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The influence of testing parameters on stress corrosion crack growth in the high strength aluminium alloy 7010-T651

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ABSTRACT
An interlaboratory testing programme to evaluate the rising displacement test for stress corrosion crack (SCC) growth investigations was carried out within the framework of the "Measurements and Testing" programme of the European Community under BCR contract nr. MATI CT 930038. The contribution of the NLR to the project consisted of testing of precracked Double Cantilever Beam (DCB) Specimens made from the high strength aluminium alloy 7010-T651 under constant displacement and by continuous immersion in substitute ocean water. The results of these static tests were to be used as reference data for the dynamic rising displacement tests carried out by other participants in the project. Further, additional static tests were carried out by the NLR using alternate immersion in substitute ocean water. The results of these tests were compared with those of 7010-T651 plate from another batch of material tested previously at the NLR.

The main results of the investigation are:

- **SCC growth was much faster during alternate immersion than during continuous immersion in substitute ocean water.**
- **Application of the concept of linear fracture mechanics was possible for continuous immersion testing in substitute ocean water. A threshold value for the stress intensity factor, K_{ISCC}, betwwen 5 and 7 MPa m was found in the tests.**
- **No K_{ISCC} value could be established for alternate immersion in substitute ocean water, owing to the occurrence of corrosion product wedging. The crack growth rate in the last phase of testing was more or less constant between 10^{-9} and 2.5×10^{-9} m/sec as a result of specimen self-loading by corrosion product wedging.**
- **No difference in SCC growth rates was found for alternate immersion testing of 19 and 30 mm high DCB specimens, nor between 30 mm high DCB specimens obtained from surface and core locations of the plate.**
- **Large differences in fracture toughness and SCC growth properties may occur between different batches of 7010-T651 plate material that meet the specified minimum mechanical properties.**

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Summary

An interlaboratory testing programme to evaluate the rising displacement test for stress corrosion crack (SCC) growth investigations was carried out within the framework of the "Measurements and Testing" programme of the European Community under BCR contract nr. MAT1 CT930038. The contribution of the NLR to the project consisted of testing of precracked Double Cantilever Beam (DCB) specimens made from the high strength aluminium alloy 7010-T651 under constant displacement and by continuous immersion in substitute ocean water. The results of these static tests were to be used as reference data for the dynamic rising displacement tests carried out by other participants in the project. Further, additional static tests were carried out by the NLR using alternate immersion in substitute ocean water. The results of these tests were compared with those of 7010-T651 plate from another batch of material tested previously at the NLR.

The main results of the investigation are:

- SCC growth was much faster during alternate immersion than during continuous immersion in substitute ocean water.
- Application of the concept of linear fracture mechanics was possible for continuous immersion testing in substitute ocean water. A threshold value for the stress intensity factor, K_{ISCC}, between 5 and 7 $MPa\sqrt{m}$ was found in the tests.
- No K_{ISCC} value could be established for alternate immersion in substitute ocean water, owing to the occurrence of corrosion product wedging. The crack growth rate in the last phase of testing was more or less constant between 10^{-9} and 2.5×10^{-9} m/sec as a result of specimen self-loading by corrosion product wedging.
- No difference in SCC growth rates was found for alternate immersion testing of 19 and 30 mm high DCB specimens, nor between 30 mm high DCB specimens obtained from surface and core locations of the plate.
- Large differences in fracture toughness and SCC growth properties may occur between different batches of 7010-T651 plate material that meet the specified minimum mechanical properties.

Contents

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Nomenclature

a	:	crack length
a_i	:	initial crack length (at start of stress corrosion test)
$a_{i,sf}$	:	initial crack length measured from specimen side faces
$a_{i,fs}$	:	initial crack length measured from fracture surface
a_f	:	final crack length (at termination of stress corrosion test)
$a_{f,sf}$	:	final crack length measured from specimen side faces
$a_{f,fs}$	:	final crack length measured from fracture surface
$a_{x,sf}$	:	instantaneous crack length measured from specimen side faces
B	:	specimen thickness
B_n	:	net specimen thickness
C_1	:	distance from front of specimen to load line
C_i	:	initial correction factor ($a_{i,fs}/a_{i,sf}$)
C_f	:	final correction factor ($a_{f,fs}/a_{f,sf}$)
C_x	:	correction factor at crack length $a_{x,sf}$
da/dt	:	stress corrosion crack growth rate
DCB	:	Double Cantilever Beam specimen
δ_{25}	:	Elongation to fracture, measured on 25 mm gauge length
E	:	Young's modulus
EC	:	European Community
EDM	:	Electric Discharge Machining
F	:	load
F_{min}	:	minimum fatigue load
F_{max}	:	maximum fatigue load
H	:	half specimen height
K	:	stress intensity factor
K_I	:	stress intensity factor for mode I loading
K_{Iapp}	:	apparent stress intensity factor
K_{IC}	:	plane strain fracture toughness
K_{Ii}	:	initial stress intensity factor (at start of stress corrosion test)
K_{If}	:	final stress intensity factor (at termination of stress corrosion test)
$K_{If,d}$	:	final stress intensity factor, derived from bolt displacement
$K_{If,L}$	:	final stress intensity factor, derived from bolt load
K_{Iapp}	:	apparent stress intensity factor
$K_{If,app}$	:	apparent final stress intensity factor
K_{ISCC}	:	threshold value of stress intensity factor for the onset of stress corrosion crack growth
S	:	short transverse direction

S-L	:	crack plane orientation (ASTM designation) with loading in the short transverse direction
SCC	:	Stress Corrosion Cracking
$\sigma_{0.2}$	:	0.2 % tensile yield strength
σ_{ult}	:	ultimate tensile strength
t	:	elapsed time
v_o	:	displacement at crack mouth
v_{LL}	:	displacement in load line
W	:	specimen width

1 Introduction

Environmentally assisted cracking (EAC) or stress corrosion cracking (SCC), i.e. crack initiation and growth due to the combined action of a sustained tensile stress and a corrosive environment, is a potential and actual failure mechanism for structural materials. In the past, numerous test methods have been developed to assess the susceptibilty to stress corrosion cracking. Initially only smooth specimens were used. Time to failure of these specimens is predominantly governed by the crack initiation period. Since the mid-1960s there has been an increasing use of precracked specimens. These specimens enable the application of fracture mechanics concepts to stress corrosion crack growth.

The parameters which characterize the susceptibility of materials to SCC growth are:

- K_{ISCC} : the threshold value of the stress intensity factor for the onset of stress corrosion crack growth.
- $da/dt = f(K)$: the crack propagation rate as a function of the stress intensity factor.

There is only a limited standardization of procedures for evaluating these parameters. Only the International Standard ISO 7539 Part 6 [1], which is identical to the British Standard BS 6980 [2], provides some guidelines for the use of precracked specimens in stress corrosion tests. According to these standards K_{ISCC} is developed in a static loading test (constant load or constant displacement). A major drawback of these standards is that the recommended testing times for evaluating K_{ISCC} for aluminium alloys and steels are very long (10,000 hours). It is thought that this disadvantage could be overcome by applying a dynamic load to precracked specimens (rising load or rising displacement tests).

An interlaboratory testing programme to evaluate the rising displacement test was defined and carried out within the framework of the "Measurements and Testing" programme of the European Community, under BCR contract nr. MAT1 CT930038. There were 17 participants from industry, universities and research institutes, and the project was coordinated by GKSS, Geesthacht, Germany. The title of the project was "Characterization of susceptibility of metallic materials to environmentally assisted cracking". Three material/ environment systems were involved in evaluation of this dynamic test method.

The contribution of the NLR to the project consisted of testing precracked DCB (Double Cantilever Beam) specimens made from the high strength aluminium alloy 7010-T651. The specimens were tested at constant displacement and by continuous immersion in substitute ocean water. The results of these static tests were to be used as reference data for the results of the dynamic tests carried out by other participants in the BCR project.

In earlier years the NLR had already done SCC growth tests on DCB specimens of 7010-T651 plate [3]. However, there were differences from the present investigation. The specimens in the earlier investigation had another geometry and dimensions, and were tested by alternate immersion instead of continuous immersion, as was done in the present BCR project. An additional NLR test programme was defined to relate the results of the BCR tests to those of the earlier NLR investigation. This enabled determining the effect of different testing parameters on SCC growth.

The present report describes the experimental details and results of the NLR's BCR and additional tests, and discusses the effect of different testing parameters on SCC growth in DCB specimens of 7010-T651.

2 Material and specimens

Two types of DCB specimens were machined from a 90 mm thick 7010-T651 plate delivered by ALCAN Plate, UK. The chemical composition is given in table 1. The mechanical properties in the short transverse (S) direction are given in table 2. The data in tables 1 and 2 were obtained from the guidelines for the SCC tests in the framework of the BCR project [4].

Figure 1 shows the DCB specimen used in the BCR project, further denoted as the BCR specimen. Figure 2 shows the DCB specimen used in earlier NLR investigations, further denoted as the NLR specimen. The NLR specimen was substantially smaller than the BCR specimen and had side grooves to confine the crack to the midplane. The A, B, C and D specimens were taken from the core of the plate and were prepared by GKSS. The N and O specimens were taken from the surface area of the plate and were prepared by the NLR. All specimens were provided with an EDM (Electric Discharge Machined) notch to obtain simultaneous fatigue crack initiation through the thickness of the specimen. A clip gauge seating was made at the front of the specimens. All specimens had an S-L orientation, i.e. they were loaded in the short transverse (S) direction, while crack growth occurred in the longitudinal (L) direction.

3 Test programme

An overview of the test programme is given in table 3. Before stress corrosion testing fracture toughness tests were done on 4 specimens with different geometry, location in the plate and initial crack length a_i. The results of these tests enabled estimating the displacements to be used in loading DCB specimens for stress corrosion testing.

The stress corrosion test specimens were loaded to a specific displacement v_o at the crack mouth. The relation between this displacement and the displacement in the load line v_{LL} has to be known as a function of crack length to enable calculation of the stress intensity factor K_I. In the guidelines of the SCC tests [4] the following linear relation, obtained from reference 1, is given:

$$v_{LL} = \frac{a}{[a + C_1]} \cdot v_o \qquad \text{or} \qquad \frac{v_o}{v_{LL}} = 1 + \frac{C_1}{a} \tag{1}$$

(see also Figs. 1 and 2 for explanation of the notations).
During the fracture toughness tests the displacements were measured both at the crack mouth and at the load line to check equation (1).

There were two programmes for SCC testing. In the first one, tests were carried out in the framework of the BCR programme of the EC. In these tests two initial stress intensity factors and two initial crack lengths were applied. The specimens were tested by continuous immersion in aerated substitute ocean water. These tests enabled checking the validity of the linear elastic fracture mechanics concept. When this concept is valid all tests should result in the same threshold value for stress corrosion crack growth K_{ISCC}. The results of the tests were also to be used as reference data for the rising displacement tests carried out by other participants in the BCR project.

In the second programme tests were carried out as an additional NLR programme to relate the results of the BCR tests to those of earlier SCC tests on DCB specimens of 7010-T651 [3]. The specimens in these tests were subjected to alternate immersion in substitute ocean water. The results enabled determining the influence of the following parameters and conditions on stress corrosion crack growth:

1. Testing by continuous immersion versus alternate immersion.
2. The location of the specimens in the plate (core or surface area).
3. Geometry of the DCB specimen:
   The BCR specimen had larger dimensions than the NLR specimen and was not provided with side grooves (see Figs. 1 and 2).

4. Batch to batch differences by comparison of the results of the present investigation with those reported in reference 3.

All the stress corrosion tests were done in duplicate.

4 Experimental details

All DCB specimens were fatigue precracked before the fracture toughness and stress corrosion tests were executed. Fatigue precracking was done in a 100 kN Amsler Vibrophore fatigue machine to obtain initial crack lengths of about 30 or 50 mm. Two specimens were mounted symmetrically opposite each other and subjected to the following total fatigue loads:

BCR specimen,	a_i = 30 mm,	F_{max} = 4.5 kN,	F_{min} = 0.45 kN
BCR specimen,	a_i = 50 mm,	F_{max} = 3.0 kN,	F_{min} = 0.3 kN
NLR specimen,	a_i = 30 mm,	F_{max} = 2.0 kN,	F_{min} = 0.2 kN.

When the desired initial crack length was obtained in one of the two specimens, it was replaced by a dummy specimen and fatiguing was continued until the desired crack length in the second specimen. After fatigue precracking the specimens were used for fracture toughness tests or stress corrosion tests.

4.1 Fracture toughness tests

Fracture toughness tests were carried out on 4 specimens (see Tab. 3). Loading of the DCB specimens was done using a high strength steel bolt with a rounded top inserted in one specimen arm and torqued against a flat steel insert in the other arm. A clip gauge was used to measure the displacement at the crack mouth v_o. Lateral pins were fixed in the load line perpendicular to the side faces of the specimen. The displacement in the load line v_{LL} was determined by measuring the distance between the lateral pins with a micrometer.

Displacement measurements at the crack mouth and at the load line were done periodically during loading until static crack extension occurred. Then further static crack extension was realized by additional turning of the bolt. After crack jumps the displacements at the crack mouth and at the load line were measured and the crack length was determined visually using a binocular at 15x magnification. A mm scale was inscribed on the specimen side faces. The bottoms of the side grooves in the NLR specimen were rounded and polished to facilitate visual observation of the crack length. An aluminium block fitting in the side grooves, which could be shifted lengthwise, was used to measure the crack length in the NLR specimen. The crack length was estimated to within 0.1 mm.

Combinations of crack lengths and related load line displacements were used to calculate the stress intensity factor in the BCR specimen using the following equation, obtained from reference 4:

$$K_I = \frac{E \cdot v_{LL} \cdot H}{4} \cdot \frac{\sqrt{3H(a+0.6H)^2 + H^3}}{[(a+0.6H)^3 + H^2 a]} \qquad (2)$$

The same relation was used for the NLR specimen, but the sidegrooves were accounted for by multiplying K_I by $(B/B_n)^{1/2}$.

4.2 Stress corrosion tests

The specimens used for the stress corrosion tests were loaded by turning the bolt to give a desired displacement at the crack mouth, measured with a clip gauge. The desired displacement at the crack mouth v_o was derived from the required initial stress intensity factor K_{Ii} in the following way. The displacement in the load line v_{LL} was calculated from K_{Ii} using equation (2). v_o was calculated from v_{LL} using equation (1). After loading the bolt, the insert and the surrounding specimen area were coated with lacquer and then covered with wax to prevent galvanic coupling. The specimens were exposed to the aqueous environment with the bolt end up. The level of the environment was maintained such that the tips of the initial fatigue cracks were at least 5 mm below the surface and the loading bolts were clearly above the surface.

Further details about the SCC testing are given below:

<u>Test solution</u>

Substitute ocean water according to ASTM specification D1141 (without heavy metals) was used for the continuous immersion (aerated) tests as well as for the alternate immersion tests. An alternate immersion cycle consisted of 1 hour wet and 11 hours dry. The test solution was replaced every two weeks. In the meantime the level of the solution was maintained by the addition of distilled water. The solution volume was 1.6 litres per specimen. The flow rate of air through the solution in the BCR tests was 0.06 cm/sec.

<u>pH of the test solution</u>

The pH of the test solution was measured just before and after its replacement. The pH of the fresh solution was 8.2, as specified in ASTM D1141. In two weeks of SCC testing the pH decreased to values of 8.10 to 8.15.

<u>Temperature and relative humidity</u>

The test temperature and relative humidity were continuously recorded during the SCC tests. The test temperature was controlled, but varied between 19 °C and 24.5 °C, owing to the hot summer in 1995 and the cold winter in 1995/1996. The mean test temperature during the BCR tests was 21.5 °C. The relative humidity was not controlled and varied between 38 % and 62 %, with an average value of 49 %.

Corrosion potential

In the BCR tests (continuous immersion) the corrosion potential was measured on 4 specimens (one for each a_i, K_{Ii} combination). The measurements were done against a standard calomel electrode. The results are shown in figure 3. The corrosion potential was rather variable. No consistent influence of replacement of the test solution and the exposure time can be observed. The average potential of the specimens with a_i = 30 mm was about 40 mVolt lower than that of the specimens with a_i = 50 mm. The variability of the corrosion potential was smaller for specimen C25 than for the other specimens.

Crack length measurement

The specimens were periodically removed from the test solution for a short time to measure the crack lengths at both side faces of the specimens. The measurements were done in the same way as with the fracture toughness tests (see section 4.1). The frequency of crack length measurement decreased from once a day in the first two weeks to once in two weeks towards termination of the tests.

The total exposure periods were about 10 months for the continuous immersion tests and about 7 months for the alternate immersion tests. The procedure at test termination was as follows:

- The specimens were removed from the test solution and the crack lengths were measured at both side faces.
- The clip gauge was mounted at the crack mouth and the specimens were unloaded by unturning the bolt. The displacement was measured during unloading.
- The specimens were reloaded in a tensile test machine to the same crack mouth displacement as measured during unloading. The load required to obtain this displacement was considered to be the applied load at test termination.
- The final crack lengths and if possible the fatigue crack lengths were measured from the fracture surfaces. The measurements were done at five positions along the crack front, viz. one at each specimen side face, one along each of the quarter thickness planes and one at mid-thickness. The average crack length was calculated from these five measurements.

This procedure enabled calculating the stress intensity factor at test termination in two ways:

(1) From the final crack length measured from the fracture surface $a_{f,fs}$ and the displacement in the load line v_{LL} using equation (2).

(2) From $a_{f,fs}$ and the load in the bolt, F, at test termination using the following equation obtained from reference 4.

$$K = \frac{F \cdot a}{B \cdot H^{1.5}} \cdot \left(3.46 + 2.38 \frac{H}{a} \right). \qquad (3)$$

5 Results

5.1 Fracture toughness tests

5.1.1 Fracture toughness

Equation (2) was used to calculate the fracture toughness of the BCR specimens from the load line displacement v_{LL} and the related crack length a. For the NLR specimens the same relation was used, but the resulting K_I was multiplied by $(B/B_n)^{1/2}$ to account for the side grooves.

A survey of the results of the fracture toughness tests is given in table 4. Three fracture toughness values can be distinguished, viz.:

a. K_{IC} derived from the fatigue crack length at the first audible click and the related v_{LL}. The audible click indicates minor crack extension from the fatigue crack in the specimen interior. No crack extension was visible at the specimen side faces.
b. K_{IC} derived from the fatigue crack length at the first crack jump, resulting in crack extension at the specimen side faces, and the related v_{LL}.
c. K_{IC} derived from v_{LL} and the related crack length during extension of the static crack. Average values for about 10 measurements are given in table 4.

Table 4 shows substantially higher K_{IC} values for the BCR specimen B4 than for the BCR specimens A18 and N1. K_{IC} for the NLR specimen was intermediate to the BCR specimen K_{IC} values.

5.1.2 Relation v_o/v_{LL} - a

During fracture toughness testing the displacements at the crack mouth v_o and in the load line v_{LL} were measured. Figure 4 shows v_o/v_{LL} ratios as functions of crack length a. Linear regression was applied to determine the optimum v_o/v_{LL} ratio for the fatigue crack. Data points for the static crack were obtained from crack length and related v_o and v_{LL} measurements.

Figure 4 shows very good reproducibility of the data for BCR specimens with different initial crack lengths. It is also seen that for a specific crack length equation (1) significantly underestimates the v_o/v_{LL} ratio: for the BCR specimen the deviation is 12 % for a crack length of 30 mm, and 7 % for a 70 mm long crack. A modified equation was established by the coördinator of the BCR programme (W. Dietzel, GKSS). This equation is:

$$\frac{v_o}{v_{LL}} = 1 + \frac{3C_1}{2a}. \qquad (4)$$

Figure 4 shows that equation (4) fits the experimental data for the BCR specimen very well. The equation slightly overestimates the displacement ratios for the side grooved NLR specimen.

5.2 Stress corrosion tests

5.2.1 BCR programme

It was intended to load the 8 specimens tested in the framework of the BCR programme to stress intensity factors of 15 MPa$\sqrt{m}$ (specimens A11, C18, C25 and B7) and 10 MPa$\sqrt{m}$ (specimens A14, D18, C21 and D21). Equation (2) was used to calculate v_{LL} from K_{Ii}, and then v_o was derived from v_{LL} using equation (1). The specimens were loaded to this v_o value as measured with a clip gauge at the crack mouth. During loading clicks were heard and static crack extension up to 1 mm occurred along the specimen side faces in specimens A11, C18 and C25. This was not unexpected in view of the measured fracture toughness values. However, no clicks were heard and no static crack extension occurred in specimen B7, indicating a higher fracture toughness for this specimen, also found for specimen B4 (see Tab. 4).

After starting the stress corrosion tests it appeared that equation (4) gave a much better fit to experimental v_o/v_{LL}-a data than equation (1). Application of equation (4) instead of equation (1) for a specific v_o results in a lower v_{LL} and thus in a lower K_{Ii}. Therefore, the actual K_{Ii} values were about 13 and 9 MPa$\sqrt{m}$ instead of the intended 15 and 10 MPa$\sqrt{m}$. The exact K_{Ii} values are given in table 5.

After 300 days (about 10 months) of testing it was found that no significant SCC growth had occurred during the last 2.5 months of testing. Therefore the stress corrosion tests were terminated. The fracture surface appearances are shown in figure 5. It is seen that most of the stress corrosion crack fronts were slightly curved, i.e. the cracks were slightly longer at the specimen midplane than at the side faces, where the crack lengths were measured during testing.

A correction factor C_f at test termination was calculated from $C_f = a_{f,fs}/a_{f,sf}$, where

af,fs = final crack length measured from the fracture surface (mean value of 5 measurements, see Tab. 5).

$a_{f,sf}$ = final crack length measured from the specimen side faces (mean value).

Then a correction factor C_x was calculated from the following linear equation:

$$C_x = \left(\frac{(a_x)_{s.f} - (a_i)_{s.f}}{(a_f)_{s.f} - (a_i)_{s.f}} \,.\, (C_f - C_i) \right) + C_i \qquad (5)$$

where

C_x = correction factor at crack length $a_{x,sf}$
C_i = $a_{i,fs}/a_{i,sf}$
$a_{i,fs}$ = initial crack length measured from the fracture surface
$a_{i,sf}$ = initial crack length measured from the specimen side faces
$a_{x,sf}$ = instantaneous crack length measured from the side faces.

It was very difficult to measure initial crack lengths from the fracture surfaces. Moreover, static crack extension occurred during loading of some specimens. Therefore, it is assumed that $a_{i,fs}$ = $a_{i,sf}$, i.e. C_i = 1. Equation (5) now becomes:

$$C_x = \left(\frac{(a_x)_{s.f} - (a_i)_{s.f}}{(a_f)_{s.f} - (a_i)_{s.f}} \,.\, (C_f - 1) \right) + 1 \qquad (6)$$

for $a_{x,sf} = a_{i,sf}$ $C_x = 1$ and
for $a_{x,sf} = a_{f,sf}$ $C_x = C_f$.

Table 5 shows that the maximum crack length correction is about 3.5 %. All crack lengths measured from the specimen side faces were multiplied by the correction factor C_x.

Figure 6 shows SCC growth curves after crack length correction. It is seen that:

- All curves show large crack jumps. The first crack jump occurred after 29 days of testing. At this testing time an additional layer of wax was put on the specimens to improve the coating. It is possible that the crack tips dried during this treatment. This may have resulted in accelerated crack growth, since alternate immersion results in faster crack growth than continuous immersion (see section 5.2.3). In view of this precautions were taken that the crack tips could not dry during inspection and refreshment of the solution. In spite of these precautions new crack jumps occurred occasionally during further SCC testing.
- There may be large differences in crack growth between duplicate specimens. In particular, crack growth was much faster in specimen C25 than in specimen B7 tested under the same conditions. Also, the crack growth in specimen B7 was only slightly faster than in specimen C21 tested at a much lower K_{Ii}.

Calculating SCC growth rates from the data points shown in figure 6 would result in strongly fluctuating growth rate data. Therefore crack growth curves were smoothed through the data points. Then about 20 a-t data pairs per specimen were read from the smoothed curves, and the SCC growth rate da/dt was calculated from

$$\frac{da}{dt} = \frac{a_{i+1} - a_i}{t_{i+1} - a_i} \tag{7}$$

da/dt was related to K_I. The crack length $a^* = (a_i + a_{i+1})/2$, which corresponds to the mean of the crack growth interval, was used in equation (2) to calculate K_I.

Figure 7 shows da/dt as a function of K_I. The data for 6 specimens fall in a scatterband. Crack growth in specimen C25 was faster, and in specimen B7 slower than in the other 6 specimens. No consistent trend of a_i and K_{Ii} on crack growth can be observed. When the results of specimen C25 and B7 are neglected the data indicate that K_{ISCC} is between 5 and 7 MPa$\sqrt{}$m.

The final stress intensity factor was calculated from the final crack length measured from the fracture surface $a_{f,fs}$ and the displacement in the load line v_{LL} using equation (2). It was also calculated from $a_{f,fs}$ and the bolt load at test termination using equation (3). The results are shown in table 5. This table also gives the ratio between both stress intensity factors, $K_{If,L}/K_{If,d}$. Differences of up to 20 % can be observed. However, there is no consistent trend of a higher or lower value for one of the stress intensity factors.

5.2.2 Additional NLR programme

The 6 specimens tested in the additional NLR programme were subjected to alternate immersion in substitute ocean water. The initial crack length was about 30 mm and the initial stress intensity factor was about 13 MPa$\sqrt{}$m. Typical fracture surface appearances after test termination are shown in figure 8. It is seen that the final stress corrosion crack fronts were fairly straight. The initial and final crack lengths and stress intensity factors are given in table 6.

Figures 9 and 10 show SCC growth curves after crack length correction. Figure 9 combines the test data for BCR specimens obtained from different locations in the plate. Figure 10 compares the test data for BCR and NLR specimens obtained from the surface location of the plate. Crack length correction was done in the same way as described in section 5.2.1. SCC testing of the NLR specimens was terminated after 155 days, because continued testing would have allowed the cracks to grow completely through the specimens. After this testing time all specimens were unloaded. For specimens A21, C28 and O2 the loading bolt had completely lifted from the opposite beam surface, while for specimens N2, N3 and O3 the displacement decrease at the crack mouth as a result of unloading was only 0.05 mm. The BCR specimens A21, C28, N2 and N3 were then re-exposed to the environment without a loading bolt. After a total time of 224 days the SCC tests on these specimens were also terminated.

The following observations can be made from figures 9 and 10:

- There were only small differences in SCC growth between duplicate specimens.
- The cracks in specimens A21, C28, N2 and N3 continued growing at about the same rate after the loading bolt had been removed. This means that these specimens were completely self-loading in this phase of testing. (Self-loading was already the case after 155 days of testing specimens A21, C28 and O2, since the loading bolt had lifted from the opposite surface).
- The location in the plate did not have an effect on SCC growth.
- There were only marginal differences between SCC growth in BCR and NLR specimens. There was a tendency to lower crack growth rates in NLR specimens at longer exposure times.

The SCC growth rates were determined as a function of the stress intensity factor using the same procedure as described in section 5.2.1 for continuous immersion testing. The results are shown in figure 11. The stress intensity factor is called the apparent stress intensity factor, K_{Iapp}, because it ceased to be caused by bolt loading in the latter phase of testing. All data are in a rather narrow scatterband. The SCC growth rate is more or less constant between 10^{-9} and 2.5 x 10^{-9} m/sec during the latter phase of testing.

5.2.3 Continuous immersion versus alternate immersion

The specimens tested in the framework of the BCR programme were continuously immersed in substitute ocean water. The specimens tested in the additional NLR programme were exposed to alternate immersion in substitute ocean water. Figure 12 compares the results of both test programmes in the form of crack growth rates versus (apparent) stress intensity factors. It is seen that the alternate immersion SCC growth rates are about a factor of 10 higher. Furthermore, the crack growth behaviour depends on the environmental conditions. In the continuous immersion tests a threshold value for the stress intensity factor is reached, whereas in the alternate immersion tests a constant crack growth rate is finally obtained and there is no threshold for crack growth.

5.2.4 Batch to batch differences

In earlier years the NLR had already done SCC growth tests on DCB specimens of 7010-T651 plate [3]. The plate tested in the earlier investigation had a thickness of 80 mm and was also delivered by ALCAN Plate, UK. An overview of the mechanical properties of the plate in the short transverse (S) direction is given below.

Yield strength:	$\sigma_{0.2}$ = 480 MPa
Ultimate tensile strength:	σ_{ult} = 557 MPa
Elongation to fracture, measured on 25 mm gauge length:	δ_{25} = 6.7 %
K_{IC}, fatigue crack, first audible click:	K_{IC} = 19 MPa$\sqrt{m}$
K_{IC}, static crack:	K_{IC} = 24 MPa$\sqrt{m}$.

DCB specimens with the same dimensions as the NLR specimens in the present investigation (see Fig. 2) were used in the tests. The specimens were obtained from surface and core locations of the plate and had an S-L orientation. The initial stress intensity factor was 18 MPa$\sqrt{m}$. The test conditions were the same as used for the alternate immersion tests carried out in the present investigation.

Figure 13 compares the SCC growth rates for the earlier tested 7010-T651 plate with those obtained in the present investigation. The following observations can be made:

- SCC growth rates could be obtained at higher K_I values for the earlier tested 7010 material. This is due to the higher fracture toughness of the earlier tested material.
- The resistance to SCC growth was much greater for the earlier tested 7010 plate.
- For the previously tested plate the SCC growth rates were higher for surface specimens than for core specimens. This is different from the behaviour of the 7010 plate tested in the present investigation, for which no effect of the position in the plate was found (see Fig. 9).
- In the very last phase of testing the SCC growth rates in the earlier investigation showed a slight tendency to turn towards a low-level plateau. A remaining displacement in the load line of about 80 % of the initial displacement was found at termination of the tests. This indicates that corrosion product wedging also played a role in these tests, as was the case in the present tests.

6 Discussion

6.1 Validity of linear elastic fracture mechanics concept

The SCC growth data obtained for continuous immersion testing in substitute ocean water showed no consistent trend of initial crack length and stress intensity factor on SCC growth. A continuously decreasing crack growth rate resulting in a threshold value for K_I (K_{ISCC}) was found. Also, there was no consistent difference in final stress intensity factor calculated from the displacements or the bolt loads at test termination. This indicates that specimen self-loading had little or no effect on SCC growth: the final stress intensity factor calculated from the bolt load at test termination would have been smaller than that calculated from the displacement in the load line if corrosion product wedging had played a role. This information indicates that the concept of linear elastic fracture mechanics is valid for exposure of DCB specimens of 7010-T651 plate to continuous immersion in substitute ocean water.

Alternate immersion testing in substitute ocean water did not result in a threshold value for the stress intensity factor, but a fairly constant crack growth rate was reached in the last phase of testing. In this phase the specimens were completely self-loading as a result of corrosion product wedging. It is obvious that a stress intensity factor calculated from the bolt load or bolt displacement does not represent the stress situation at the crack tip because there is a major stress contribution by corrosion products, and this cannot be quantified. Thus the concept of linear elastic fracture mechanics is invalid for exposure of DCB specimens of 7010-T651 plate to alternate immersion in substitute ocean water.

6.2 Specimen geometry and dimensions

The 19 mm high NLR specimens were provided with side grooves to prevent deviation of the stress corrosion crack. The 30 mm high specimens did not have side grooves. Crack plane deviation did not occur during SCC growth in either specimen type. The 7010-T651 plate had a pancake shaped grain structure (see Fig. 14), and sidegrooves are probably not necessary for aluminium alloys with such a grain structure, provided they are loaded in the short transverse direction.

In the present investigation similar crack growth curves were obtained for 19 and 30 mm high specimens. Complete specimen self-loading occurred in both specimen types after 155 days of testing.

Hasse and Dorward [5] carried out long-term SCC growth tests in a marine environment on a number of overaged 7000 series aluminium alloys. DCB specimens with total heights of 2H = 25 mm and 2H = 76 mm were tested. The tests were terminated after 105 months. Specimen self-loading was found for the 25 mm high specimens, but not for the 76 mm high specimens. A smaller effect of specimen self-loading might be expected for the greater height specimens owing to their greater beam stiffness, as was found in reference 5. It is unknown why such an effect was not found in the present investigation. It is possible that specimens with a height of 30 mm were not stiff enough to prevent specimen self-loading. Also the different environments (marine [5] versus substitute ocean water in the NLR tests) may have resulted in a different behaviour.

6.3 Batch to batch differences

The specified minimum mechanical properties for 7010-T651 plate in the short transverse direction are $\sigma_{0.2}$ = 390 MPa, σ_{ult} = 480 MPa and δ = 2 % [6]. Both the 7010-T651 plate tested in the present investigation and the plate tested in the earlier investigation were delivered by ALCAN Plate, UK, and amply met the minimum specified values. In spite of this significant differences in fracture toughness and SCC growth properties were found. The fracture toughness and the SCC growth resistance were higher for the earlier tested plate. The difference in SCC growth resistance was of the same order of magnitude as that observed for continuous and alternate immersion testing (compare Figs. 12 and 13).

The earlier tested plate showed faster SCC growth in surface material than in core material. This difference was explained from a difference in grain structure. The earlier tested plate had more elongated grains at the plate surface than at its core. The presently tested plate did not show any difference in SCC growth between surface and core material: figure 14 shows the grain structure in the crack plane of surface and core specimens. No difference in grain structure can be observed, which probably explains the similar SCC growth rates for surface and core material.

The A, B, C and D specimens in the present investigation were obtained from different sections of the plate. It was found that the B-specimens had higher fracture toughness and SCC growth resistance than the other specimens. On the other hand, specimen C25 showed much faster SCC growth than other specimens.

The test results discussed above show that large differences in properties may occur between different batches of plate material and even between different locations in plate material that meets the specified minimum mechanical properties.

6.4 Significance of SCC growth behaviour for structures

In the present investigation specimen self-loading owing to corrosion product wedging occurred during alternate immersion testing of DCB specimens at constant load line displacement, i.e. under K-decreasing conditions. Such an effect may be much less for K-increasing conditions owing to an increasing crack opening with crack growth. However, K-decreasing conditions often occur in actual structures because residual stresses and assembly stresses are far more frequent causes for SCC than service stresses [7].

In the present investigation wet-dry cycles were applied in the alternate immersion tests and resulted in faster SCC growth than continuous immersion tests. Wet-dry cycles may also occur in actual structures, for example in aircraft.

Alternate immersion under K-decreasing conditions may be more realistic for actual structures. Thus care has to be taken to translate results obtained from continuous immersion tests under both K-increasing and K-decreasing conditions to real structures with K-decreasing conditions, since a too optimistic picture can be obtained of the service performance.

7 Conclusions

Continuous and alternate immersion SCC growth tests in substitute ocean water were carried out on DCB specimens of a 90 mm thick aluminium alloy 7010-T651 plate. The results were compared with those of an 80 mm thick 7010-T651 plate tested previously at the NLR. The following conclusions are drawn:

(1) Linear interpolation of the displacement measured at the crack mouth of 30 mm high DCB specimens to that at the load line overestimates the displacement at the load line by 12 % to 7 % for crack lengths of 30 mm to 70 mm, respectively. A modified equation was established which fits the experimental data well.

(2) SCC growth was much faster during alternate immersion than during continuous immersion in substitute ocean water.

(3) Application of the concept of linear elastic fracture mechanics was possible for <u>continuous</u> immersion testing in substitute ocean water. A threshold value for the stress intensity factor, K_{ISCC}, between 5 and 7 MPa$\sqrt{m}$ was found.

(4) Corrosion product wedging played a major role during <u>alternate</u> immersion testing in substitute ocean water. No K_{ISCC} value could be established because a more or less constant crack growth rate between 10^{-9} and 2.5 x 10^{-9} m/sec was reached in the last phase of testing, as a result of specimen self-loading.

(5) Side grooves are not necessary in DCB specimens of aluminium alloys with a pancake shaped grain structure if they are loaded in the short transverse direction during SCC testing.

(6) No difference in SCC growth rate was found for alternate immersion testing of DCB specimens with 19 mm and 30 mm height, nor between 30 mm high DCB specimens obtained from surface and core locations of the plate.

(7) Large differences in fracture toughness and SCC growth properties may occur between different batches of 7010-T651 plate material that meet the specified minimum mechanical properties. Also, substantial differences can occur between different locations in one plate.

(8) Care has to be taken to translate results obtained from <u>continuous</u> immersion tests under both K-increasing and K-decreasing conditions to structural parts with K-decreasing conditions, especially when they are periodically wetted with aggressive environments. A too optimistic picture could be obtained of the service performance.

8 References

1. Corrosion of metals and alloys - stress corrosion testing, Part 6: Preparation and use of precracked specimens, ISO 7539-6, 1989.
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7. Speidel, M.O., Stress corrosion cracking of aluminum alloys, Metallurgical Transactions A, Vol. 6A, April 1975, pp. 631-651.

Table 1 Chemical composition of aluminium alloy 7010-T651 plate [4]

Element, weight %								
Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
0.036	0.087	1.74	0.01	2.43	0.01	0.005	6.41	0.04

Table 2 Mechanical properties in the short transverse (S) direction [4]

Yield strength:	$\sigma_{0.2}$	= 436 MPa
Ultimate tensile strength:	σ_{ult}	= 588 MPa
Elongation to fracture:	δ	= 4.7 %
Young's modulus:	E	= 70 GPa
Fracture toughness:	K_{IC}	~ 20 MPa$\sqrt{m}$.

Table 3 Test programme

a. Fracture toughness tests

Specimen nr.	Specimen type	Location in plate	a_i, mm
B4	BCR	core	30
A18	BCR	core	50
N1	BCR	surface	30
O1	NLR	surface	30

Also the determination of relation v_o/v_{LL} - crack length, see figures 1 and 2 for measurement locations of displacements v_o and v_{LL}.

b. Stress corrosion tests

	BCR programme		Additional NLR programme	
	Continuous immersion		Alternate immersion	
	Core of plate		Core of plate	Plate surface
K_{Ii}	a_i = 30 mm	a_i = 50 mm	a_i = 30 mm	a_i = 30 mm
~ 13 MPa$\sqrt{m}$	A11 - C18	C25 - B7	A21 - C28	N2-N3-O2-O3
~ 9 MPa$\sqrt{m}$	A14 - D18	C21 - D21		

The specimens were exposed by <u>continuous</u> immersion in aerated substitute ocean water or by <u>alternate</u> immersion in substitute ocean water. The water composition was according to ASTM spec. D1141 (without heavy metals).
The alternate immersion cycle was 1 hour wet and 11 hours dry.

Test temperature 21 °C.

Table 4 Survey of fracture toughness values

Specimen type	Specimen number	Position in plate	a_i mm	K_{IC}, MPa$\sqrt{m}$		
				audible click	crack jump	static crack
BCR	B4	core	30.5	15.0	18.0	20.3
	A18	core	50.3	11.2	14.0	16.5
	N1	surface	30.0	11.3	13.6	16.4
NLR	O1	surface	29.8	13.9	15.5	17.3

Explanation of indications for different K_{IC} values

audible click: K_I at first audible click, indicating minor crack extension from the fatigue crack, but without crack extension at the specimen side faces

crack jump: K_I at first crack jump from the fatigue crack, resulting in crack extension at the specimen side faces

static crack: Average K_{IC} for different measurements during extension of the static crack

Table 5 Survey of initial and final crack lengths, and initial and final stress intensity factors for continuous immersion testing in substitute ocean water

Spec.	v_{LL} mm	initial conditions		final crack length			final stress intensity factor		
		$a_{i,sf}$ mm	K_{Ii} MPa√m	$a_{f,sf}$ mm	$a_{f,fs}$ mm	C_f	$K_{If,d}$ MPa√m	$K_{If,L}$ MPa√m	$K_{If,L}$/ $K_{If,d}$
A11	0.406	31.45	12.8	51.00	52.1	1.0216	5.82	7.02	1.21
C18	0.407	31.40	12.8	49.85	51.5	1.0331	5.94	7.07	1.19
A14	0.269	30.75	8.7	41.15	42.0	1.0207	5.45	4.99	0.92
D18	0.270	30.80	8.8	37.55	38.2	1.0173	6.34	6.45	1.02
C25	0.897	50.45	13.5	104.70	105.5	1.0076	3.76	3.44	0.91
B7	0.896	50.15	13.7	69.35	71.7	1.0339	7.48	7.36	0.95
C21	0.597	50.10	9.1	67.80	69.9	1.0310	5.21	5.36	1.03
D21	0.598	50.00	9.2	58.00	59.4	1.0241	6.89	6.55	0.95

Explanation of notations:

subscript sf added to a_i and a_f: crack length measured from specimen side faces (mean value)
subscript fs added to a_f: crack length measured from fracture surface (mean value of surface, 1/4B, 1/2B, 1/4B, surface measurements)

$C_f = a_{f,fs}/a_{f,sf}$

$K_{If,d}$: Final stress intensity factor derived from bolt displacement using equation (2)
$K_{If,L}$: Final stress intensity factor derived from bolt load using equation (3)

Table 6 Survey of initial and final crack lengths, and initial and final stress intensity factors for alternate immersion testing in substitute ocean water

Spec. type	Position in plate	Specimen	v_{LL} mm	initial conditions		final crack length			$K_{If,app}$ MPa√m
				$a_{i,sf}$ mm	K_{Ii} MPa√m	$a_{f,sf}$ mm	$a_{f,fs}$ mm	C_f	
BCR	core	A21	0.428	32.25	13.0	108.70	109.8	1.0101	1.7
		C28	0.438	32.95	12.9	100.10	100.8	1.0070	2.0
BCR	surface	N2	0.390	30.20	13.0	96.90	97.7	1.0083	1.9
		N3	0.387	29.85	13.1	91.85	92.3	1.0049	2.1
NLR	surface	O2	0.568	29.90	13.8	81.50	83.4	1.0233	2.3
		O3	0.574	30.10	13.8	77.55	78.6	1.0135	2.6

$K_{If,app}$: apparent final stress intensity factor, derived from bolt displacement using equation (2)

See table 5 for explanation of other notations