EFFECT OF A REDUCED DUCTILITY AT LOW TEMPERATURES ON FATIGUE CRACK GROWTH IN 7075-T6 SHEET MATERIAL TESTED IN VACUUM

by

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SUMMARY

Fatigue crack propagation in two types of 7075-T6 Clad material was studied in air at 20°C and in vacuum at 20°C, -50°C and -100°C, supplemented by crack closure measurements and fractographic observations. Crack growth rates in vacuum were lower than in air. One 7075-alloy (fine grained) showed similar crack rates in vacuum at 20°C and -100°C at low ΔK values. The behaviour of the second 7075 alloy (coarse grained) was exceptional in several ways which had to be attributed to extensive slip band cracking. Both materials showed secondary cracks perpendicular to the crack front if tested at low temperatures and sufficiently high ΔK-values. The secondary cracks caused a macroscopic retransition from a shear mode failure to a tensile mode failure. Practical significance of the results for fail-safe properties at low temperatures is indicated.
1. INTRODUCTION

The growth rate of fatigue cracks in aluminium alloy sheet material is strongly dependent on the ductility of the material. This effect has been recognized for a long time by aircraft designers. It clearly affects material selection if fatigue resistance is significant. Unfortunately it has to be admitted that the effect of ductility on crack growth is not completely understood. An important contribution to a better understanding was offered by Elber (Ref. 1) by introducing the crack closure concept. A lower ductility implies smaller plastic zones at the crack tip and subsequently the amount of crack closure will be less. As a result the effective stress intensity factor ($\Delta K_{\text{eff}}$) will be larger and the crack will grow faster. Adopting this simple argument it should be kept in mind that a change of ductility is usually combined with a change of the structure of the material. An example is offered by the comparison between 2024-T3 and 2024-T8. The ductility is lower for the T8-condition and it turned out that the crack growth rate is higher (Ref. 2). However, the precipitation is different also. Another example is the comparison between 2024-T3 in the as received condition and the same material after prestraining. The prestrained material shows a lower ductility and a faster crack growth (Ref. 3). Crack closure measurements were made in this case, confirming less crack closure in the prestrained material. However, measured values of $\Delta K_{\text{eff}}$ could not fully account for the effect on crack growth. It should be recognized that prestraining obviously modifies the dislocation structure of the material.

The ductility of a material is affected also by temperature. The starting point of the present investigation was the idea that lower temperatures will decrease the ductility without changing precipitation or strain hardening. The effect of ductility could thus be studied by performing fatigue crack propagation tests at room temperature and at lower temperatures. Since previous work (Ref. 4) revealed a systematic effect of environment on the mode of crack propagation (tensile mode or shear mode) it was decided to exclude any environmental effect by performing
tests in vacuum. This also allowed a comparison with results of Boers (Ref. 5), who performed crack growth tests in vacuum on specimens of the same sheet, but at elevated temperature. The results are included in this report for completeness.

At room temperature some tests were also carried out in air to confirm the difference between crack growth in air and in vacuum. All tests were carried out on 7075-T6 clad material. The first tests indicated a remarkable crack growth behaviour, which initially was not well understood. The material showed a somewhat coarse-grained structure. Additional specimens were then cut from another 7075-T6 sheet with a fine-grained structure. More systematic data were obtained with this second material. A survey of the conditions in the crack growth test is given in the table below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Environment</th>
<th>Temperature</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>7075-T6 fine-grained</td>
<td>air</td>
<td>20°C</td>
<td>2 (D7, D8)</td>
</tr>
<tr>
<td></td>
<td>vacuum</td>
<td>-100°C</td>
<td>2 (A3/A4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20°C</td>
<td>2 (C3, C4)</td>
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<td>20°C</td>
<td>2 (Ref. 5)</td>
</tr>
<tr>
<td></td>
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<td>53°C</td>
<td>2 (Ref. 5)</td>
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<td></td>
<td>88°C</td>
<td>3 (Ref. 5)</td>
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<td>120°C</td>
<td>2 (Ref. 5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>140°C</td>
<td>2 (Ref. 5)</td>
</tr>
<tr>
<td>7075-T6 coarse-grained</td>
<td>air</td>
<td>20°C</td>
<td>6 (D1-D4, D5a, D6a)</td>
</tr>
<tr>
<td></td>
<td>vacuum</td>
<td>-100°C</td>
<td>2 (A1, A2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-50°C</td>
<td>3 (B1, B2, B3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20°C</td>
<td>2 (C1, C2)</td>
</tr>
</tbody>
</table>

All crack growth tests carried out at: \( \sigma_m = 8 \text{ kgf/mm}^2 \), \( \sigma_a = 4 \text{ kgf/mm}^2 \), \( R = 1/3 \), frequency = 20 Hz

Supplementary to the crack growth tests the fracture surfaces were examined macroscopically. A fairly large number of cross sections of fractures were made for observations in the optical microscope. This
work was triggered by some interesting details, related to slip band cracking and to secondary cracks parallel to the sheet surface (delamination). Crack closure measurements were made also.

The results are analyzed in a discussion, attempting to present a consistent picture of the crack growth observations. The report is completed by a summary of the information obtained and a number of conclusions.
2. SHEET MATERIALS 7075-T6

Material structure

Both fine-grained and coarse-grained materials were in the clad condition with a sheet thickness of 2.5 mm. The microstructures are shown in figure 1, which indicates an apparent difference in grain dimensions. Quantitative grain size measurements were made by Bowles (Ref. 6) including a comparison with a third material, also 7075-T6 alloy. For the fine-grained material an "average grain size" of 22 μm was found and this value seems to be quite normal for this alloy. For the coarse-grained material the size was 71 μm, confirming that it should be labelled as coarse-grained.

In the Metallurgical Department (Mr. N.M. van der Pers) X-ray diffraction patterns were obtained to check the possibility of significant texture. (Ref. 7). However, such indications were not found.

Mechanical properties

Results of tensile tests have been compiled in figure 2. A relatively long gage length (L = 100 mm, L/√cross section = 22) was adopted to avoid a large effect of necking on the elongation at failure (6). Figure 2 shows that the coarse-grained material has a somewhat lower elastic limit, a slightly lower yield stress and a somewhat higher tensile strength, implying that it exhibits somewhat more strain hardening. Differences are not large, however. The elongation is also superior, and in view of the large gage length, it is quite high. The tensile specimens of the coarse-grained material after failure clearly showed an "orange peel" surface, whereas the fine-grained material did not.
3. EXPERIMENTAL DETAILS

All crack growth tests were carried out in an Amsler electro-hydraulic testing machine (max. capacity 20 tons), see figure 3. As indicated before all tests were carried out under constant-amplitude loading with a mean stress \( \sigma_m = 8 \text{ kgf/mm}^2 \), a stress amplitude \( \sigma_a = 4 \text{ kgf/mm}^2 \) and a frequency of 20 Hz. Specimen dimensions are shown in figure 4. A central notch for crack growth initiation was produced by drilling a small hole and making two saw cuts. For crack growth tests in vacuum precracking occurred in air until a crack length \( a = 2.5 \text{ mm} \) was reached. This was done to avoid unduly long initiation periods. The test was then continued in vacuum and the first crack growth observation was made at \( a = 3 \text{ mm} \).

Crack growth tests in air were carried out at room temperature only (\( \sim 20^\circ \text{C} \)) with the specimen fully exposed to the air in the laboratory. The average value of the relative humidity was 50%.

Vacuum conditions were obtained in a home-made vacuum chamber, employing an oil-diffusion pump in series with a mechanical first-stage vacuum pump, both pumps being procured from Baltzer.

Temperature control occurred by means of two block of brass, clamped on the specimen. The blocks were provided with internal channels connected by flexible vacuum tubing to the door of the vacuum chamber. Cooling occurred by pumping liquid nitrogen through the system, whereas oil was used for obtaining elevated temperatures. The temperature was measured by a thermocouple attached to the central part of the specimen with the thermocouple signal being used for temperature control. The scatter was \( \pm 4^\circ \text{C} \) as a maximum for the lower temperature, whereas the accuracy was significantly better for the elevated temperatures.

Crack closure measurements were carried out with a COD-meter with a gage length of 4 mm, see figure 5. This COD-meter was developed by the German laboratory DFVLR in Porz-Wahn (Ref. 8). The crack closure
load \( P_{cl} \) was derived from the transition between the linear part and the non-linear part of the COD-record, see figure 5b. Crack closure records were also made with the COD signal compensated for the linear output if the crack is fully open (suggestion of P.C. Paris). As a result the linear part of the record is a vertical line (fig. 5c). The advantage is that the compensated COD signal can now amplified much more and this allows a better observation of the transition between the linear part and the nonlinear part of the record. The COD-meter was always mounted on the centre line of the specimen.
4. TEST RESULTS

4.1. CRACK GROWTH IN AIR AND IN VACUUM AT ROOM TEMPERATURE

Crack growth records were obtained by visual observations of the crack length at both sides of the central notch and related numbers of load cycles. Full test data are presented in a separate report (Ref. 9), which can be obtained on request. The results of the left hand crack and the right hand crack in the same specimen have been averaged. These data were used for calculating the crack growth rate by adopting the so-called three-points formula:

\[
\frac{\text{d}a}{\text{d}n} = \frac{a_{i+1} - a_{i-1}}{n_{i+1} - n_{i-1}}
\]

Subscript \( i \) is used as a rank number of the observations, while \( n \) is the number of cycles and \( a \) is the crack length. The stress intensity factor was calculated from:

\[
\Delta K = C \Delta \sigma \sqrt{a}
\]

with the geometry factor \( C \) according to Fedderson:

\[
C = \sqrt{\sec \left( \frac{\pi a}{2b} \right)}
\]

In these equations \( \Delta \sigma = 2\sigma_a = 8 \text{ kgf/mm}^2 \) and \( 2b \) is the specimen width (100 mm). Results of \( \text{d}a/\text{d}n \) as a function of \( \Delta K \) have been plotted in figures 6a, 6b and 6c. A monotonously increasing crack rate is observed in figs. 6a and 6b. However, this does not apply to the results for the coarse-grained material tested in air, see fig. 6c, which shows an intermediate maximum and minimum. To check this unexpected trend an additional test was carried out, however, the crack length now being measured with the electrical potential method (Ref. 10). The results of the test are shown in figure 6d, which fully confirms the observations made visually.
Average curves of figures 6a-6c have been replotted in figure 7, which clearly indicates an effect of the environment. Cracks were growing faster in air as compared to vacuum. Figure 7 also shows an apparent difference between the results of the fine-grained and the coarse-grained material. The behaviour of the coarse-grained material is quite remarkable and this has led to crack-closure measurements and microscopical studies (sections 4.3-4.5).

4.2. CRACK GROWTH IN VACUUM AT DIFFERENT TEMPERATURES

Test at elevated temperatures (20°, 53°, 86°, 120° and 140°C) were carried out on fine-grained material only (results of Boers, Ref. 5). The results in figure 8 show that most data points are in a fairly narrow scatter band. At low ΔK-values some data points are above the scatter band, but this might be due to an initially slant crack front orientation. A more systematic trend is observed for ΔK > 50 kgf/mm², indicating that results for the higher temperatures (120° and 140°C) are dropping below the scatter band, even more for 140°C than for 120°C.

Test results for low temperatures were obtained for both fine-grained material (-100°C) and coarse-grained material (-50° and -100°C). Crack growth in the fine-grained material is faster at -100°C as compared to room temperature, see figure 9. However, the difference is small until ΔK = 43 kgf/mm², while it increases at higher ΔK-values. The increase of the crack growth rate corresponds to the occurrence of secondary cracks (delamination, see section 4.4).

Results of the coarse-grained material as shown in figure 10 indicate the following trends:
- crack growth rates at low ΔK-values are smaller for lower temperatures and scatter is fairly large in this area;
- crack growth rates at high ΔK-values are hardly different for 20°C, -50°C and -100°C;
- at intermediate ΔK-values the crack rate suddenly increases. At the
same time scatter becomes smaller and secondary cracks (delamination) are observed (section 4.4). This change occurs at a lower $\Delta K$-value for the lower temperature (-100°C).

4.3. MACROSCOPIC FRACTOGRAPHY

Tests at room temperature in air and in vacuum

Fracture surfaces are shown in figure 11. The cracks in air apparently start to grow in the tensile mode, developing shear lips later on. In vacuum, however, the cracks (after initiation in air) immediately exhibit some type of multiple shear failure. These trends are found for both fine-grained and coarse-grained material. A similar difference of the behaviour in air and in vacuum was found before (Ref. 4).

Figure 11 also illustrates a noticeable difference between fine-grained and coarse-grained material. The appearance of the fracture surface is much rougher for the coarse-grained material. It is also more facetted and glittering.

Another remarkable difference is associated with the shear lips in air. In the fine-grained material the shear lips start rather early with a smoothly increasing width at increasing crack length. This is supposed to be the normal trend in air. However, the coarse-grained material in air shows a fairly late start of shear lip development followed by a rapid transition to the full shear mode. The fairly abrupt transition coincides with a decreasing crack rate as shown in figure 6c and 6d!

Tests at low temperatures in vacuum

Fracture surfaces are shown in figure 12. Fine-grained material tested at -100°C does not clearly exhibit multiple shear, whereas it did at 20°C (fig. 11). A transition to the shear mode did occur, but surprisingly a retransition to the tensile mode occurred at a large crack length ($a>22$ mm).
The coarse-grained material showed essentially the same features, but the fracture surfaces were much rougher again. At -50°C the retransition to the tensile mode occurred at a ~ 35 mm. However, at -100°C crack growth remained in the tensile mode over the full width of the specimen, at least from a macroscopic point of view (fig. 12). A slight tendency to develop some shear lips is observed only at intermediate a-values.

4.4. MACROSCOPICAL RESULTS

In order to obtain more information about the topography of the fracture surface several cross sections were made, both perpendicular and parallel to the sheet surface. For this purpose only completely fractured specimens were available, except in a single case, where a partly cracked specimen could be sectioned.

Fine-grained material

Cross sections and longitudinal sections of specimens tested in air, in vacuum at 20°C and in vacuum at -100°C are shown in figures 13, 14 and 15 respectively. Obvious microscopic differences between the results obtained in air and in vacuum at 20°C cannot be indicated. An exception should perhaps be made for the multiple shear phenomenon, which was already found macroscopically. It is confirmed here by figure 14b at a magnification of 50x.

A more interesting observation is found for crack growth in vacuum at -100°C. Small secondary cracks parallel to the sheet surface, indicated by arrows in figures 15b and c, occur at larger values of the crack length. The first secondary cracks are found when the fracture surface starts with the retransition to the tensile mode (fig. 12). It is clear, however, that the macroscopical tensile mode is not a flat fracture at
large magnification (400x in figs. 15b and c).

**Coarse-grained material**

A survey of cross sections at low magnification (14x) is presented in figure 16. More detailed information follows in figures 17 to 22. Fracture profiles obtained in air (fig. 17) rarely suggest a growth of the crack in a crystallographic plane. However, profiles of cracks grown in vacuum are completely different. This applies both to crack growth at 20°C (fig. 18) and lower temperatures (figs. 19-21), provided the crack length is not too large. A clear correlation between crack growth and crystallographic planes is obvious in several pictures (e.g. figs. 18c, 19a and b, 20a). As a result crack branching is frequently observed, see figs. 18b and c, 19b and especially figure 20a. Crack branching sometimes has caused separation of significant fragments of material from the fracture surface, see figure 21a.

At larger values of the crack length both crack branching and growth along crystallographic planes becomes less obvious (figs. 19c and 20b). This observation is combined with the occurrence of secondary cracks parallel to the sheet surface, see figure 22. However, in comparison to the fine-grained material the secondary cracks are much more evident. Figure 22 is related to a test temperature -100°C, while similar, but somewhat smaller secondary cracks were found at -50°C. At both temperatures the impression was obtained that the first occurrence of the cracks is associated with the suddenly increasing crack rate (fig. 10).

The occurrence of secondary cracks at -100°C cannot be related to a retransition to the tensile mode (macroscopically), because the crack never was in the shear mode. At -50°C a transition to the shear mode was found (fig. 12), followed by a retransition to the tensile mode later on (completed at a 35 mm). Secondary cracks were found already at a 10 mm.
4.5. CRACK CLOSURE MEASUREMENTS

Crack closure measurements on fine-grained material specimens did not give any clear indications of the occurrence of crack closure. The same is true for the coarse-grained material tested in air, as shown by the records in figure 23b. The decreasing part of the loop is virtually linear between maximum and minimum load, indicating no change of stiffness and hence no crack closure. The increasing part is slightly non-linear, but it is difficult to deduce any crack closure from this trend. On the contrary the tests on coarse-grained material tested in vacuum gave unambiguous indications of crack closure, see figure 23a.

In view of the above results it was decided to test coarse-grained material alternately in vacuum and in air to study crack closure after a transition from vacuum to air. The fracture surface of the specimen is shown in figure 24 with part of the central notch at the far left followed by a crack initiation in air. Subsequent crack growth occurred in vacuum until \( a = 3.0 \) mm. Crack closure measurements were made at \( a = 2.5 \), \( a = 2.65 \) and \( a = 3.0 \) mm, see figure 25. The recordings are very much similar to those in fig. 23a, as had to be expected. After the third measurement the vacuum chamber was filled with normal air. Without any additional cyclic loading a fourth crack closure measurement was made and it did not show any difference with the last one in vacuum. Cyclic loading continued in air failed to produce visible crack extension after 1000 cycles, however, a crack closure measurement gave a COD-record, which was highly different from the previous one (see figs. 25 and 26). The crack-opening load \( (P_{op}) \) had increased considerably and there is also more hysteresis. Since 1000 cycles in air did not produce a visible crack extension the increased \( P_{op} \) should be related to the effect of exposure of the fracture surface obtained in vacuum to air.

This part of the fracture clearly shows black fretting corrosion debris, indicating rubbing between poorly fitting fracture surfaces. Subsequent fatigue testing of 20,000 cycles after the transition from vacuum to air
did not yet produce visible crack extension. The crack opening load $P_{op}$ had increased still further, (figs. 25 and 26) probably due to increased fretting damage. Continued cyclic loading then produced crack growth and after 50,000 cycles in air ($a \approx 5.35$ mm) the crack opening load had a considerably reduced value, although crack closure was still apparent. Since a test carried out in air only did not indicate crack closure (fig. 23b) it must be concluded that the fracture part obtained in vacuum is still having some effect. Later on in the test a second transition from vacuum to air was applied and again fretting corrosion damage can be observed on the vacuum part of the fracture. Since shear lips were already present the fretting damage is then more evident on these lips.
5. DISCUSSION

5.1. EFFECT OF LOW TEMPERATURES AND COMPARISON WITH RESULTS OF BROEK

The effect of low temperatures on crack growth rate is shown in figures 9 and 10 for fine-grained and coarse-grained material respectively. Obviously the effect is different for the two materials.

In Ref. 11 Broek reported a crack propagation in 2024-T3 and 7075-T6 material, tested at room temperature and lower temperatures down to -75°C. These tests were carried out in normal air, but at room temperature some tests occurred in very dry air also. The mean stress was $\sigma_m = 7.0 \text{ kgf/mm}^2$, while three amplitudes were adopted, viz. $\sigma_a = 2.5 \text{ kgf/mm}^2$, 4.0 kgf/mm$^2$ and 6.5 kgf/mm$^2$, however, the amplitude hardly had any effect on the trends observed. Results for $\sigma = 7 \pm 4 \text{ kgf/mm}^2$ have been replotted here in figure 27. These stresses are almost the same as those of the present investigation ($\sigma = 8 \pm 4 \text{ kgf/mm}^2$). Broek's results clearly show a temperature effect at low $\Delta K$-values. He explained the low crack rates at -75°C by referring to the low water vapour content of the air at this temperature as combined with the high test frequency (100 Hz). It was confirmed by tests in very dry air at room temperature (see fig. 27). At high $\Delta K$-values Broek found a slight tendency to increased crack rates at -75°C.

In figure 28 the results of Broek are compared to the present data for fine-grained material. It should then be considered that very dry air and a high frequency imply an almost inert environment, and secondly very cold air is also very dry. Then a comparison is allowed for three sets of conditions.

<table>
<thead>
<tr>
<th>present investigation</th>
<th>Broek's investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. normal air at 20°C</td>
<td>normal air at 20°C</td>
</tr>
<tr>
<td>2. vacuum at 20°C</td>
<td>very dry air at 20°C</td>
</tr>
<tr>
<td>3. vacuum at -100°C</td>
<td>air at -75°C</td>
</tr>
</tbody>
</table>
For all three sets the crack rates observed in the present investigation are larger than the results of Broek, but the tendencies of the curves show a good deal of similarity. In other words the fine-grained material and the material tested by Broek show a similar behaviour. Keeping in mind the significant differences between the results of coarse-grained material and fine-grained material, it must now be concluded that the behaviour of the coarse-grained material is quite exceptional. Microscopical observations and crack closure measurements did confirm this view.

Accepting that the fine-grained material showed a normal behaviour the effect of low temperatures on fatigue crack growth can be indicated as follows: The effect of a low temperature is rather small at low ΔK-values, but at higher ΔK-values an increasing effect is found, implying faster growth at lower temperatures. At these ΔK-values the macroscopic and the microscopic pictures are different also for room temperature and lower temperatures.

The small temperature effect up to ΔK \approx 40 \text{ kgf/mm}^2 might seem a surprising result, because the ductility of 7075-T6 at -75°C is lower than at room temperature (see fig. 29). The yield stress is about 7% higher and, plastic zones at crack tips will then be about 14% smaller. It then should be expected that plastic deformations at the crack tip will be smaller. Although it may also imply higher tensile stresses at the tip of the crack this should not be significant in vacuum according to the model presented in reference 4, in view of the absence of any aggressive agent. However, already the comparison between 2024-T3 and 2024-T8 both tested in vacuum fatigue (Ref. 2) suggested that this picture may be too simple. Apparently the low ductility is a disadvantage, also in an inert environment.
5.2. BEHAVIOUR OF THE COARSE-GRAINED MATERIAL

Behaviour in air

Crack growth rates initially were very high in the tests carried out in air (20°C), see figure 7. A corresponding observation was the initial absence of shear lips (fig. 11). When shear lips were formed at a later stage, a transition to a full shear mode occurred fairly rapidly and, simultaneously, the crack rate decreased to a lower value (fig. 6c and d). Consequently the main question seems to be why the shear lips were suppressed so long, whereas they were not in the fine-grained material. In view of the significance of the environment for forming shear lips and the transition from tensile mode to shear mode (Ref. 4), it must be assumed that fatigue crack growth in the coarse-grained material was more sensitive to the environment. The origin of the higher sensitivity is unknown, but it is partly confirmed by the behaviour in vacuum.

Slip-band cracking in vacuum

The microscopic crack growth behaviour of the coarse-grained material in vacuum is quite remarkable. The crack apparently is growing along crystallographic planes both at room temperature (fig. 18) and at low temperatures (figs. 19 and 20). A similar behaviour is not observed in the fine-grained material. Crack growth in the coarse-grained material in vacuum may well be labelled as "slip-band cracking", a phenomenon defined by Forsyth (Ref. 13) as "Stage I crack growth". Slip-band cracking was accompanied by frequent and intensive crack branching (fig. 20a), which implies a severe restraint on maintaining a continuous and coherent crack front. Cracks in different grains apparently want to grow in different directions. It is expected that the incompatibility involved in slip-band cracking will considerably affect the crack rate, that means it will make crack growth more difficult and less continuous. This may well explain the low crack rates and the large scatter as shown in figure 10 for low ΔK-values.
The remarkable crack-closure behaviour of the coarse-grained material can be explained by the same arguments. Crack branching with a somewhat erratic front will hinder crack opening. Fragments, loosened from the fracture surface will obstruct crack closure. A non-linear behaviour should be expected, although it is not necessarily the simple crack closure and opening mechanism described by Elber (Ref. 1).

Another observation can also be explained now. After transition from vacuum to air the crack initially did not grow, inspite of an aggressive environment being added. However, at the moment of the transition a continuously coherent crack front did not exist due to slip-band cracking and crack branching. Due to the presence of (humid) air slip-band cracking could no longer occur. It then requires many cycles to restore again a more or less continuous crack front line.

The main question now appears to be: why does the coarse-grained material exhibit slip-band cracking, whereas the fine-grained material does not? Employing the identifications "coarse-grained" and "fine-grained" it is tempting to relate the observations to a grain-size effect. In large grains the restraint on slip exerted by adjacent grains will be less effective than in small grains. This explanation seems questionable in view of recent test results (Ref. 14). Tests were carried out on round specimens (diameter 10 mm), which showed internal crack initiation due to residual stresses. The residual stresses were purposely introduced by a cold water quench. The internal cracks growing in vacuum also showed slip-band cracking, although the grain size was rather small.

Temperature effect on slip-band cracking

At low ΔK-values the crack rate was smaller at a lower temperature (fig. 10). It may be assumed that this trend results from higher shear stresses required for slip at lower temperatures. This explanation could apply in view of slip-band cracking, but it has to be admitted that more should be known about the slip-band cracking mechanism for postulating
such an explanation with more certainty.

5.3. SECONDARY CRACKS

Secondary cracks as found in the present investigation are not mentioned in the literature. Three questions are of interest:

(1) How are secondary cracks initiated?

(2) Why are secondary cracks in the coarse-grained material much more clearly observed than in the fine-grained material?

(3) What is the effect of secondary cracks on crack growth?

The orientation of secondary cracks is schematically indicated in figure 30. The cracks are supposed to extend ahead of the crack front also. Indications for this can be drawn from figure 22c, a cross section made at the crack tip, parallel to the crack front and the loading direction (// YZ-plane). It shows the main crack to be at different levels at opposing sides of the secondary crack. This suggest that the secondary crack was present there before the main crack reached that location. As a result a crack profile should show vertical parts after full separation of both specimen halves. As a matter of fact such vertical parts were frequently observed, see figure 22a.

It should be assumed that the secondary cracks are caused by a tensile stress in the Z-direction ($\sigma_z$, see fig. 30). This stress can be large if the material near the crack tip is approximately in a state of plane strain. An estimate of the size of the plastic zone ($r_p$) in plane strain can be obtained with:

$$r_p = \frac{1}{6\pi} \left( \frac{\Delta K}{\sigma_{0.2}} \right)^2$$

For a high $\Delta K$-value ($70$ kgf/mm$^2$ at $\sim 20$ mm) and $\sigma_{0.2} = 53$ kgf/mm$^2$ at $-50^\circ$C the result is:

$$r_p = 0.093 \text{ mm}$$
which is much smaller than the sheet thickness \((t = 2.5 \text{ mm})\). It may then be assumed that plane strain will be approximately valid and:

\[
\sigma_z = \nu (\sigma_x + \sigma_y)
\]

will arrive at high values. Since the load was cyclic the secondary cracks should also grow by fatigue! The impression obtained is that the secondary cracks are predominantly intercrystalline, but a more detailed microscopical examination should confirm this.

It is difficult to answer the question why secondary cracks are much more evident in coarse-grained material as compared to fine-grained material. Nevertheless the latter material also shows vertical parts in a crack profile parallel to the YZ-plane (figs. 15b and c). It appears that secondary crack in the fine-grained material, although being smaller, are more numerous than in the coarse-grained material.

The effect of secondary cracks on crack growth was more significant for the coarse-grained material. This should not be surprising since the larger secondary cracks almost implied a local delamination along the crack front. As soon as secondary cracks occurred in the coarse-grained material both slip-band cracking and crack branching were far less evident, compare fig. 20b to fig. 20a. Apparently the delamination allows a more coherent crack front between secondary cracks. An increased crack rate may then be expected and this can explain the rapid increase of the crack rate at low \(\Delta K\)-values shown in figure 10.

A consideration of the effect of secondary cracks in the fine-grained material is more difficult. The curves in figure 9 suggest that the crack rate at \(-100^\circ\text{C}\) for \(\Delta K\) larger than 45 kgf/mm\(^{3/2}\) is increasing more rapidly than at \(20^\circ\text{C}\). Secondary cracks, found at \(-100^\circ\text{C}\) and not found at \(20^\circ\text{C}\), will reduce the plastic restraint in Z-direction and thus allow more plastic deformation. However, it is rather speculative to say that this is a full qualitative explanation of the above trend.
5.4. RETRANSITION TO THE TENSILE MODE

Fatigue cracks in sheet material growing with an increasing propagation rate usually show the well-known transition from the tensile mode to the shear mode. It was quite remarkable to see in the present tests, carried out in vacuum at low temperature, that the shear mode was followed at a later stage by a retransition to the tensile mode (fig. 12). The beginning of the retransition had to be associated with the occurrence of secondary cracks. It is possible indeed that secondary cracks have caused the retransition. Considering secondary cracks as a kind of delamination there is no reason why shear modes in the separate lamella should macroscopically line up to a single shear mode. On the contrary, it should be expected that shear modes in the separate lamella will converge to similar locations in Y-direction. Macroscopically, that would imply a quasi-tensile mode as observed (fig. 12), however, microscopically the fracture profile could locally be in the shear mode, which was observed also (figures 15, 16 and 22).

5.5. CONCLUDING REMARKS

The starting point of the present investigation was to study how ductility could affect crack growth in an inert environment (vacuum in this case), if the ductility is modified by changing the testing temperature only, i.e. without changing the structure of the material. The results of the fine-grained 7075-T6 alloy tested at +20°C and -100°C, supplemented by results of Boers at elevated temperatures (Ref. 5) indicate a surprisingly small influence, since the effect on crack growth rate was practically negligible. Only high temperatures (120 and 140°C) and high ΔK-values induced a slightly lower crack rate, but at these temperatures the stability of the smaller precipitated zones will be affected.

A lower ductility at low temperatures will imply smaller plastic zones with the following consequences:
a. higher tensile stresses in the plastic zone.
b. smaller plastic deformations in the plastic zone.

c. if crack closure occurs it will be less (higher $\Delta K_{\text{eff}}$).

In an aggressive environment (also in humid air) aspects a and c will increase crack growth rates, but b might reduce growth rates. Experience has learned (e.g. Refs. 2 and 3) that cracks in a low ductility material grow faster in an aggressive environment as compared to crack growth in a more ductile material. However, in an inert environment the higher tensile stresses at the crack tip should be less significant according to the crack growth model presented in Ref. 4.

This model assumes that crack extension under cyclic load is mainly depending on:

- slip and consequently on shear stresses in an inert environment,

whereas

- decohesion induced by an aggressive agent and high tensile stresses are controlling crack growth in an aggressive environment.

In its most simple form this model suggest that tensile stresses (aspect a) should not be significant in an inert environment. Since crack closure (aspect c) could not be indicated in the fine-grained material the conclusion should be that slip in the plastic zone (aspect b) should have a large effect on crack growth. However, the absence of a ductility effect on crack growth in the fine-grained material now suggest that an effect of higher tensile stresses on one hand (aspect a) and smaller plastic deformations on the other hand (aspect b) have balanced fairly well. It is difficult then to say something about the specific significance of each aspect on its own. It must be concluded, however, that higher tensile stresses in the plastic zone are not irrelevant for crack growth in vacuum. A similar indication was obtained before in a comparison between 2024-T3 and 2024-T8, both in air and in vacuum (Ref. 2), as mentioned before.

The occurrence of secondary cracks at low temperatures should primarily be related to the lower ductility. The retransition to the tensile mode is a subsequent consequence of the secondary cracks. The secondary cracks, not reported before in the literature, may be more evident if the
crack growth resistance is relatively poor in planes parallel to the sheet surface. Apparently this applied to the coarse-grained material.

Probably the occurrence of secondary cracks during fatigue is significant at low temperatures only. However, it could be equally significant for residual strength at low temperatures and perhaps at room temperature also. Further studies should be advised.

Finally a few comments have to be made on slip-band cracking, occurring abundantly in the coarse-grained material tested in vacuum. Slip-band cracking in Al-Zn alloys is not a new phenomenon, see a review given in a recent paper by Nageswararao, Kralik and Gerold (Ref. 15). These authors arrive at the conclusion that the occurrence of the phenomenon is dependent on the environment (as confirmed here), the stress amplitude and the microstructure. With respect to the microstructure they draw attention to chemical composition and heat treatment. Precipitation only until the formation of GP zones should encourage slip-band cracking, whereas over-aging until η' would obstruct it. Examination of the fine-grained and coarse-grained material would be of interest to resolve the difference between the two materials.
6. SUMMARY OF RESULTS AND CONCLUSIONS

Crack growth tests were carried out in two different types of clad 7075-T6 sheet material, thickness 2.5 mm, employing a fatigue load of \(8 \pm 4\) kgf/mm\(^2\) and 20 Hz. The two materials were nominally identical but grain sizes were considerably different. The materials are labelled as fine-grained and coarse-grained material, respectively. Tests were carried out in vacuum at 20°C and at low temperatures: \(-100^\circ\)C for the fine-grained material and \(-50^\circ\)C and \(-100^\circ\)C for the coarse-grained material. Some tests were carried out in air at 20°C.

Crack growth measurements, supplemented by macroscopic and microscopic examinations and crack-closure measurements, have led to the following results and conclusions.

(1) Crack growth behaviour \((da/dn as a function of \Delta K)\) of the fine-grained material compared well with information from the literature. Data for low temperatures were rather limited. It appears that the temperature effect in vacuum is small.

(2) The coarse-grained material showed a remarkable behaviour in several respects. In air the crack rate initially was very high, while shear lips did not occur. This is pointing to a high environmental sensitivity. At a later stage shear lips were formed fairly abruptly inducing a temporarily lower crack rate. In vacuum at low temperatures (-50 and -100°C) the crack rate was very low at low \(\Delta K\)-values. This had to be related to slip-band cracking, which also occurred in vacuum at 20°C, but not in air due to the aggressive effect of water vapour. The occurrence of slip-band cracking is promoted by vacuum conditions, while it is dependent on material structure also, since it was not observed in the fine-grained material.

(3) Secondary cracks parallel to the sheet surface and perpendicular to the crack front were observed in both fine-grained and coarse-grained material tested at low temperatures. These cracks are not mentioned in the literature. The initiation of secondary cracks is considered to be due to a lower ductility at low temperatures, inducing higher \(\sigma_z\)-stresses. Secondary cracks are significant for fatigue crack growth and probably
also for residual strength. Secondary cracks in the coarse-grained material were larger but less numerous than in the fine-grained material.

(4) Another phenomenon not mentioned in the literature is the retransition from the shear mode to a macroscopic tensile mode. The retransition is thought to be due to the occurrence of secondary cracks.

(5) Indications of crack closure above $\sigma_{\text{min}}$ were not obtained in tests on the fine-grained material. The coarse-grained material, however, showed a remarkable crack closure behaviour, especially in tests when changing from vacuum to air. The behaviour had to be related to slip-band cracking and associated crack branching. This upsets the material continuity and coherency along the crack front.

(6) The investigation confirms the importance of crack closure measurements and macroscopic and microscopic surveys of fracture surfaces.

(7) Both slip-band cracking and secondary cracks should be studied further in order to understand in more detail the fail-safe properties of Al-alloys.

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7. REFERENCES


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11. D. Broek - Fatigue crack growth and residual strength of aluminum
alloy sheet at temperatures down to -75°C. Nat. Aerospace Lab. NLR, Amsterdam, TR 72096, June 1972.


Figure 1. Microstructure of the two 7075-T6 materials (etchant Keller-Wilcox, magn. 105x).

Tensile specimen cross section: 8 x 2.5 = 20 mm²
Gage length: 100 mm

Average results of 4 tests

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_{0.2}$ (kgf/mm²)</th>
<th>$\sigma_u$ (kgf/mm²)</th>
<th>$\delta$</th>
<th>$\sigma_{0.2}/\sigma_u$</th>
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<tbody>
<tr>
<td>fine grained</td>
<td>48.1</td>
<td>53.9</td>
<td>9.1%</td>
<td>0.89</td>
</tr>
<tr>
<td>coarse grained</td>
<td>47.5</td>
<td>55.7</td>
<td>12.1%</td>
<td>0.85</td>
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<tr>
<td>material Ref.1</td>
<td>51.6</td>
<td>56.6</td>
<td>12% (t=2)</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Figure 2. Results of tensile tests.
Figure 3. Amsler fatigue machine with vacuum chamber and minocular microscope (14x) for crack growth measurements.

Figure 4. Sheet specimen with central notch (small hole with two saw cuts).
Figure 5. Two different methods for recording crack-closure measurements.
Figure 6a. Crack propagation rates at room temperature.
Figure 6b. Crack propagation rates at room temperature.
Figure 6c. Crack propagation rates at room temperature.

Figure 6d. Crack propagation rates at room temperature.
Figure 7. Comparison of crack growth rates in air and in vacuum (curves of fig. 6).
Figure 8. Effect of increased temperature on crack growth in the fine grained material (Results of Ref. 5).
Figure 9. Effect of low temperature on crack growth in the fine-grained material.
Figure 10. Effect of low temperatures on crack growth in the coarse-grained material.
Figure 11. Fracture surfaces at room temperature (1.8x).

Figure 12. Fracture surfaces at low temperatures (1.3x) (vacuum).
Figure 13. Fracture profiles, fine-grained material tested in air at 20°C.
Figure 14. Fracture profiles, fine-grained material tested in vacuum at 20°C.
Figure 15. Fracture profiles, fine-grained material tested in vacuum at -100°C.
Figure 16. Fracture profiles, coarse-grained material (14x)
Figure 17. Fracture profiles, coarse-grained material tested in air.
Figure 18: Fracture profiles in Z-direction, coarse-grained material tested in vacuum at 20°C.
Figure 19. Fracture profiles in X-direction, coarse-grained material tested in vacuum at 20°C.
Figure 20. Cross sections of crack in coarse-grained material tested in vacuum at -100°C.
Figure 21. Fracture profiles, coarse-grained material tested in vacuum at low temperature.
Figure 22. Secondary cracks parallel to sheet surface, coarse-grained material.
Figure 23. Crack closure measurements with compensation of linear part of COD (Fig. 5c).
Figure 24. Fracture surface of specimen alternately tested in air and in vacuum.
Figure 25. Crack closure measurements with compensation for linear part of COD. Effect of transition vacuum/air.
Figure 26. Uncompensated crack closure measurements. Effect of transition vacuum/air.

Coarse-grained 7075-T6

$\sigma_{\text{max}} = 12 \text{ kgf/mm}^2$

$\sigma_{\text{min}} = 4 \text{ kgf/mm}^2$
Fig. 27. Comparison between crack growth in normal air, dry air and cold air.

Results from the literature (Ref. 11).
Figure 28: Comparison between the results of the fine-grained material and the results from Broek (Ref. 11).
Figure 29. Effect of low temperatures on mechanical properties of 7075-T6.
Figure 30. Secondary cracks parallel to the sheet surface (XY-plane).