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ABSTRACT
In 1991 a simple automated stress corrosion testing method called the ASCOR (Automated Stress COrrosion Ring) test was developed to test aluminium alloys according to ASTM specification G49. The present investigation concentrated on evaluating two aspects of the test method:
- The SCC initiation criterion (2 % load decrease).
- The possibility of defining a threshold stress for micro SCC growth in addition to that for macro SCC growth.

It was found that substantial SCC growth had occurred at 2 % load decrease. We therefore propose reducing the load decrease criterion to 1 % as an improved compo40romise between determining the SCC initiation life in a well-defined way and limiting the contribution of SCC growth to this life.

Fracture strength ratios (fracture strength of loaded exposed specimens divided by fracture strength of unloaded exposed specimens) less than 100 % were found at exposure stresses below the threshold stress for macro SCC growth. Fractographic investigation showed SCC on the fracture surfaces of specimens tested at these exposure stresses. A threshold stress for micro SCC growth was determined and is defined as the exposure stress at and below which the fracture strength ratio is 100 %.

Keywords: stress corrosion, accelerated testing, constant load, threshold stress, alternate immersion, aluminium alloys

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FURTHER EVALUATION OF THE ASCOR TEST FOR STRESS CORROSION TESTING OF ALUMINIUM ALLOYS

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ABSTRACT:
In 1991 a simple automated stress corrosion testing method called the ASCOR (Automated Stress COrrosion Ring) test was developed to test aluminium alloys according to ASTM specification G49. The present investigation concentrated on evaluating two aspects of the test method:

- The SCC initiation criterion (2 % load decrease).
- The possibility of defining a threshold stress for micro SCC growth in addition to that for macro SCC growth.

It was found that substantial SCC growth had occurred at 2 % load decrease. We therefore propose reducing the load decrease criterion to 0.5 % to limit the contribution of SCC growth to the SCC initiation life.

Fracture strength ratios (fracture strength of loaded exposed specimens divided by fracture strength of unloaded exposed specimens) less than 100 % were found at exposure stresses below the threshold stress for macro SCC growth. Fractographic investigation showed SCC on the fracture surfaces of specimens tested at these exposure stresses. A threshold stress for micro SCC growth was determined and is defined as the exposure stress at and below which the fracture strength ratio is 100 %.

KEYWORDS: stress corrosion, accelerated testing, constant load, threshold stress, alternate immersion, aluminium alloys

In 1991 a simple automated stress corrosion testing method called the ASCOR (Automated Stress COrrosion Ring) test was developed at the NLR for testing aluminium alloys according to ASTM specification G44. The method uses cylindrical or sheet specimens in a strain-gauged loading ring, see Fig. 1. Initiation of a stress corrosion crack results in a small load decrease. During the test the load is measured periodically and stored in a Data Acquisition system

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controlled by a Personal Computer. Also, the load signal is recorded continuously, enabling assessment of the stress corrosion process.

Figure 2 shows a typical load-time record for a failed sheet specimen. First there is a linear load decrease with time. Some creep of the strain gauges may have contributed to this load decrease, but the main load decrease is considered to be attributed to a decrease in cross-section of the specimen owing to corrosion. This is especially because alternate immersion of aluminium alloys in NaCl solution results in severe pitting corrosion. The linear load decrease is followed by a faster load decrease indicating SCC growth. During later crack growth there may be sudden load decreases due to ligament overloads. A 2 % load decrease has been used as the criterion for determination of the SCC initiation life. This enables the construction of stress-lifetime curves with clearly defined SCC initiation lives and without time-consuming and subjective inspections that also disturb the test procedure. More detailed information about the test method is given in reference 1.

The present investigation concentrated on a more detailed evaluation of the following two aspects of the ASCOR test.

<u>Load decrease criterion for determination of the SCC initiation life</u>

The 2% load decrease criterion to establish the SCC initiation life was a compromise intended to include evident initiation of one or more stress corrosion cracks but to minimise crack growth. In the present investigation the load decrease in different stages of the SCC test was related to the amount of stress corrosion measured from the fracture surfaces.

<u>Threshold stress for micro SCC growth</u>

The SCC initiation lives determined with the ASCOR test enable the construction of a stress-lifetime curve including a threshold stress. This has to be considered as a threshold stress for evident (macro) SCC growth, because it has been based on the 2 % load decrease criterion. This means that after the maximum test duration a small amount of stress corrosion crack growth may be present in specimens tested at or even below this threshold stress. We investigated whether it is possible to define a threshold stress for micro SCC growth in addition to the threshold stress for macro SCC growth.

Test programme and experimental details

An overview of the test programme is given in table 1. Three materials were used. Cylindrical specimens were machined from an 80 mm thick 7010-T651 plate and loaded in the short transverse direction. A previous investigation showed this material with this loading direction has a low stress corrosion resistance [2]. Sheet specimens were machined from 1.6 mm thick 8090-T81 sheet and loaded in the long transverse direction. Two versions of this material were tested: an old version with high SCC resistance [3], and a new version with unintentionally lower SCC resistance [4]. The chemical compositions and mechanical properties of all three materials are given in tables 2 and 3. The newer version of 8090-T81 had a lower Zr content to improve recrystallization through the sheet thickness. Also the ageing time at 150 °C was increased from 12 to 24 hours to obtain slightly higher strength for the newer version, but table 3 shows that for the sheets tested in the present investigation the old version sheet had a higher strength. An explanation of the low SCC resistance for the new version is not known to the authors. The specimens were alternate immersion tested in 3.5 % sodium chloride solution according to ASTM specification G44.

Three types of tests were done. The first was to determine stress-lifetime relationships for the three materials (test type a). These relationships enabled definition of stress levels to be used in tests to investigate the load decrease criterion for determining the SCC initiation life (test type b). In these tests which did not include 8090-T81 old version, because of its high SCC resistance, loaded and unloaded specimens were exposed to the environment for identical times, and also until specific deviations of the load-time records from the initial linear relation were reached. Then both the loaded and unloaded specimens were tensile loaded to failure. The ratio of the fracture strengths (R_{fs}) indicated the influence of loading on the attack during exposure. The amount of stress corrosion (and corrosion) was measured from the fracture surfaces of the specimens using optical fractographs and an image analysis system.

The stress-lifetime relationships (test type a) also enabled selecting stress levels for investigation of the threshold stress for micro SCC growth (test type c). In these tests loaded and unloaded specimens were exposed during the maximum test duration of 30 days and then tensile loaded to failure. The exposure stress was lowered until the fracture strengths of the loaded specimens had increased to the same value as those of the unloaded specimens (R_{fs} = 100 %). SEM investigations of the fracture surfaces were done to detect micro SCC features.

The geometries and dimensions of the specimens used in the SCC tests are shown in figure 3. Two types of cylindrical specimens are depicted. Initially we used a cylindrical specimen with threaded ends fitting into the loading fixtures of the rings. The loading fixtures, made from 17-4 PH steel, and the aluminium specimens were coated with wax to avoid corrosion attack and galvanic coupling. The central parts of the specimens were left uncoated. This proved unable to completely prevent galvanic coupling. Subsequently the cylindrical specimens and loading fixtures were modified to use ceramic (yttria-stabilised zirconia) pins for load transfer. This modification was not necessary for the sheet specimens because steel pins simply could be replaced by ceramic ones.

Results

Stress-lifetime relationships

Figure 4 shows SCC initiation lives for the 7010-T651 cylindrical specimens and 8090-T81 new version sheet specimens before and after modification of the loading fixtures. The SCC initiation life $N_{2.0}$ corresponds to a 2 % load decrease from the initial linear load-time record (see Fig. 2). The effect of improved electrical insulation is negligible for lives up to 100 hours. However, improved electrical insulation resulted in higher threshold stresses, especially for 8090-T81 new version. The reason is a larger reduction in pitting attack for 8090-T81 [5].

For 8090-T81 old version 4 of 5 specimens failed at S_{exp} = 280 MPa and 1 of 5 specimens failed at S_{exp} = 250 MPa before use of ceramic pins. When ceramic pins were used no failures occurred at stresses up to 280 MPa.

The stress levels indicated in figure 4 were selected for investigating the load decrease criterion for determining the SCC initiation life. These tests were done before modification of the loading fixtures but were not repeated, since the main objective was to establish the relation between the load decrease ΔP in the load-time curve and the SCC growth. In our opinion galvanic coupling accelerated both ΔP and SCC growth, but did not alter the relation between them.

SCC initiation criterion

Loaded and unloaded specimens were exposed for the same time in the tests to investigate the significance of the 2 % load decrease criterion in terms of SCC growth. Figure 5 shows the ratio of fracture strength for unloaded exposed and unexposed specimens as a function of exposure time for 7010-T651 and 8090-T81 new version. It can be seen that the decrease in fracture strength was much larger for 7010-T651 owing to much more pitting corrosion in this alloy.

Figure 6 shows the fracture strength ratios R_{fs} and the load decreases ΔP in the load-time record of the SCC test as functions of the maximum crack depth a_{max} in the fracture plane of 7010-T651 cylindrical specimens. A narrower band of data points can be observed in the R_{fs} - a_{max} plot. This is because R_{fs} and a_{max} are governed by corrosion attack and stress corrosion only in the fracture plane. However, ΔP results from an overall stiffness decrease of the specimen, and this depends on the total number and depths of cracks whatever their locations. The ΔP - a_{max} plot shows that the original SCC initiation criterion ($\Delta P = 2$ %) corresponds to a maximum crack depth between about 0.8 and 1.4 mm.

A meaningful crack depth could not be established for the 8090-T81 new version sheet specimens because SCC growth occurred from different surfaces and often merged at the edges. For this material, and also for 7010-T651, the areas of the fracture surface attacked by corrosion and stress corrosion were measured. For $\Delta P = 2$ % the attack varied between 25 % and 45 % of the fracture surface area for 7010-T651, and between 25 % and 55 % of the fracture surface area for 8090-T81.

Threshold tests

Figure 7 shows the fracture strength ratios for loaded and unloaded specimens versus exposure stress after 30 days of exposure and after modification of the loading fixtures. The fracture strength ratios are between 80 % and 90 % at the threshold stress for macro SCC growth and increase with decreasing exposure stress for all three materials. Trendlines are drawn in the figure. The intersection of the trendlines with $R_{fs} = 100$ % gives the threshold stress for micro SCC growth. It is seen that the difference between the threshold stresses for macro and micro SCC growth are much larger for the SCC susceptible alloys, 7010-T651 and 8090-T81 new version, than for the SCC resistant alloy 8090-T81 old version.

Fractography

An extensive fractographic investigation was carried out on specimens used for determination of the threshold stress for micro SCC growth. Detailed results are given in reference 5. The following procedure was used to determine whether SCC features were present.

- Investigation of fracture surfaces of exposed unloaded specimens to establish the characteristics of corrosion attack after 30 days of exposure.
- Investigation of the fracture surfaces of exposed and loaded specimens for which there were obvious deviations from the linear part of the load-time record, indicating SCC.
- Investigation of the fracture surfaces of loaded specimens exposed for 30 days and still having linear load-time records (threshold tests).

For all three alloys corrosion and SCC resulted in intergranular fracture surface appearances. This made it difficult to distinguish between corrosion and SCC. However, a distinction could be made on the basis of differing corrosion attack of the grain boundary facets, as will be illustrated for 8090-T81.

Figure 8 shows the transition from corrosion attack to overload on the fracture surface of an unloaded specimen of 8090-T81 new version after 30 days exposure. Severely corroded grain boundary facets can be observed up to overload.

Figure 9 shows part of the fracture surface of a specimen of 8090-T81 new version after 338 hours exposure at a stress of 170 MPa and before modification of the loading fixtures. The deviation from the linear part of the load-time record (1.53 %) and the fracture strength ratio (50 %) show that SCC had occurred. In the figure there is a transition from intergranular corrosion with corroded (pitted) facets to intergranular SCC with facets that are hardly attacked.

Figure 10 shows fractographic characteristics of a specimen of 8090-T81 new version after 30 days exposure at a stress of 170 MPa. There was no deviation from the linear load-time record (ΔP = 0 %), but the fracture strength ratio (89 %) indicated that SCC might have occurred. At and near the specimen surface there was intergranular separation with corroded grains, i.e. corrosion attack. Deeper into the specimen there was also intergranular separation, but with decreasing corrosion attack, i.e. SCC. Near the transition to overload the grain boundary facets were uncorroded and had markings on them owing to plastic deformation during tensile overload: internal plastic deformation (slip) exited to the previously separated grain boundary facets.

Figure 11 shows the fracture surface of a corrosion pit in a specimen of 8090-T81 old version exposed for 30 days at a stress of 270 MPa. There was no deviation from the linear load-time record and the fracture strength ratio was 99 %. There were severely corroded grain boundary facets in the surface area, but uncorroded grain boundary facets near the transition to tensile overload, indicating SCC. SCC features were also found in corrosion pits of other specimens with a fracture strength ratio nominally 100 %.

Discussion

SCC initiation criterion

At a load decrease $\Delta P = 2$ % from the initial linear load-time record all specimens were found to have substantial SCC growth (see Fig. 6). This means that the load decrease criterion for defining the SCC initiation life should be lowered. Figure 12 shows SCC initiation lives determined from 0.5 %, 1.0 % and 2.0 % load decreases versus the exposure stress, before modification of the loading fixtures. The data points represent logarithmic means of lifetimes of different specimens tested at a specific stress level. A stricter (smaller) load decrease criterion for the SCC-initiation life has a clear effect for lifetimes up to about 100 hours. Thereafter it is negligible, and the threshold stress for macro SCC growth is not affected.

Basing the SCC initiation life on a specific load decrease inevitably means the inclusion of some SCC growth in this life. However, SCC growth has to be limited as much as possible. Figure 6b shows that changing the load decrease criterion from 2.0 % to 0.5 % results in a significant reduction of the maximum crack depth, by a factor of 2. We therefore propose to use a load decrease of 0.5 % for determining the SCC initiation life for macro SCC growth.

Threshold tests

Fractography showed that stress corrosion cracks can initiate at stress levels substantially below the threshold stress for macro SCC growth. Small amounts of SCC were found even on the fracture surfaces of specimens of 8090-T81 old version with fracture strength ratios nominally 100 %. It is therefore important to define a threshold stress for micro SCC growth in addition to that for macro SCC growth. This is especially true when micro stress corrosion cracks could initiate fatigue cracks. Notwithstanding the possible presence of small amounts of SCC, we consider it acceptable to define a threshold stress for micro SCC growth as the stress at and below which the fracture strength ratio is nominally 100 %. But in cases where small stress corrosion cracks could occur in combination with or before fatigue loading an additional safety criterion - notably a fatigue crack growth threshold - should be applied.

The table below surveys the threshold stresses for macro and micro SCC growth in the three materials. There are large differences for SCC-susceptible materials. For 7010-T651 and 8090-T81 new version the threshold stresses for macro SCC growth are nearly 3 times those for micro SCC growth. This emphasizes the importance of using materials with maximised resistance to SCC.

Alloy	Threshold stress, MPa	
	Macro SCC growth	Micro SCC growth
7010-T651	160	60
8090-T81, new version	220	80
8090-T81, old version	> 280	250

Proposed use of the ASCOR test: macro and micro SCC growth

The present investigation has shown that the ASCOR test can be used at two levels of refinement. Stress - lifetime relationships and a threshold stress for macro SCC growth can be determined as a first estimate of the SCC resistance of an alloy. An additional determination of the threshold stress for micro SCC growth gives more insight into the resistance of the alloy to SCC initiation. An overview of the procedure to determine the threshold stresses for both micro and macro SCC growth is given below.

a. <u>Threshold stress for macro SCC growth</u>
Cylindrical or sheet specimens are exposed to the environment at different stresses down to stress levels resulting in a linear load-time record up to the maximum exposure period (often 30

days). SCC initiation lives can be determined from the load-time records and are defined as the time at which the load has decreased 0.5 % from the initial linear load-time record ($N_{0.5}$). The results enable the determination of a stress - lifetime relationship and a threshold stress for macro SCC growth, which is defined as the exposure stress at and below which $N_{0.5}$ is larger than the maximum exposure period.

b. Threshold stress for micro SCC growth

In addition to the tests mentioned under (a), specimens are exposed for the maximum exposure period at a number of stress levels below the threshold stress for macro SCC growth. Also, unloaded specimens, say 3 - 4, are exposed for the maximum exposure time. After exposure the fracture strengths of the unloaded and loaded exposed specimens are determined. Then the fracture strength ratios are calculated by dividing the fracture strengths of loaded specimens by the average of the fracture strengths of the unloaded specimens. The threshold stress for micro SCC growth can be determined from the fracture strength ratios and is defined as the exposure stress at and below which the fracture strength ratio is nominally 100 %.

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[4] Schra, L. and 't Hart, W.G.J., Corrosion and stress corrosion properties of damage tolerant aluminium sheet materials (NLR contribution to BREU 3250, task 2), National Aerospace Laboratory NLR Technical Publication 92305 U, Amsterdam, The Netherlands, November 1992.

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Table 1 Test programme

- **Materials**

  - 7010-T651, 80 mm thick plate, cylindrical specimens, loaded in short transverse direction, low SCC resistance
  - 8090-T81, 1.6 mm thick sheet, sheet specimens, loaded in long transverse direction
    old version: high SCC resistance
    new version: low to moderate SCC resistance

- **Environmental conditions**

  Alternate immersion in 3.5 % NaCl solution according to ASTM spec. G44, 1 hour cycle: 10 min. wet - 50 min. dry, T = 27°C, R.H. = 45 %

- **Test types and objectives**

  a. Determination of stress - lifetime relationships

  b. Load decrease criterion for determination of SCC initiation life
     - Testing at preselected stress levels
     - Exposure of loaded and unloaded specimens
     - Tensile loading to failure
     - Measurement of SCC from fracture surfaces

  c. Threshold stress for micro SCC growth
     - Testing below threshold stress for macro SCC growth
     - Exposure of loaded and unloaded specimens for 30 days
     - Tensile loading to failure
     - SEM investigation of fracture surfaces

Table 2 Chemical compositions

Alloy	Element, weight %							
	Li	Zn	Cu	Mg	Zr	Ti	Si	Fe
7010-T651	-	6.20	1.86	2.28	0.19	0.04	0.12	0.09
8090-T81, old version	2.38	0.02	1.20	0.71	0.11	0.02	0.03	0.03
8090-T81, new version	2.42	0.02	1.14	0.83	0.06	0.02	0.02	0.05

Table 3 Mechanical properties

Alloy	Loading direction	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %
7010-T651	short transverse	480	557	6.7(1)
8090-T81, old version	long transverse	300	447	10.5(2)
8090-T81, new version	long transverse	286	415	16.0(2)

(1) elongation measured along 25 mm gauge length
(2) elongation measured along 50 mm gauge length

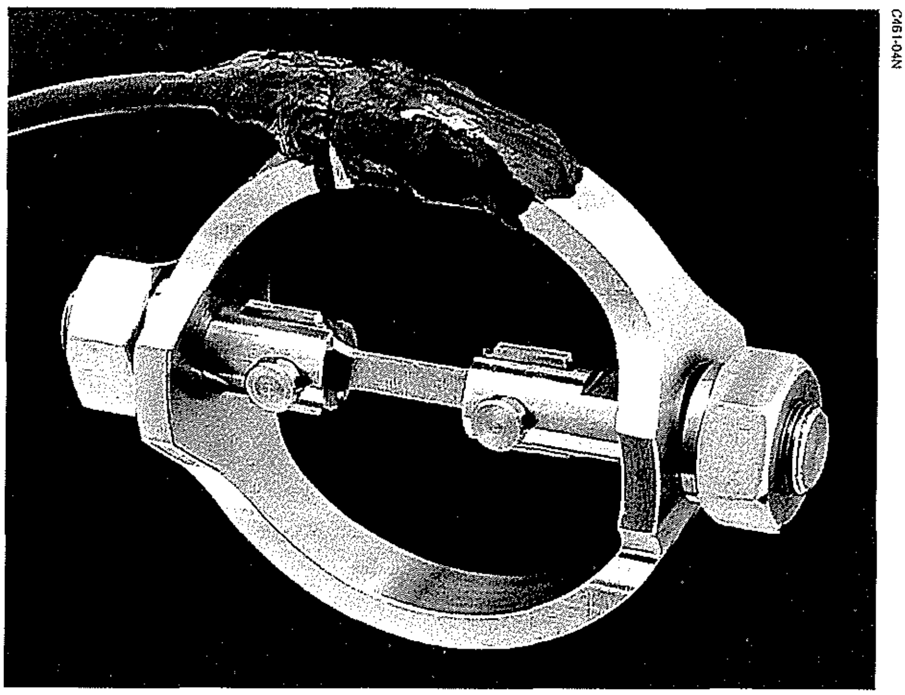


Fig. 1 Sheet specimen mounted in a loading ring

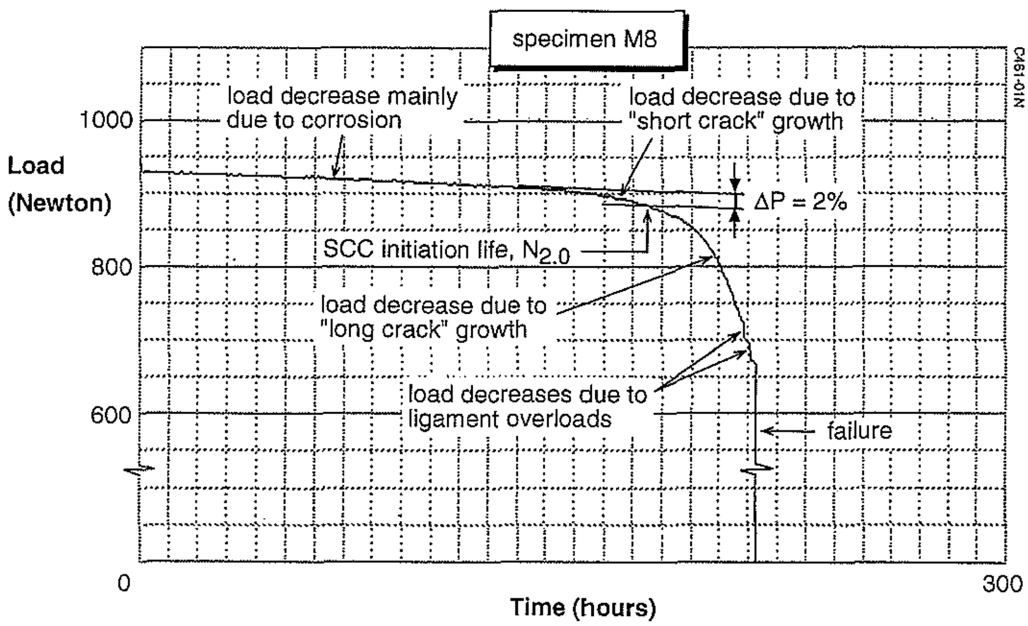


Fig. 2 Typical load-time record of a failed sheet specimen

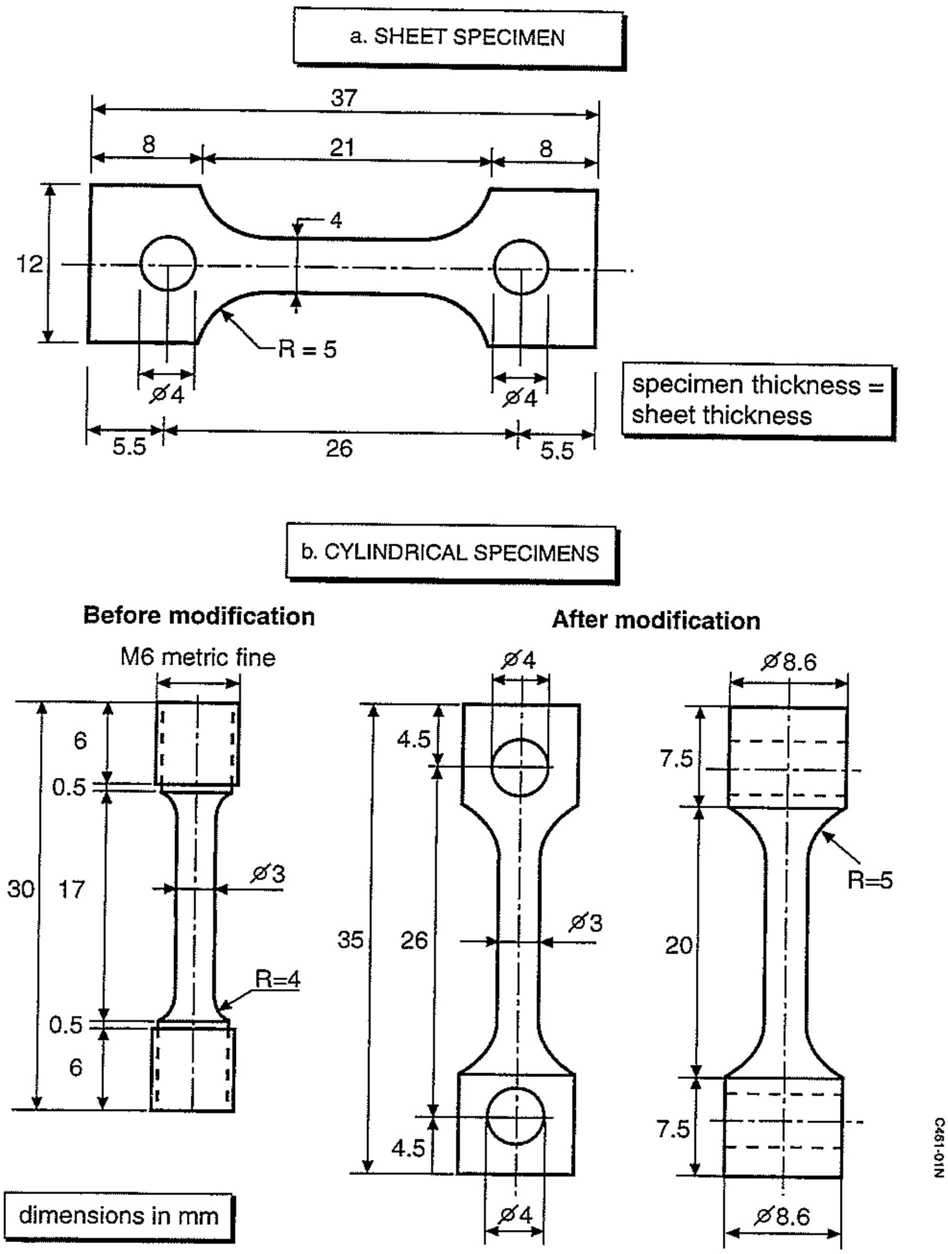


Fig. 3 Geometries and dimensions of test specimens

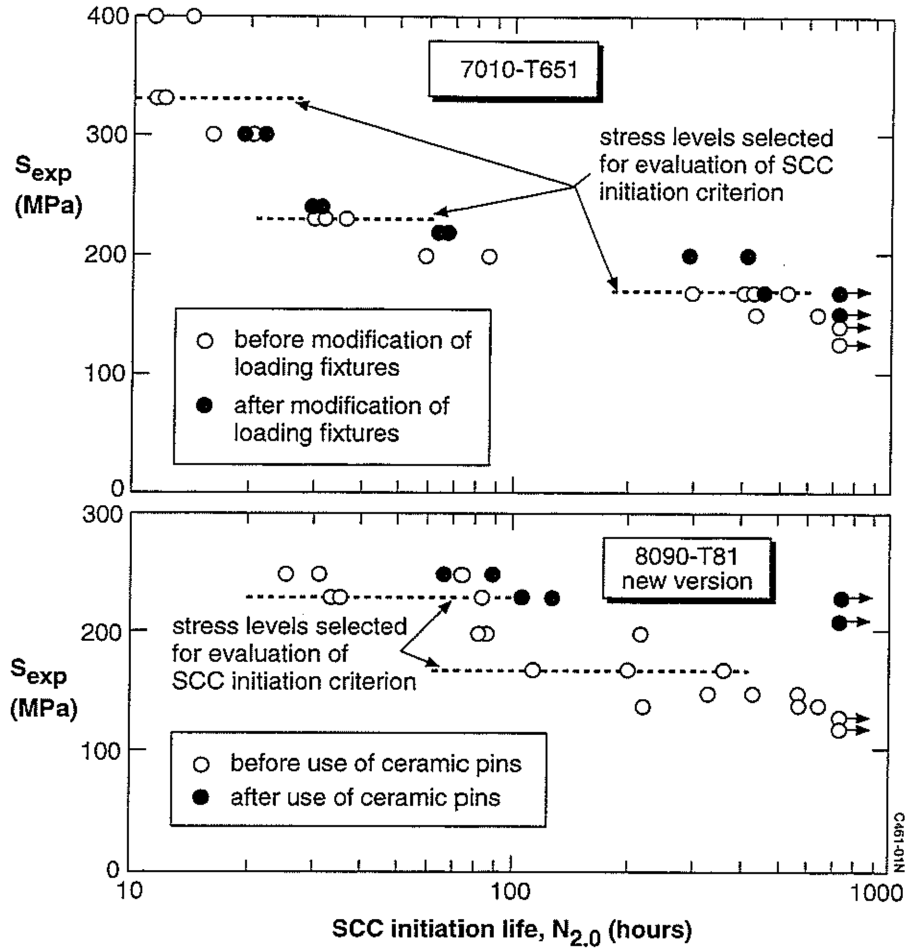


Fig. 4 SCC initiation life versus exposure stress

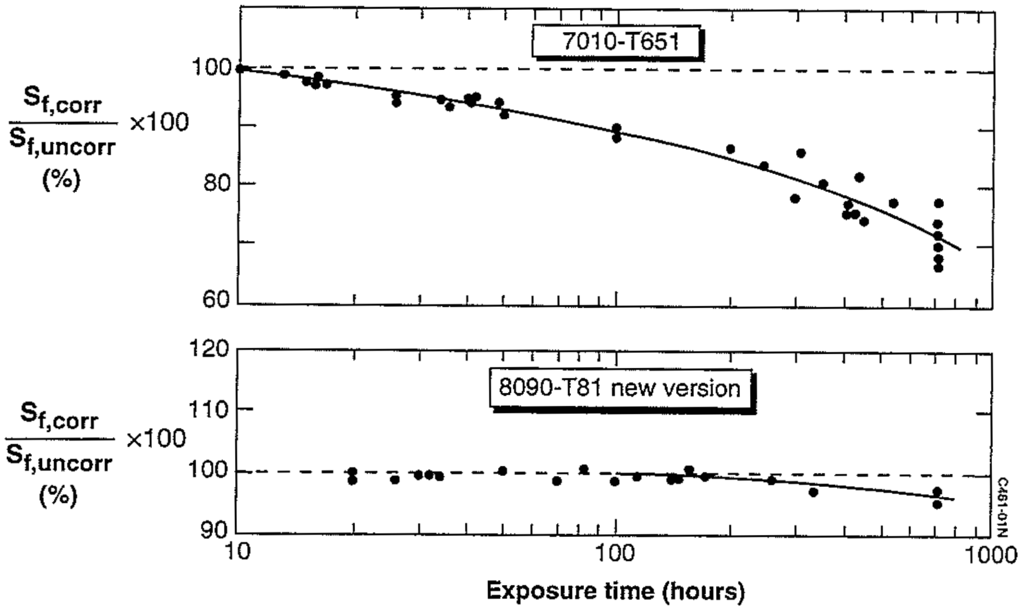


Fig. 5 The ratio of fracture strength for unloaded corroded and uncorroded specimens versus exposure time

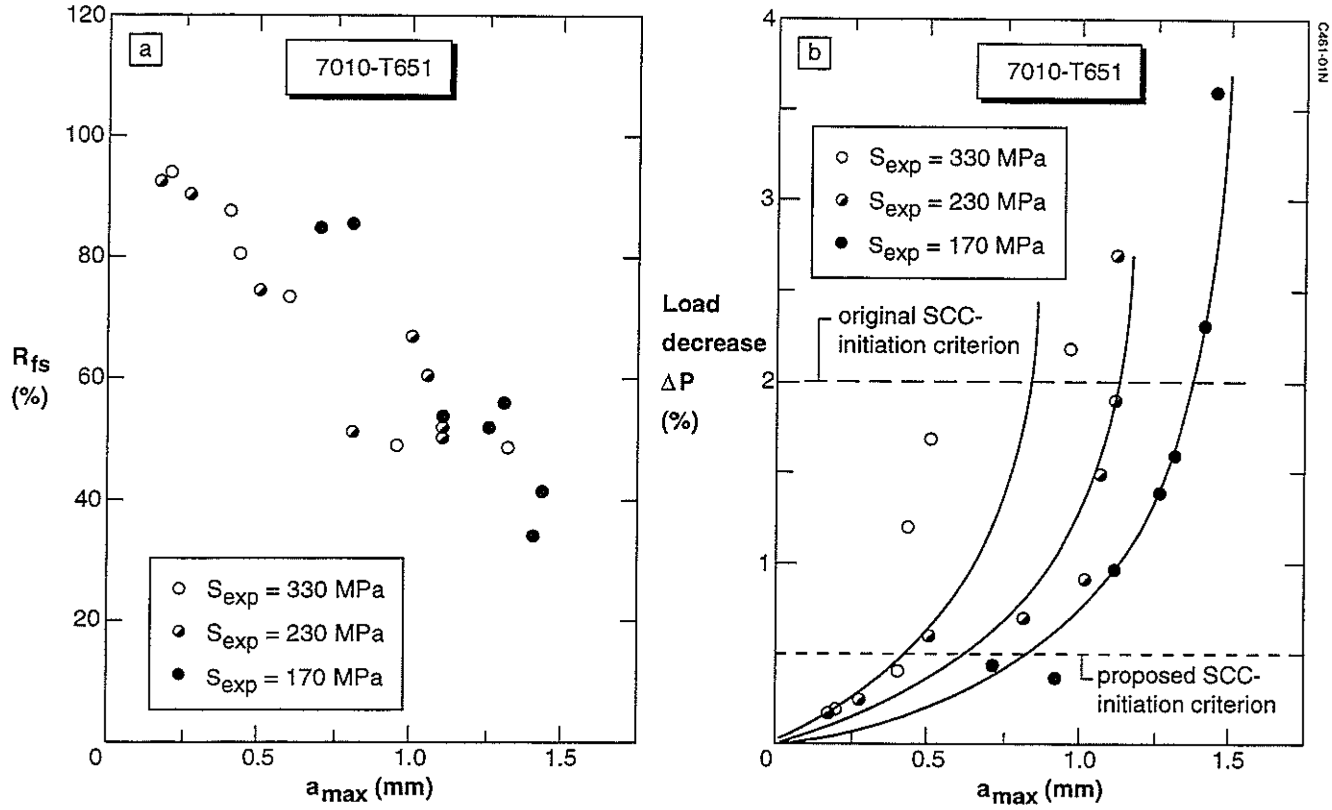


Fig. 6 The ratio of fracture strengths for exposed and loaded or unloaded 7010-T651 cylindrical specimens and the corresponding load decreases in the load-time records as functions of maximum crack depth

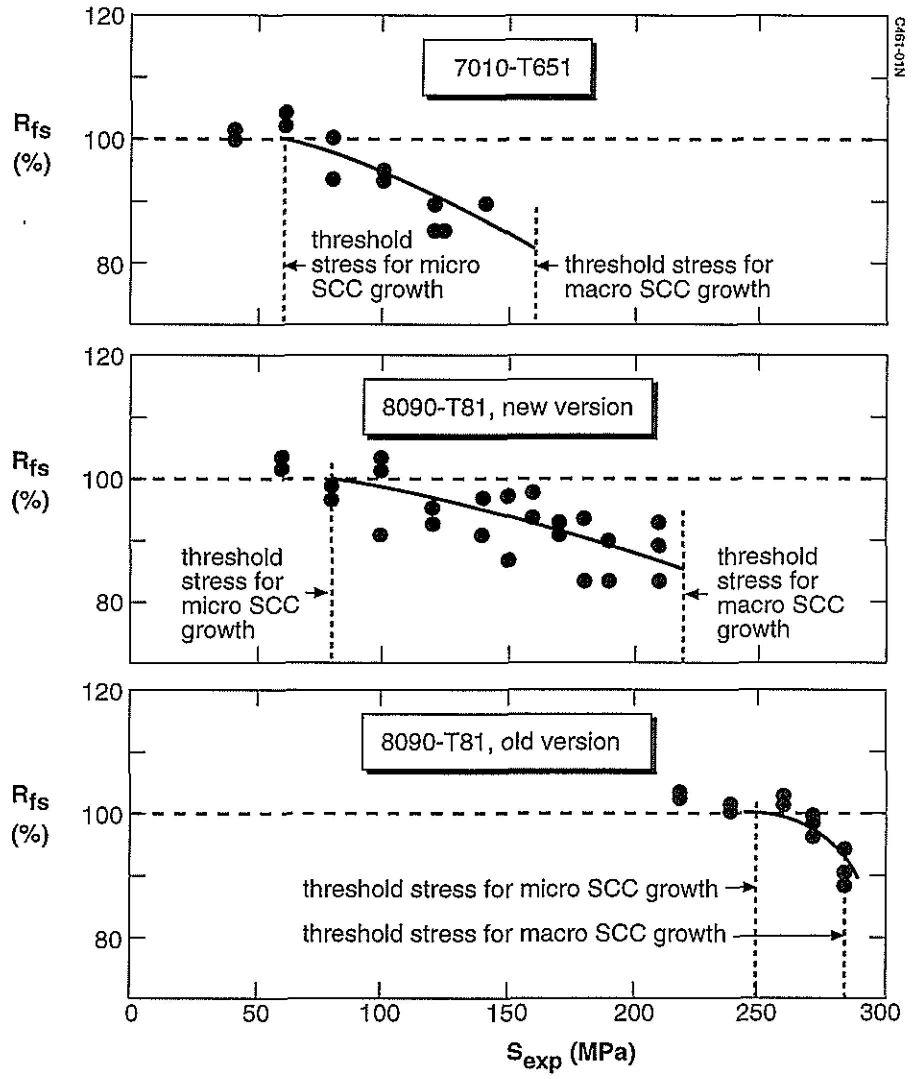


Fig. 7 Fracture strength ratio versus exposure stress after 30 days of exposure and after modification of the loading fixtures

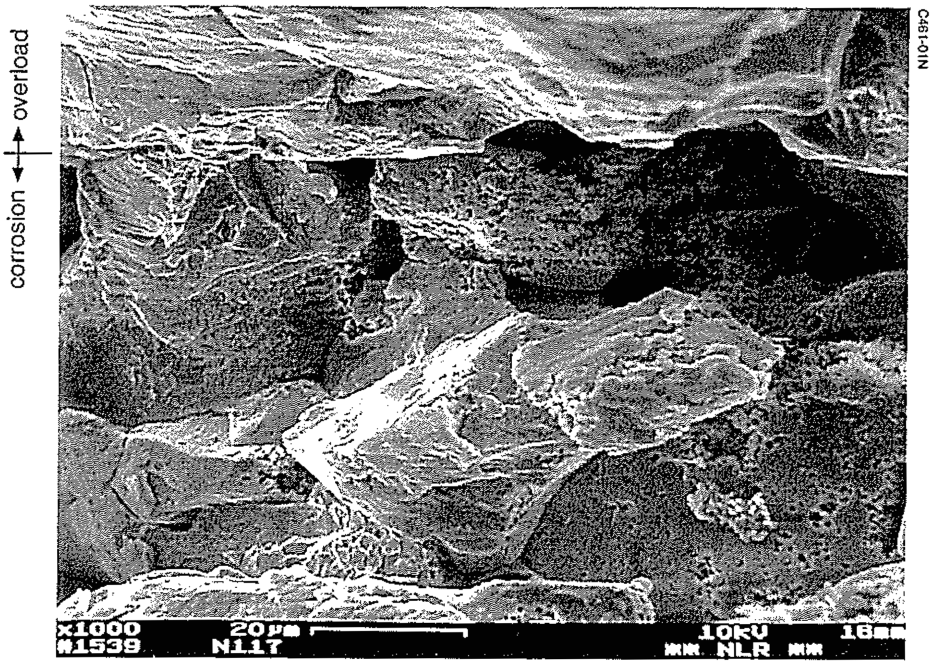


Fig. 8 The transition from corrosion to overload on the fracture surface of a specimen of 8090-T81 new version, exposed in unloaded condition to the environment for 30 days

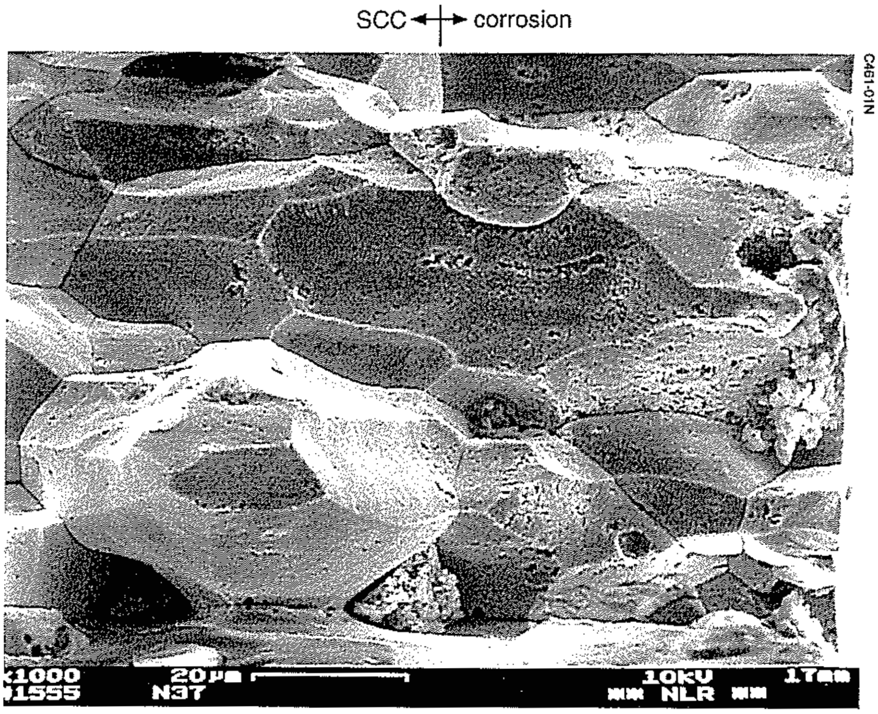
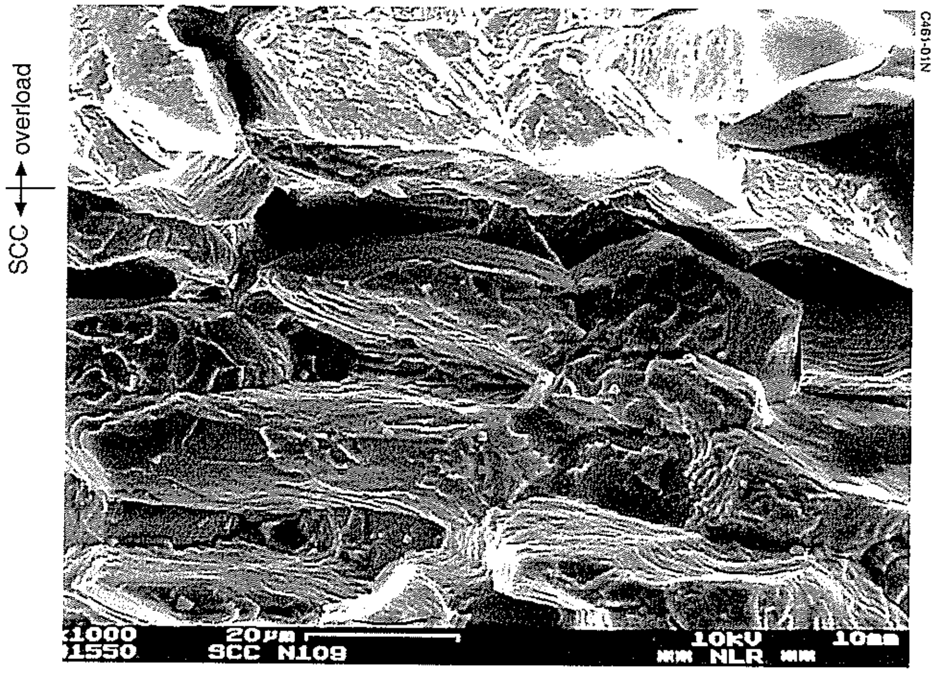


Fig. 9 The transition from corrosion to SCC on the fracture surface of a specimen of 8090-T81 new version exposed to the environment for 338 hours at a stress of 170 MPa (ΔP = 1.53%, R_{fs} = 50%)

Transition SCC-overload



Surface area: attacked grain boundary facets

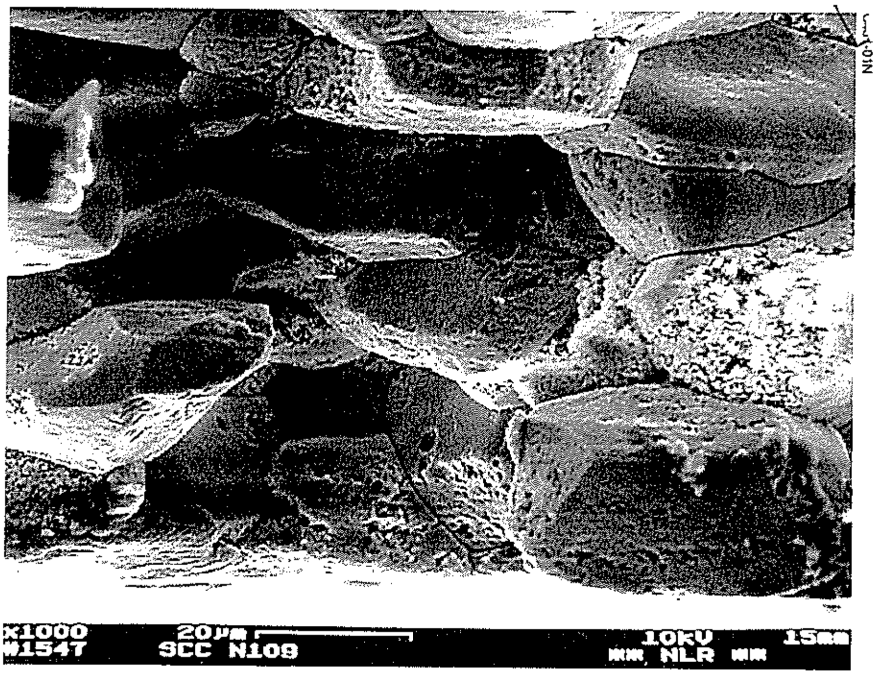


Fig. 10 Fractographic characteristics of a specimen of 8090-T81 new version exposed to the environment for 30 days at a stress of 170 MPa (ΔP = 0%, R_{fs} = 89%)

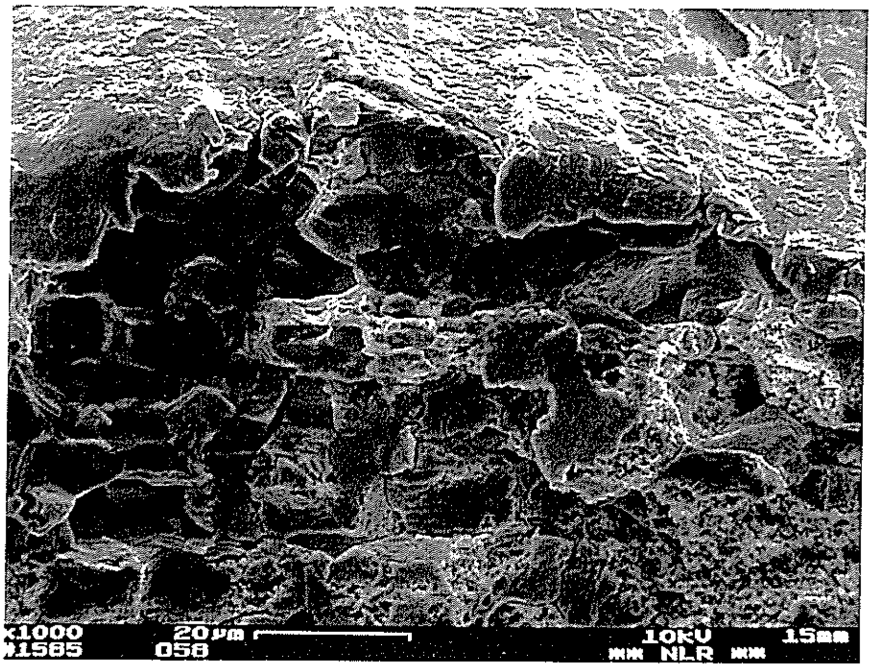


Fig. 11 *Fractographic characteristics of a specimen of 8090-T81 old version exposed to the environment for 30 days at a stress of 270 MPa ($\Delta P = 0\%$, $R_{fs} = 99\%$)*

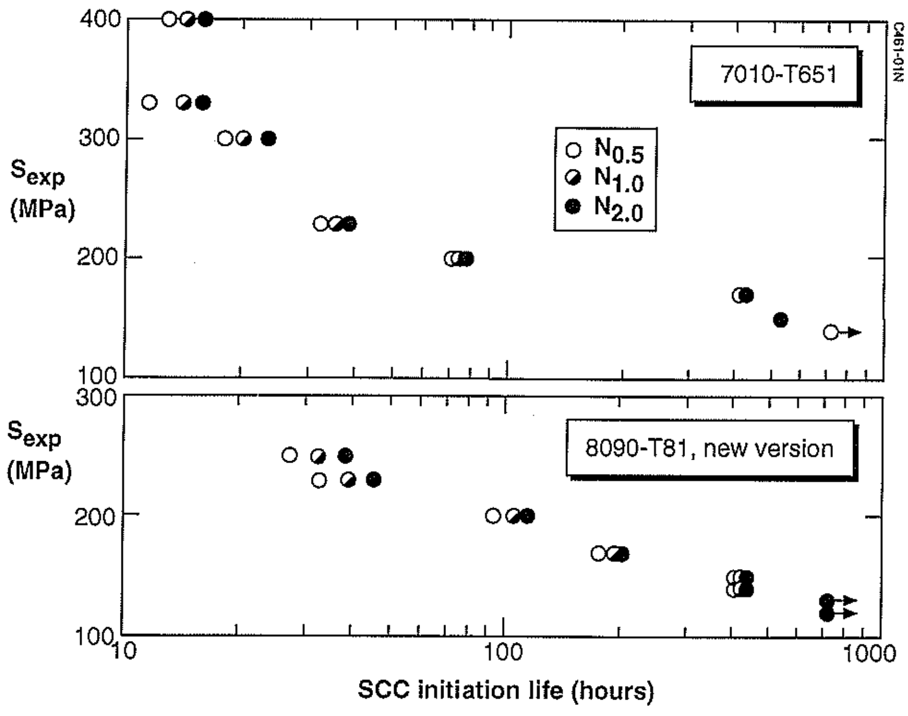


Fig. 12 *Average SCC initiation life for different load decrease criteria (0.5%, 1.0%, 2.0%) versus exposure stress, before modification of the loading fixtures*