	0.469	2.036	1.571	26.19
18	77.0	0.590	2.458	1.931	32.19
19	83.0	0.742	2.980	2.378	39.65
20	87.0	0.909	3.317	2.672	44.54
21	90.5	1.022	3.810	3.092	51.50
22	96.0	1.280	4.340	3.561	59.40
23	100.0	1.454	4.522	3.737	62.30
24	105.0	1.681	5.173	4.311	71.86
25	110.5	2.136	5.961	5.009	83.49
26	116.0	2.567	6.703	5.676	94.60
27	120.5	3.067	7.703	6.650	109.34
28	126.0	3.749	8.680	7.440	124.01
29	130.0	fracture at 4.726 P=56.4 kgf	---	---	---

Table 4: The corrected compliance of the specimen with residual stresses.

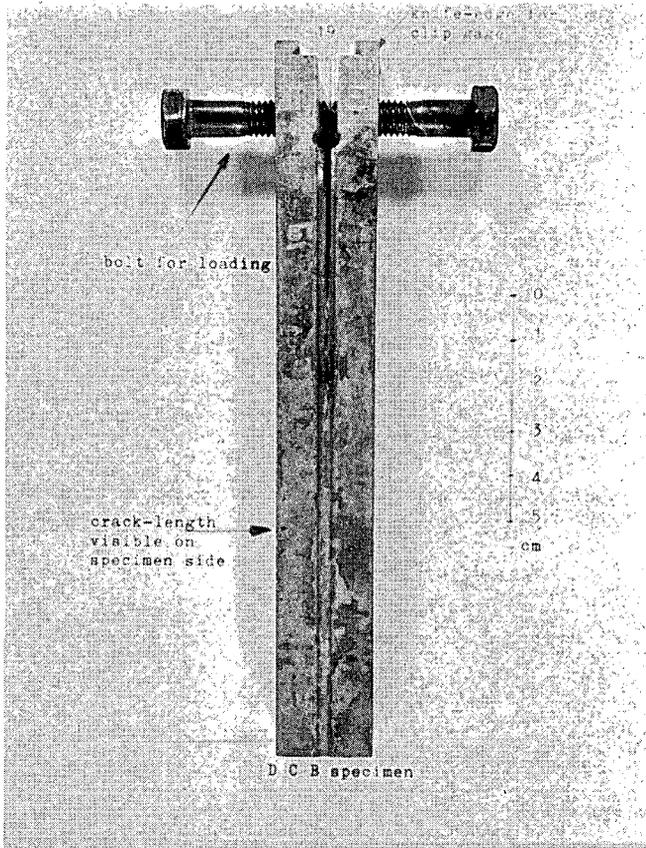


Fig. 2. Specimen of the Double
Cantilever Beam type.

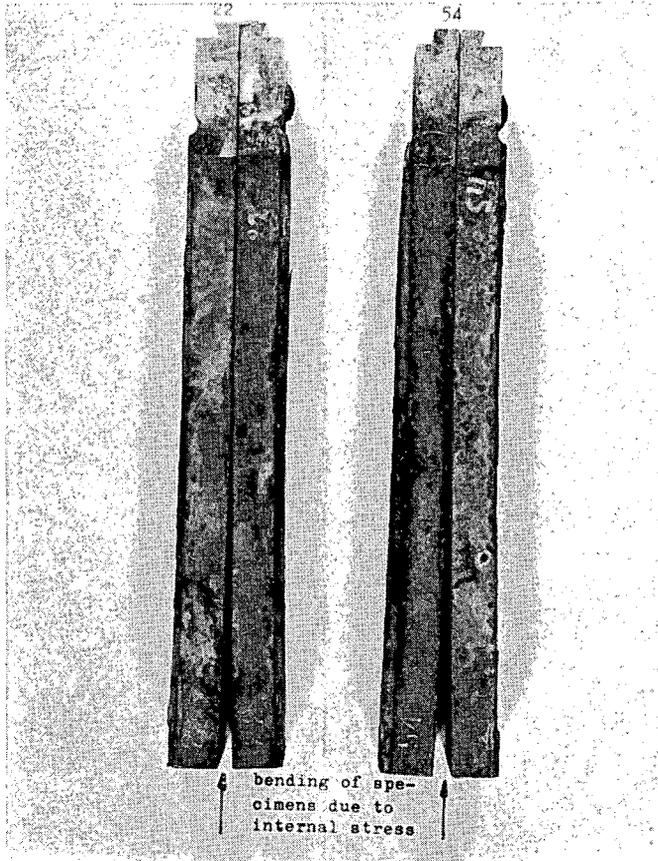


Fig. 3. Bending of the specimen after failure.

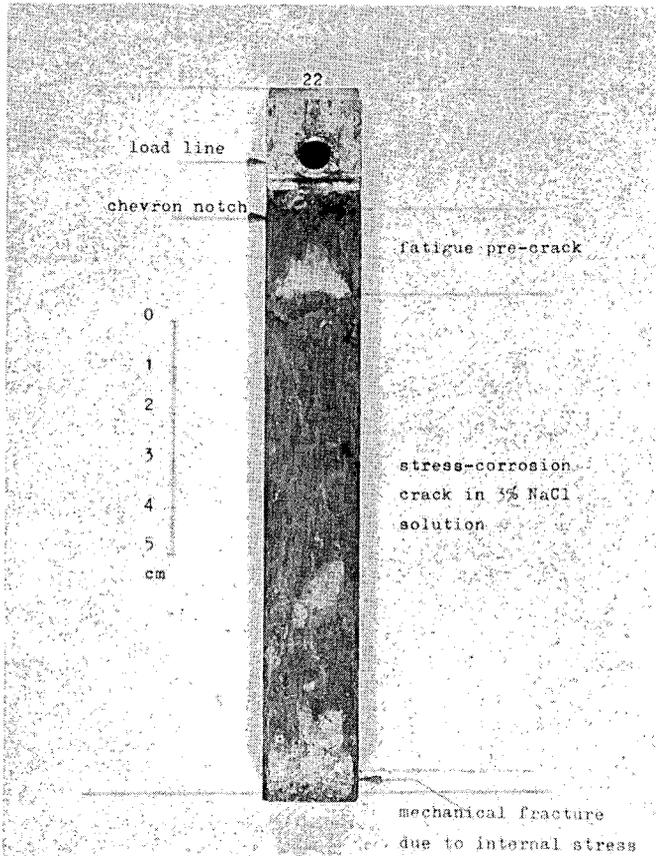


Fig. 4. Mechanical fracture due to residual stress of the almost completely failed specimen.

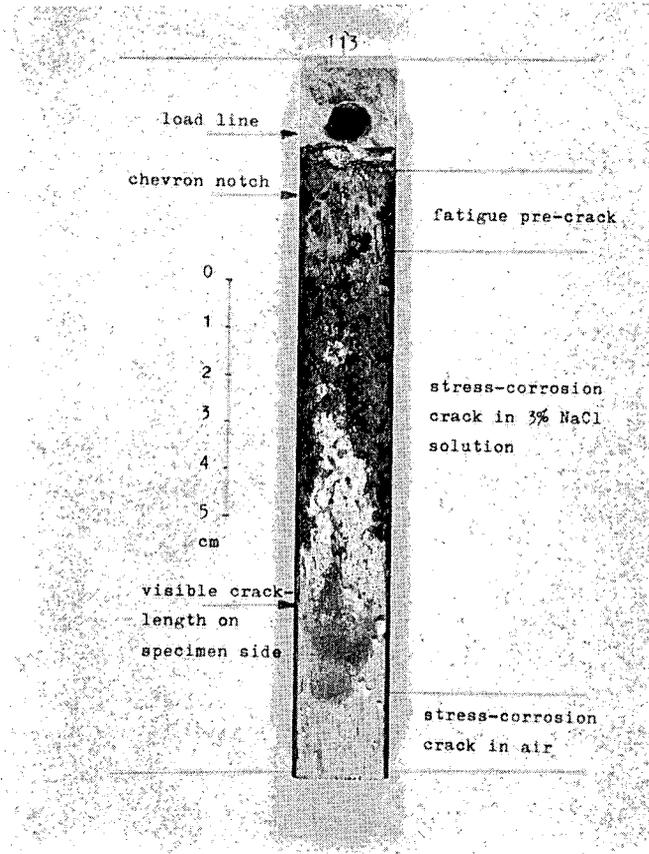


Fig. 5. Fracture surface of stress corrosion crack in NaCl-solution and in air.

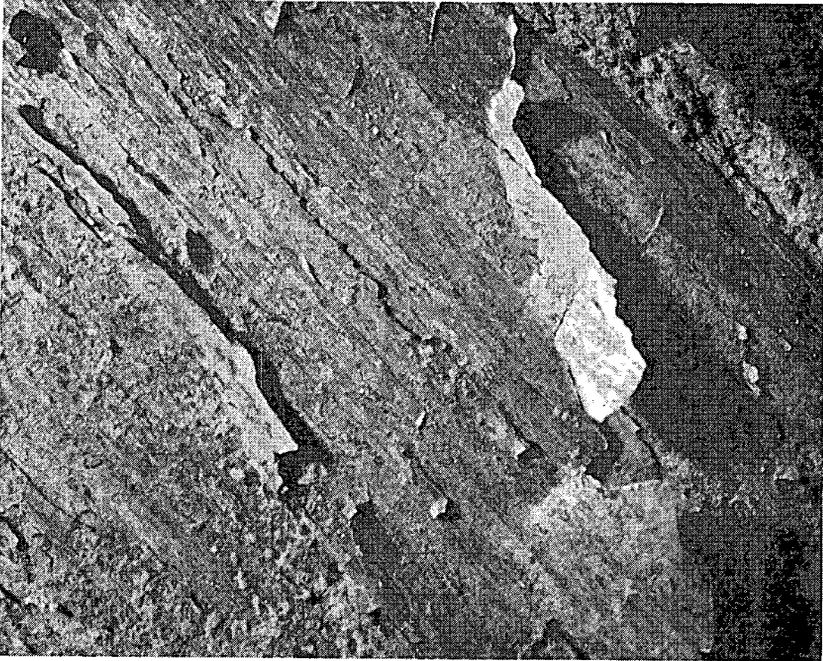


Fig. 6. Fracture surface of stress corrosion crack
in NaCl-solution (Magn.: 10 x).

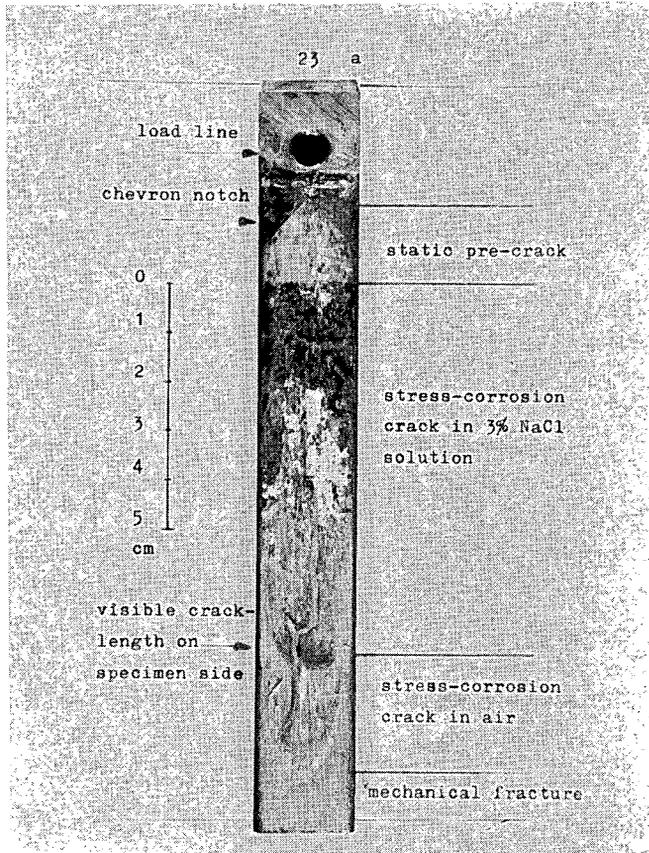


Fig. 7. Curved crack-front.

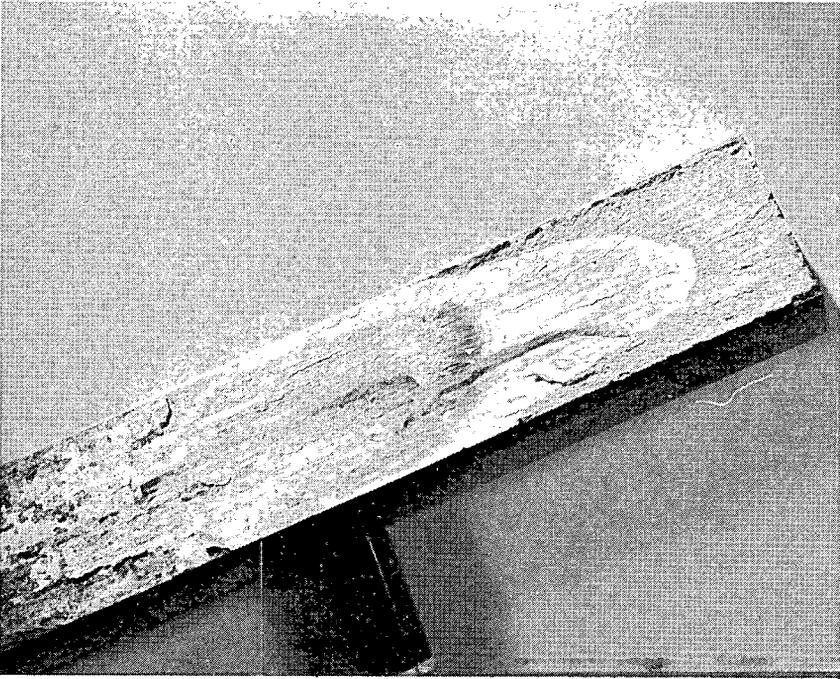


Fig. 8. Curved crack-front (same specimen as fig. 6).

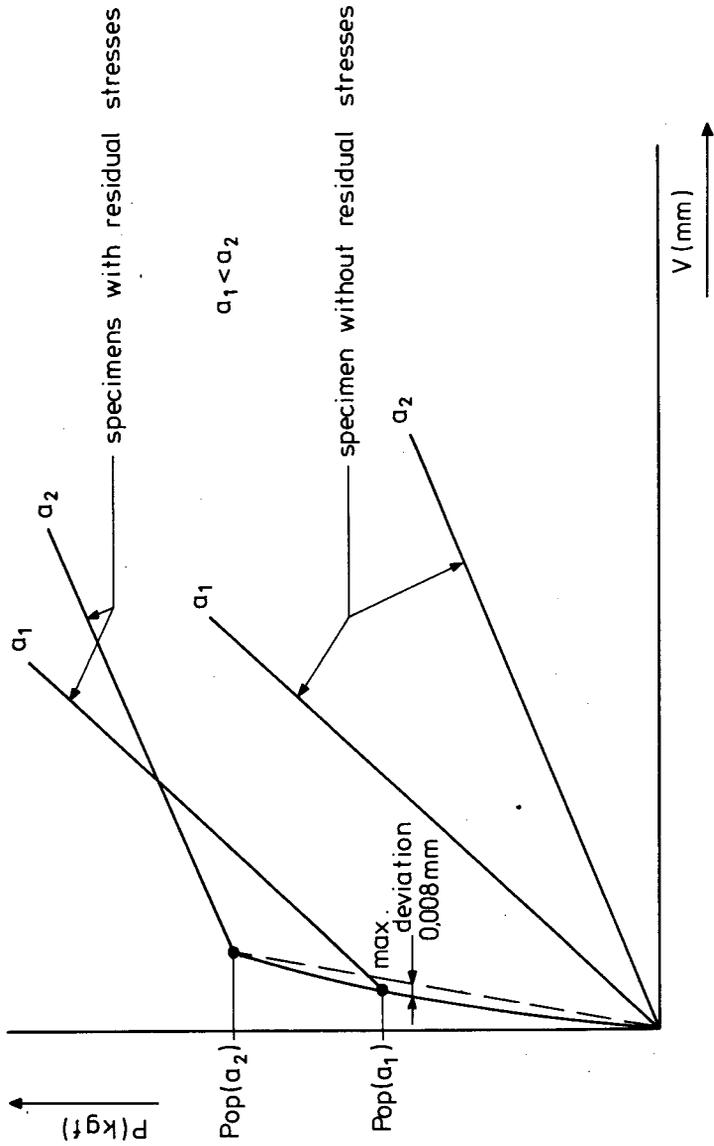
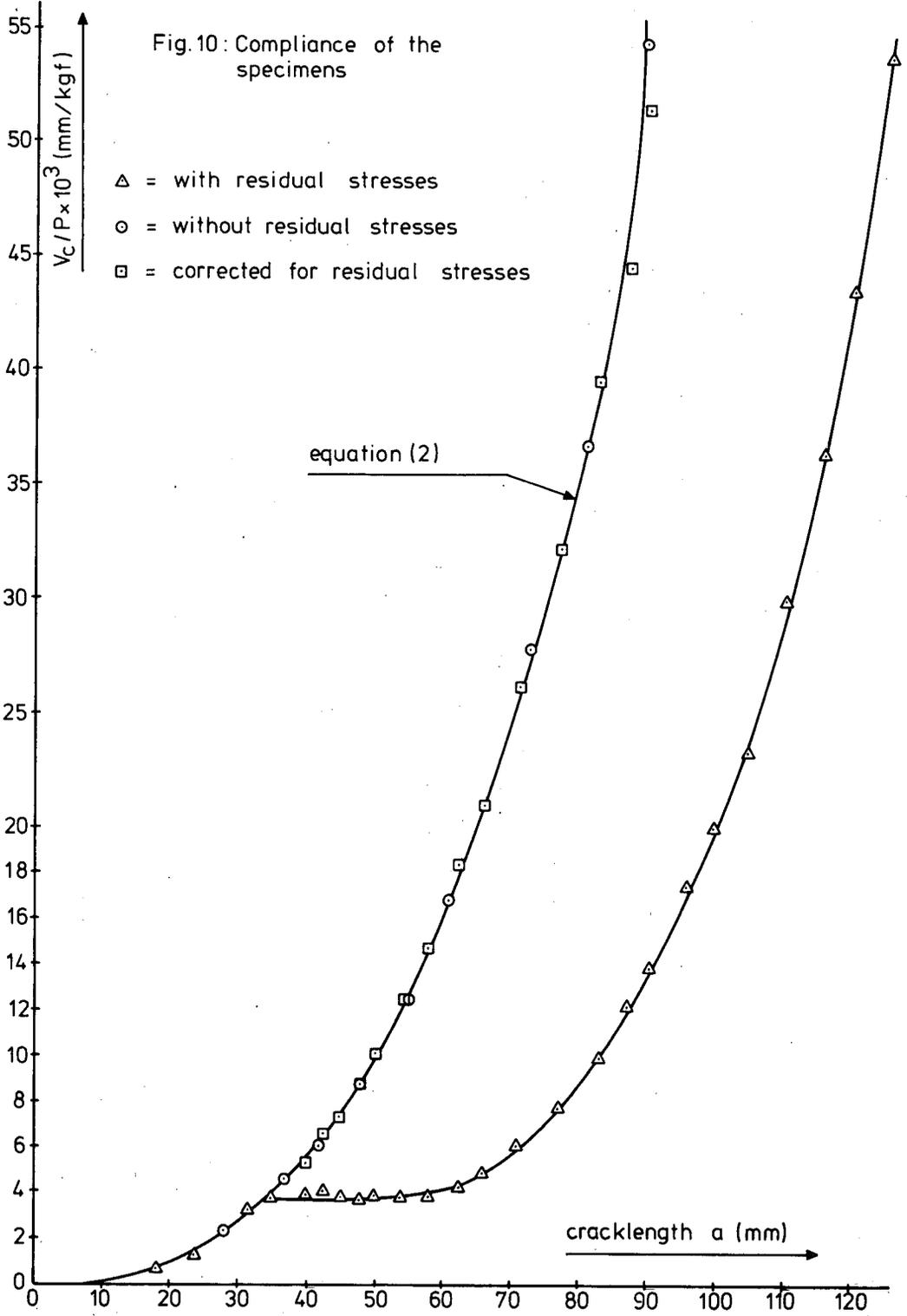


Fig.9: Schematic P-v registration for specimens with and without residual stresses

Fig.10: Compliance of the specimens



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