Fractographic analysis of fatigue crack growth under simple variable-amplitude loading in 2024-T351 material

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Abstract

To get a better understanding of the sequence effects, two series of fatigue crack growth tests were carried on 2024-T351 sheet material under two-block loading conditions. Besides the macroscopic crack growth records, fractographic observations were made by optical and electron microscopes. Delayed crack growth retardations have been found after applying the overload block in all tests with overload(s). However, an acceleration immediately following the overload(s), found in some other investigations, has not been found in the present tests. The crack growth rate was reduced immediately after applying overload(s). After applying underload(s), a transitional crack growth behaviour, associated with a possible transitional change of $S_{op}$, could not be observed. There was even a small retardation after applying underload(s). The crack growth during the overload- or underload-cycles was accelerated in general. A simple crack closure concept adopted for CA-loading can not completely explain the experimental results. Other sources of crack closure, induced by the VA-loading like crack front incompatibilities and increased crack surface roughness, may contribute to interaction effects. However, it is not clear to which degree these mechanisms can influence the crack growth rate.
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\( \Delta a \) : crack extension in the second load block
\( a_{\text{tr}} \) : crack length where the transition from tensile mode to shear mode is completed
\( q_1 \) : total crack extension during the first load block
\( q_2 \) : total crack extension during the second load block
\( q \) : \( q_1 + q_2 \)
\( m_1 \) : number of cycles in the first load block
\( m_2 \) : number of cycles in the second load block
\( m \) : \( m_1 + m_2 \)

\( \frac{\text{d}a}{\text{d}N} \) during the first load block
\( \frac{\text{d}a}{\text{d}N} \) during the second load block

\( B_1 \) : load type with an overload block
\( B_2 \) : load type with an underload block
\( t_s \) : shear lip width
\( t_s' \) : quasi-stable shear lip width in 2-block loading
\( t_{s,\text{eq}} \) : stable shear lip width in CA-loading

Abbreviations

CA : constant amplitude
VA : variable amplitude
OL : overload
UL : underload
TEM : transmission electron microscope
SEM : scanning electron microscope

Subscripts used for \( \frac{\text{d}a}{\text{d}N} \)

1 : in the first load block
2 : in the second load block
eff : effective
op : opening
start : at the beginning of one load block
ma : macroscopically measured
1. Introduction

Fatigue crack growth tests were carried out under two-block loading conditions. The purpose of the tests was to study sequence effects under simple variable-amplitude (VA) load histories as shown in figure 1. More in particular, the intention was to collect test results on accelerated and retarded crack growth, which at a later stage could be used for checking crack growth prediction models. The investigation is part of a co-operative program (Ref.1) between DFVLR in PorzWahn (Institut für Werkstoff-Forschung), the National Aerospace Laboratory NLR and the Department of Aerospace Engineering of the Delft University of Technology. Results obtained by DFVLR have been published in Ref.2. Predictions made by NLR are presented in Ref.3.

Observations were made at different levels:
1. Macroscopic crack growth records obtained by using the electrical potential drop technique.
2. Optical microscope observations on the width of crack growth bands of the two blocks of load cycles.
3. Electron microscope pictures to investigate delayed crack growth retardation by measuring striation spacings and to examine the features of the crack surfaces under VA-loading.

The experiments were carried on 2024-T351 sheet material. In a first test series the number of cycles at the low stress amplitude was 50 or 100. It turned out that these numbers were too low for complete observations on delayed crack growth retardation. For that reason a second test series was started with much larger numbers. Moreover the second test series was run under constant-K conditions, whereas the first one was carried out under constant-stress control. The results of both tests will be evaluated in this report.
2. Experimental details and macroscopic results

The tests were performed on sheet specimens as shown in figure 2. The material properties are also presented in figure 2. The tests were carried out in a computer controlled servo-hydraulic testing machine at frequencies between 2 and 10 Hz. All tests were done in a laboratory air environment at room temperature.

A survey of the tests carried out in the first test series is presented in table 1. In addition to the two-block VA-tests several constant amplitude tests (CA) with similar load levels were also carried out. Macroscopic crack growth data were obtained with the d.c. electro-potential drop technique as described in Ref.4. The average macroscopic crack growth rates calculated from these data are presented in figure 3. Full macroscopic crack growth records for both test series are given in a separate document (Ref.5). For tests under CA condition, the crack growth rates are also presented as a function of the effective stress intensities. The effective stress intensities were derived with the following formulas:

\[ \Delta K_{\text{eff}} = U \cdot \Delta K \]  \hspace{1cm} (1)

and

\[ U = \frac{S_{\text{max}} - S_{\text{op}}}{\Delta S} = f(R) = 0.55 + 0.33R + 0.12R^2 \]  \hspace{1cm} (2)

with \( R = \frac{S_{\text{max}}}{S_{\text{min}}} \).

Macroscopic crack growth rates in two-block tests at a number of selected values of the crack length are presented in table 3. These results are compared with the crack growth rates under CA condition at the same load levels applied in the two load blocks.

A survey of the tests carried out in the second test series is presented in table 2. The load parameters are given directly in stress intensities because the tests were performed under constant-K conditions. The macroscopic crack growth data were also obtained with the d.c. electro-potential drop technique. The average macroscopic crack growth rates calculated from these data are presented in table 4. The crack growth rates under CA condition associated with each load block are also presented in this table.
3. Microscopic results

3.1. General comments on the microscopic techniques

Microscopic examinations were performed by using different types of microscopes:
- Olympus optical microscope, used at a magnification of 600x
- Philips EM300 transmission electron microscope (TEM), magnifications 1000x to 6000x
- JEOL SE-U3 scanning electron microscope (SEM), magnifications 100x to 6000x

Under the optical microscope the depth of focus is too small for fractographic pictures. However, observations on striation bands could be made. The type of picture observed is schematically indicated in figure 4a. Batches of striations could be seen, which apparently correspond to the first block (large amplitude) cycles. This was checked by measuring q-values \( q = q_1 + q_2 \) with a calibrated line measuring ocular, as used for Vickers hardness testers. Average crack growth rates derived from q-values were in very good agreement with the macroscopic test results. Moreover, the number of individual striations observed in the band width \( q_1 \) agreed with the number of cycles in the first block \( (m_1) \). In the other band \( q_2 \), striations in general could not be observed with the optical microscope.

Better fractographic pictures were obtained with the electron microscopes. The TEM gives the best resolution of fine details as shown in figures 4b and 4c, however replicas have to be made for this microscope. Moreover, it is not so easy to get a picture at a specified crack length. The quality of SEM pictures is not as good as for TEM pictures, as shown in figure 4d, but the SEM is much more convenient to use. A significant improvement of both TEM and SEM is that the individual striations of 0.1 \( \mu \text{m} \) could be distinguished by a magnification of 6000x in most of our cases. The striations in the \( q_2 \)-band could be observed in this way.

Two types of fractographic observations were made:
(1) the average (fractographic) crack growth rates in both load blocks, and
(2) the crack growth rate development in the second block (with small amplitude cycles).

The average crack growth rates were obtained from \( q_1 \) and \( q_2 \) measurements. The crack growth rate development in the second load block was obtained from measuring striation spacings. The measured data will be processed in section 3.2 and some trends in the fractographic results will be shown in 3.3.

3.2. Processing of the measured data

3.2.1. Calculation of the average crack growth rates

The local crack growth rate can be derived as (Fig.4a):

\[
\frac{da}{dN_1} = \frac{q_1}{m_1}
\]

\[
\frac{da}{dN_2} = \frac{q_2}{m_2}
\]

However, this might not lead to accurate results, mainly because of scatter in general and also because of scatter of the local inclination of the crack surface. Therefore the following procedure was adopted. For each crack length considered a number of \( q_1/q_2 \) measurements was made. From these results the average ratio \( \frac{q_1}{q_1 + q_2} \) was determined. The local crack growth in the first and second block is then obtained as:

\[
\frac{da}{dN/VA,1} = \frac{q_1}{q_1 + q_2} \cdot \frac{m_1}{m_1} \cdot \left( \frac{da}{dN/macrosopic} \right)
\]

\[
\frac{da}{dN/VA,2} = \frac{q_1}{q_1 + q_2} \cdot \frac{m_2}{m_2} \cdot \left( \frac{da}{dN/macrosopic} \right)
\]

where \( m = m_1 + m_2 \)

Such results can be compared to crack growth rates observed in constant amplitude tests to see whether retardations or accelerations have occurred. It should be clear that crack growth rates obtained with these equations are averages for a block of cycles (either in \( m_1 \) or in \( m_2 \) cycles). Delayed crack growth retardation cannot be observed in this way.
In the first test series a slight tendency to a decreasing \( \frac{q_1}{q_1 + q_2} \) ratio at larger \( a \)-values was observed. However, there was a fair amount of scatter of local values (for one specific \( a \)-value) which was comparable to the variation of the average \( \frac{q_1}{q_1 + q_2} \) ratio for different \( a \)-values. It was considered to be more appropriate to calculate one single average value for each specimen, independent of the crack length. Such average \( \frac{q_1}{q_1 + q_2} \) ratios for each individual test (both for the first and the second test series) are presented in table 5 and 6. These \( \frac{q_1}{q_1 + q_2} \) values were used for calculating the average fractographic crack growth rate according to equations (3) and (4). The results are presented in table 5 and 6, where a comparison is made with \( da/dN \)-values obtained in the constant amplitude tests. Interactions can now be quantified by considering the crack growth retardation factors:

\[
\beta = \frac{\frac{da}{dN/VA}}{\frac{da}{dN/CA}}
\]

A value \( \beta > 1 \) implies an acceleration and \( \beta < 1 \) a retardation. Values for the first and the second block (\( \beta_1 \) and \( \beta_2 \)) are presented in table 5 and 6 and also in figure 5 to 8 for further evaluation.

3.2.2. Corrections on striation spacings measured with the electron microscope

Striation spacings occurring after applying large amplitude cycles were measured from pictures made with the electron microscope (Fig.4a). The numbers (n) of cycles included in one measurement are chosen between 5 and 20. Illustrative results are presented in figure 9 as a function of \( \Delta a \) (total crack extension after applying the large amplitude block). The measurements were repeated several times at different locations for the same load conditions. The scatter illustrated by figure 9 is due to local variations of the crack growth rate and other possible measurement deviations (for example an inclination of the areas where striation measurements were taken.
from). Striation measurements were corrected in a somewhat similar way as described in section 3.2.1. Striation spacings (and thus also \( \Delta a \)) measured by the electron microscope were multiplied by a factor equal to:

\[
\Delta a \text{ in (1st + 2nd) block derived from } (da/dN)_{\text{macroscopic}} / \Delta a \text{ observed in the electron microscope}
\]

Data corrected in this way are presented in figures 10, 11 and 12. There is still some scatter left. It appears that the scatter is lower for smaller crack lengths, which indicates a more homogeneous crack growth.

With the measured striation spacings, the \( \Delta K_{\text{eff}} \)-values can be read from figure 3b. The corresponding \( K_{\text{op}} \)-values can be derived then with formula:

\[
K_{\text{op}} = K_{\text{max}} - \Delta K_{\text{eff}}
\]

An example of the \( K_{\text{op}} \)-development during the test is given in figure 13.

3.3. Some trends of the fractographic results

3.3.1. The crack growth after applying overload(s)

Delayed retardation

Delayed retardation during the small amplitude cycles (second block) has been observed in most tests with overload cycle(s) (load type A1) as shown in figure 10 and figure 11. The difference between the \( da/dN \) immediately after applying overload(s) and the average \( da/dN \) during the complete second block is another indication of the decreasing \( da/dN \) (the last two columns in tables 7 and 8). The striations in some tests with higher overload ratios could not be observed, because the crack growth rates were too low (< 0.1 \( \mu m/cycle \)).

In contrast to some other investigations (Ref.2), no acceleration has been found immediately after applying overload(s). The \( da/dN \) immediately after applying overload(s) is compared with the predicted
da/dN assuming a constant $S_{op}$ stress level (Ref.6). They are in good agreement for the tests with a lower overload ratio (1:2) as shown in table 7. For tests with higher overload ratios (in the second test series), the observed da/dN-values are even lower than the predicted da/dN-values (table 8). The predicted da/dN-values were read from figure 3b with $\Delta K_{eff}$ obtained from formula (5), and:

$$K_{op} = C \cdot S_{op,1}^{1/4}$$

with $C = \sqrt{\sec(\pi a/\lambda)}$

(6)

$S_{op,1}$ of the first block was assumed to be applicable to the second block (constant $S_{op}$, figure 14) and could be obtained with equation (1).

To eliminate the influence of the previous overloads, a test with 10000 small amplitude cycles in the second block (test 508) was carried out. The crack grew completely out of the influence zone of the applied overloads during the small amplitude cycles. The same initial da/dN-development has been found in this test as shown in figure 11b.

**Influence of the overload ratio**

A larger overload ratio leads to a larger retardation in the tests with overloads as shown in figure 6. Associated with the larger retardation, the da/dN immediately after applying overload(s) are also lower in tests with larger overload ratios (table 8). A higher $S_{op}$ will be induced by larger overload as implied by equation (1). The average fractographic da/dN are then compared with the predicted da/dN assuming constant $S_{op}$. However, the higher $S_{op}$ can only account for a part of the larger retardation, the differences between the observed da/dN-values and the predicted da/dN-values increase obviously with the increased overload ratio (tables 7 and 8).

**Influence of numbers of cycles in load blocks**

The results in figure 5 show a systematic effect of the number ($m_1$) of large amplitude cycles (block 1) on the crack growth retardation during the low amplitude cycles (block 2). Larger $m_1$-value causes more retardation. This may be associated with the larger extent of delayed retardation by more overloads as shown in figure 15. More delayed retardation has also been observed in a test with 5 overloads...
in comparison to the test with one single overload. The difference of delayed retardation after 5 overloads and 10 overloads is not obvious (Fig.16).

The test with 50 cycles in the second block (with small amplitude), instead of 100 cycles, showed slightly less retardation. A similar trend was also found by Zhang et al (Ref.2). This can be explained by delayed retardation as shown in figure 17. The initial da/dN-developments are similar in test with different numbers of cycles in the second block (see also Fig.11). However, the retardation further continues if there are more cycles in the second block.

Influence of ΔK
Figure 5 suggests an increasing/decreasing behaviour of $B_2$ for increasing ΔK-values (corresponding to an increasing crack length). A similar phenomenon was observed by Ichsan (Ref.7) from macroscopic growth bands during two-block loading tests with much larger numbers of cycles in each block. His results are shown here in figure 18 (I-β). Ichsan has associated the trend with the transition of a tensile mode crack to a shear mode crack in CA-test. The crack growth rate in the shear mode should be lower than in the tensile mode. The crack length $a_{tr}$ is the a-value at which the transition is completed. Ichsan's results show a increasing I (decreasing retardation) when the a-value is approaching $a_{tr}$ of the small amplitude block. In the present tests a similar behaviour is noticed, although not as explicitly as in Ichsan's results (Fig.5).

Delayed retardation was more significant (Fig.10), if a, and thus ΔK, was larger. This will contribute to the increased average retardation for larger ΔK-values.

3.3.2. The crack growth after the underloads

There is also a slight retardation ($B_2 = 0.86$) during the second load block (with small amplitude cycles) in the underload tests as shown in figure 5. In contrast to the overload tests, a systematic variation of da/dN as a function of $a_0$ has not been observed (see Fig.12). The $K_{op}$-values for the two blocks were calculated with equations (1), (2)
and (5). As should be expected $K_{op,1}$ is lower than $K_{op,2}$ (table 3). Zaiken and Ritchie (Ref. 8) also found that there was no obvious acceleration after small underloads. In another investigation (Ref. 9) only a slight acceleration was found after applying underloads.

More underloads has led to a little more retardation in the second block as shown in figure 5 ($m_1 = 10$ and $m_1 = 1$). The results in this figure suggest a similar increasing/decreasing trend for increased $\Delta K$-values as found in the overload tests, but the trend is less pronounced.

3.3.3. The crack growth during the large amplitude cycles

In agreement with some other investigations (Ref. 2, 6), the average fractographic crack growth rate during the large amplitude cycles is higher than observed under CA-loading (figures 7 and 8). This trend might not be expected because the $S_{op,2}$ derived from fractographic values just before applying the large amplitude cycles, was higher than $S_{op,1}$ under CA-condition (Fig. 13). Retardations during large amplitude cycles were observed only for larger $\Delta K$-values (when $(\frac{d\alpha}{dN})_{CA,1} > 2 - 3 \mu m$). It is interesting that decreasing I-values ($I_1$) for the large amplitude cycles were also found by Ichsan for large $a$-values (Fig. 18).

Although the accuracy of measuring the striation width of one single large amplitude cycle is rather limited, there is a trend that $\Theta$, for a single large amplitude cycle is larger than for more large amplitude cycles. There is no significant difference between the behaviour of the crack growth rate during large amplitude cycles in tests with load type A1 (overloads) and in tests with load type A2 (underloads) as shown in figure 7.
4. Some other observations on the crack surfaces

In addition to the fractographic da/dN determinations, it has been tried to look for fractographic features, which may contribute to the interaction effects. Some observations are presented in this section which includes:
- the change of shear lips, and
- the increased roughness of the crack surface

4.1. Variations of the shear lip width under VA-loading

The development of shear lips along the edges of fracture surface of fatigue cracks is a well known phenomenon for Al-alloys. In relation to crack closure, it is supposed to be the first part where mating crack surfaces will touch during unloading (Ref.10). The significant contribution of shear lips to crack closure was confirmed by several authors (e.g. Ref.11 and 12). Other complications induced by the incompatible crack front may also influence the crack growth (Ref.14). The development of shear lips is a function of the loading parameters (Ref.13 and 14). Under CA-loading the shear lip will develop to a stable width (Ref.14), which depends on $\Delta K_{\text{eff}}$:

$$t_{s,\text{eq}} = 0.67 \Delta K_{\text{eff}} - 3.72 \text{ (mm)}$$ (7)

The rate at which the shear lips grow to their stable width is:

$$\frac{dt_s}{da} = 0.0167 \exp\left(\frac{22.1}{\Delta K_{\text{eff}}^\text{eff}}\right) \cdot (t_{s,\text{eq}} - t_s)$$ (8)

where $t_s$ is the current shear lip width.

Under VA-loading the width of shear lips tend to change with the variation of the load amplitude (Fig.19). The crack growth path will become more tortuous by these changes. Moreover, when the number of cycles with a certain $\Delta K_{\text{eff}}$ is not large enough, the width of shear lip will not be able to reach the stable value associated with that $\Delta K_{\text{eff}}$. In the present case of repeated block loading, the width of the shear lips during the first block can not fully develop to the stable value associated with the large amplitude, and the crack is
forced to grow with a smaller shear lip. During the second block the width of the shear lip will be reduced, but not completely to a stable value. Again the crack is forced to grow with a non-conforming shear lip width. When the number of cycles in both blocks are small, the width of the shear lip will vary around a quasi-stable level between the stable values of the large and the small amplitudes respectively (Fig. 19c).

The change of the shear lip width during one load period (=2 blocks) could hardly be observed in most of the present tests. However, these changes are quite clear in a test with larger overload cycles as shown in figure 19b. A very tortuous crack path should be expected in the shear lip region and it could certainly influence the crack closure behaviour. Moreover, fretting oxide debris and some crack type lines, which according to Ritchie (Ref. 8) may be caused by cracking of surface asperities, were found in the shear lip region. They are indications of severe crack closure.

The development of the shear lip width under VA-loading (experiment 301 with five overload cycles) is shown in figure 20a in comparison to the shear lip development under CA-loading. A surprising observation is that the shear lip width in the VA-test is smaller than shear lip width under CA-loading for the load ranges of both the first block (overload) and the second block. In other words the shear lip width in the VA-test is smaller than in both corresponding CA-tests (Fig. 20b). In view of the work of Zuidema et al (Ref. 14), it then should be expected that the smaller shear lip width will imply an acceleration at both stress levels in the VA-test. Such an acceleration was observed for the overload cycles (\( \beta_1 \) in table 5), but in the second block a significant retardation occurred (\( \beta_2 \approx 0.4 \), table 5). It then should be concluded that a retarding crack closure effect has overruled an accelerating shear lip width effect. It now is of some interest to compare the shear lip width obtained in the VA-test and the CA-test at similar da/dN-values (and thus not a similar a-values), having in mind that similar da/dN-values might imply similar \( \Delta K_{eff} \)-values. Such a comparison is made in figure 20c. The da/dN values for the VA-test apply to the second load block. Figure 20c shows that the shear lip width in the VA-test is systematically larger than in the CA-test, probably due to the overload cycles, except for large growth rates. The implication then is that the shear
lip width in the VA-test is larger than in the CA-test at the same 
$\Delta K_{eff}$. The width of the shear lip was also studied in the K-controlled tests 
(second test series). Results are shown in table 9 which illustrates 
the effects of the numbers of overload cycles and of the difference 
between $K_{max,1}$ and $K_{max,2}$. The shear lip is much wider in the test 
with 10 overload cycles than in test with only one overload (see also 
Fig.21). Table 9 also shows that a larger $K_{max}$ in the second block 
increased the shear lip width, as should be expected (see also 
fig.22).

4.2. Increased micro-roughness at the crack surface

The concept of roughness induced crack closure during CA-loading was 
introduced by Suresh and Ritchie several years ago (Ref.16). For VA-
loading Suresh has recently introduced a (fracture face) micro-
roughness model concerning increased roughness as a result of possible 
stage I growth in the post-overload region. Stage I growth could 
happen when the crack growth rate decreased to the near threshold 
level. The rougher fracture surface should enhance the roughness 
induced closure further and consequently also further reduce the 
effective stress intensity amplitude. The extent of this reduction 
has been estimated by Suresh (Ref.17).

In the present tests, the crack growth rates were normally far above 
the threshold level. Stage I growth has not been found on these 
specimens, but crack growth at locally deviating directions has been 
found, which was clearly related to the load amplitude changes 
(Fig.23). Such deviations may not happen along the full crack front 
(Fig.23b), but probably in grains with favourable crystal 
orientations. The extent of these deviations depends also on the 
number of cycles in both load blocks. Obviously it will be small for 
one single overload cycle (Fig.23c). Rougher crack surfaces should be 
expected from such deviations, and the increased roughness may enhance 
crack closure.
5. Discussion

5.1. The current interaction mechanisms

Fatigue under variable-amplitude loading is a complex process. Apart from other influences, like environmental effects, it will be significantly affected by the load history conditions. The effective stress intensity amplitudes were introduced to characterize the real driving force of crack growth during cyclic loading. Cycles with the same effective stress intensity amplitude are supposed to produce the same crack length increment. Many experiments were done to determine the effective stress intensity amplitude for different load situations. The results for CA-loading were quite satisfactory. The problem for VA-loading is complicated by sequence effects. Several mechanisms were introduced to explain the sequence effects as shown in figure 24. Crack closure probably is the most direct mechanism. It includes three main sources as proposed by Ritchie et al (Ref.16). They are plasticity induced, roughness induced and oxide induced crack closure.

Due to the residual plastic deformation in the wake of the crack, the crack will be fully or partially closed during unloading. During the next increase of the load a continuous unfolding of the crack flanks will occur until the crack is fully open at $S = S_{op}$. From then on a further increase of the load will cause a "singular increment" of the stress intensity at the crack tip. The effects of the plasticity induced crack closure have been examined experimentally, analytically and numerically. Overload(s) can increase $S_{op}$ when the crack grows through the region with excessive plastic deformation. Delayed retardation may happen because the excessive plastic deformation ahead of the crack tip may increase the crack opening at the end of the unloading as suggested by de Koning (Ref.18). Underload(s) are supposed to diminish the residual plastic deformation (Ref.8). However, experiments did not always clearly indicate an increase of the crack growth rate after underload(s).

Mismatch of the crack surfaces is another very important source of crack closure. It is a result of crack surface roughness, asperities, crack branching and mixed mode crack opening. Under VA-loading, stage
I growth may happen when the driving force for crack advance is reduced to the threshold level (Ref.17). It will increase the surface roughness. Besides, the crack surface can become rougher by locally deviating crack growth directions as a results of load amplitude variations (see section 4.2). Moreover, tensile mode/shear mode (shear lips) transitions may also contribute to roughness induced closure as shown in section 4.1. Underloads can reduce the roughness induced crack closure by flattening and cracking the fracture surface asperities as suggested by Ritchie (Ref.8). However, it appears to depend on the severity of the applied underloads. Oxide induced crack closure can be enhanced or reduced by interactions with the other forms of closure.

The experimental results presented in section 3 will be discussed keeping in mind the mechanisms summarized above. The results have revealed three main trends:

1) retardations and delayed retardations in the tests with overload(s)
2) retardation in tests with underloads
3) an increased crack growth rate during the large amplitude cycles

5.2. Discussion of the experimental results

5.2.1. crack growth after the overload(s)

Many investigations (Ref.2,11,18) showed no retardation or even an acceleration immediately after applying overload(s). It appears that the result depends on the type of material and the load history parameters. An immediately reduction of the crack growth rate after overload(s) has been found in the present test series. This trend has been confirmed by recent calculations of Liefting (Ref.3) based on a strip yield model. He has made calculations for one of our test conditions. The prediction is in good agreement with the test results.

The level to which the crack growth rate is reduced, strongly depends on the applied overload ratio \( \frac{K_{\text{max},2}}{K_{\text{max},1}} \). This trend can partly be the result of the higher \( S_{\text{op},1} \) introduced by larger overload(s), as
implied by the model assuming constant $S_{op}$ (Ref.6). However, for higher overload ratios in the second test series (table 8), the crack growth rates reduced to a lower level than the predicted growth rate assuming a constant $S_{op}$. This can not be understood by the simple crack closure model adopted for CA-loading. Other mechanisms, induced by the VA-loading, might also be effective. For example, the crack front incompatibilities may increase with the larger overload(s) as shown in the last section.

Delayed retardation has been found during the low amplitude cycles in most of the present tests. The behaviour was depending on the load amplitudes and on the number of overload cycles. More overloads led to more delayed retardation and thus also to a larger average retardation. This appears to be in agreement with the crack closure concepts of de Koning (Ref.18), which predict more residual plastic deformation behind the crack tip if there are more overloads. Besides, the shear lip associated with the larger amplitude cycles will develop to a further extent by more overloads as shown in section 4.1. Also the crack surface may be rougher for more overloads as shown in figure 23. The increased extent of retardation at higher $\Delta K$-values can be partly contributed to the accelerated shear lip development.

5.2.2. The crack growth after underload(s)

Small retardsations have been found during the second load block in tests with underload(s). From the viewpoint of a simple closure behaviour, it was expected that the underload block would induce crack growth acceleration instead of a small retardation. The calculated $K_{op}$ in the first block (large amplitude) is lower than that in the second block (small amplitude), see table 3. If there is some kind of a transition from $K_{op,1}$ to $K_{op,2}$, some acceleration should occur. Recently Liefting (Ref.3) has calculated the crack growth for one of the conditions under load type A2 (test with underloads). Although an average retardation has been predicted for the complete second load block, the calculation indicate an acceleration immediately after applying underload cycles. However, a systematic transitional behaviour of the crack growth rate has not been found in the experimental results (Fig.11). Additional arguments are required to
explain the immediate change of $da/dN$, which in fact is a retarded crack growth, although the retardation is not large. Possibly the incompatible crack front and shear lip developments can be significant here, but explanations are rather speculative.

5.2.3. Acceleration and retardation during the large amplitude cycles

Although the effective $S_{op}$ just before applying large amplitude cycle(s) were all higher than the $S_{op}$ associated with the large amplitude cycles in CA-case (see section 3, Fig.13), an acceleration has been found in all tests for medium $ΔK$-values. The incompatible shear lips may play some role for this acceleration because the crack is forced to grow with a smaller shear lip during the overload cycles. Moreover, the incompatible shear lips will also affect the closure process. In addition, some other mecha-nisms than closure alone might contribute to the accelerated crack growth.

If the average crack growth rate during a block of large amplitude cycles is lower in comparison to the growth rate in a single overload cycle, it indicates a decrease of the crack growth rate during the large amplitude cycles. Although the present results are not very systematic, they appear to indicate such a trend (Fig.7 and 8). The trend was confirmed by fractographic observations in Ref.2. It may be that the excessive residual plastic deformation left by the first overload becomes more effective when the crack extends further. Moreover, the tortuous path induced by the change of shear lips will become effective after several large amplitude cycles.

Retardation has been found during the large amplitude cycle(s) ($β_1<1$) in the higher $ΔK$-region. The crack growth in a CA-test with the same high $ΔK$ occurs mainly in the shear mode, while in VA-tests it may still largely remain in the tensile mode due to the small amplitude cycles of the second block. The accelerated crack growth in the CA-test (at end of the Paris region) could be a reason for the lower $β_1$ ($<1$) observed in the first block for test at high $ΔK$-values.
6. Summary and conclusions

Crack growth tests were carried out on 2024-T351 specimens, employing two simple variable-amplitude load sequences, i.e. with periodic blocks of overload cycles or periodic blocks of underload cycles. The number of the large amplitude cycles \( m_1 \) varied from 1 to 10, while the number of small amplitude cycles \( m_2 \) between the periodic over- or underload cycles was 100 or 900, except in two cases with 50 and 10000 respectively. Fractographic observations were made with an optical microscope (600x) and two electron microscopes (TEM and SEM, 100x to 6000x). Striation measurements and macroscopic crack growth records have led to the following observations and conclusions:

1. Overload cycles gave significant crack growth retardations during the small amplitude cycles. The retardation was more significant for larger numbers of overload cycles per block and larger overload ratios.

2. Underload cycles induced small crack growth retardations (by an average factor of 0.86) rather than accelerations. A transitional crack growth behaviour, associated with a possible transitional change of \( S_{op} \), could not be observed after applying underload cycles.

3. The fractographic observations (striation measurements) clearly indicated delayed crack growth retardation after overload cycles. The crack growth rate directly after the transition from the overload cycles to the smaller amplitude cycles was in good agreement with predicted values assuming a constant crack-opening stress level if the overload ratio was small (1.2). For higher overload ratios, the \( da/dN \) directly after applying overload(s) was lower than the predicted value. During delayed crack growth retardation the observed growth rate decreased further below these levels.

4. Accelerations during the large amplitude cycles were found for both over- and underload tests. Only for high \( \Delta K \)-values the \( da/dN \) during the large amplitude cycles is lower than it is under CA-loading.

5. The conventional concept of crack closure under CA-loading conditions could not completely explain the experimental results. Fractographic observations indicate that other sources of crack closure induced by VA-loading, may contribute to interaction
effects. Some trends in the experimental results should be associated with crack front incompatibilities and increased crack surface roughness.

6. It is not clear to which degree the crack front incompatibilities or the increased surface roughness can contribute to crack closure. Other mechanisms than crack closure may also be effective. Quantitative investigations on shear lip and surface roughness may lead to a better understanding of the sequence effects under VA-loading conditions.
Reference

(1) Schijve J. "Proposal for a basic investigation on the growth of fatigue cracks in separate cycles of selective load histories". Document b2-83-05, Department of Aerospace Engineering, Delft University of Technology.

(2) Zhang S. et al "Crack propagation studies on Al 7475 on the basis of constant amplitude and selective variable amplitude loading histories". (to be published).

(3) Liefting C. "Numerieke analyse van scheuropening en scheurgroei onder variabele amplitude belasting". Memorandum no. SC-86-031U, the National Aerospace Laboratory (NLR), the Netherlands (1986).


(14) Zuidema J. and Blaauw H.S. "Slant fatigue crack growth in Al 2024 sheet material" Report of Faculty of Metals Science, Delft University of Technology, the Netherlands (1986).


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a) Constant-Amplitude tests

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b) Variable-Amplitude tests

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Table 3: The macroscopic crack growth rate at selected $a$-values under CA-loading and under VA-loading in the first test series.
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Table 5  The acceleration or retardation in VA-loading in the first test series.
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Table 6. The acceleration or retardation in VA-loading in the second test series. (load type A1 only).
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<th>(da/dN)_{start}</th>
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Table 7: Comparison between predicted and observed crack growth rate after the 1st load block in the first test series.
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<th>( K_{\text{op},1} )</th>
<th>( K_{\text{max},2} - K_{\text{op},1} )</th>
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<th>( da )</th>
<th>( \frac{da}{dn} ) ( VA,2 )</th>
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<td>12.84</td>
<td>7.73</td>
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<td>0.048</td>
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<td>0.041</td>
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Table 8. Comparison between predicted and observed crack growth rate after the overload block in the second test series.

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<th>( K_{\text{max},2} )</th>
<th>( \frac{da}{dn} ) ( t' )</th>
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<td>( K_{\text{max},2} )</td>
<td>( \frac{da}{dn} ) ( m_1 )</td>
<td>( t' ) ( \text{s} )</td>
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<td>10</td>
<td>0.68</td>
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<tr>
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<td>20.57</td>
<td>1</td>
<td>0.34</td>
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Table 9. Quasi-stable shear lip width \( (t' \) \) in some tests of the second test series (K-controlled).
A: Periodic change of $S_{\text{max}}$ or $S_{\text{min}}$.

Figure 1: Load sequences with one block of larger cycles and one block of smaller cycles

Material: 2024-T351 (bare), thickness 6.35 mm
Properties (literature data)
- $S_u = 469$ MPa
- $S_{\text{0.2}} = 324$ MPa
- $\delta(50\text{ mm}) = 20\%$

Figure 2: Dimensions of specimen and material properties
Fig. 3a Macroscopic da/dN in CA-tests

Fig. 3b Macroscopic da/dN in CA-tests as a function of $K_{eff}$.

Fig. 3c Macroscopic da/dN in VA-tests with load type A1.

Fig. 3d Macroscopic da/dN in VA-test with load type A2.

Fig. 3 The macroscopic da/dN measured with electro-potential drop method in the first test series.
Fig. 4a  Schematic picture under the microscope

Fig. 4b  TEM 1240X, tilt angle 30°
  test 301, m₁ + m₂ = 5 + 100
  a = 18 (mm)

Fig. 4c  TEM 3800X, tilt angle 30°
  test 306, m₁ + m₂ = 1 + 100
  a = 14 (mm)

Fig. 4d  SEM 1000X, tilt angle 30°
  test 613, m₁ + m₂ = 1 + 900
  a = 31.6 (mm)
Fig. 5 The retardation factor ($p_2$) of the crack growth rate in the second load block in the first test series.
Fig. 6 The retardation factor ($\beta_2$) of the crack growth rate in the second load block in the second test series.
Fig. 7 Acceleration and retardation during the large amplitude cycles in the first test series.
Fig.8 Acceleration and retardation during the large amplitude cycles in the second test series.
Fig. 9  Crack growth rate development during the small amplitude cycles, as measured from striation spacings. Results of test 301, $a=17$ (mm). The four symbols ($\times$, $\Box$, $\Delta$, $\bigcirc$) refer to measurements along four different lines. The arrows indicate the end of the second block ($\Delta N=m_2=100$).
Fig. 10 The crack growth rate development in the small amplitude block after overloads. First test series.
Fig. 11 The crack growth rate development in the small amplitude block after overload(s). Second test series.
Fig. 12 The crack growth rate development in the small amplitude block after underload(s). The first test series.
Fig. 13 The $K_{op}$ values derived from measured $\frac{da}{dN}$ values.
Fig. 14 The crack opening stress intensity and the $\Delta K_{\text{eff}}$

$k_{\text{op}} = k_{\text{max}} - k_{\text{eff}}$

with $\Delta k_{\text{eff}} = u \cdot \Delta k$

where $u = 0.55 + 0.33r + 0.12r^2$

and $r = s_{\text{min}}/s_{\text{max}}$

assuming constant $s_{\text{op}}$,

$\Delta k_{\text{eff},2} = k_{\text{max},2} - k_{\text{op},1}$
Fig. 15  Different crack growth rates in the small amplitude block after a single overload and after 10 overloads (a=17 mm).

Fig. 16  The crack growth rates in the small amplitude block after 5 or 10 overloads at 2 crack lengths.
Fig. 17 Crack growth rate development in the small amplitude block after overloads in test with different $m_2$. 

Symbols:
- $\triangle$ for testnr. 301, $m_1 + m_2 = 5 + 100$
- $\bullet$ for testnr. 303, $m_1 + m_2 = 5 + 50$

$m_2 = 50$ and $m_2 = 100$ are indicated for tests 303 and 301, respectively.

End of 2nd block:

$\Delta a$ in second block ($\mu$m)
Fig. 18 Acceleration and retardation factors in two level block tests as observed by Ichan (Ref. 7) from macrogrowth bands in 4 mm thick 2024-T3 specimens.
Fig. 19 Sketch of the development of shear lip under 2-block loading
Fig. 20 Development of shear lips under two CA-load ranges and under VA-loading with the same two load ranges (load controlled tests).
Fig. 21. The transition of the shear lip between tests with different numbers of overload cycles (test 604 to test 605).
Fig. 22 The transition of shear lip between tests with different $K_{\text{max},2}$ (from test 606 to test 607).
load type A1

crack growth from left to right for all the pictures

Fig. 23a SEM 1000X, tilt angle 30°
test no. 611, m\textsubscript{1}+m\textsubscript{2} = 10+200

Fig. 23b SEM 600X, tilt angle 30°
test no. 603, m\textsubscript{1}+m\textsubscript{2} = 10+900

Fig. 23c SEM 500X, tilt angle 30°
test no. 614, m\textsubscript{1}+m\textsubscript{2} = 1+900

Fig. 23 Change of crack growth direction by different load blocks
Fig. 24  Mechanisms for sequence effects