LR-651

The Effect of Intermediate Heat Treatments on Overload Induced Retardation During Fatigue Crack Growth in an Al-Alloy

March 1991

M.R. Ling and J. Schijve

TU Delft

Delft University of Technology

Faculty of Aerospace Engineering

The Effect of Intermediate Heat Treatments on Overload Induced Retardation During Fatigue Crack Growth in an Al-Alloy

M.R. Ling and J. Schijve

THE EFFECT OF INTERMEDIATE HEAT TREATMENTS ON OVERLOAD INDUCED RETARDATION DURING FATIGUE CRACK GROWTH IN AN AL-ALLOY

ABSTRACT - Crack growth fatigue tests were carried out on 2024-T3 specimens. Constant-amplitude loading was periodically interrupted by 10 overload cycles. Intermediate heat treatments (T4) were applied to remove the residual stress in the crack tip zone and the crack closure wake behind the crack tip. Retardation effects induced by crack closure due to the previous load history, were fully erased by the heat treatments. Overload effects were easily introduced again by new overload cycles afterwards. Crack growth rate results and fractographic observations indicate that primary crack tip plastic deformation (in virgin material) is more effective for crack extension than secondary plastic deformation in an existing plastic zone. This conclusion is significant for cycle-by-cycle crack growth prediction models for variable-amplitude loading.

INTRODUCTION

During fatigue crack extension plastic deformation occurs in the material ahead of the crack tip. The residual stress/strain situation after unloading is very important for subsequent crack growth. Several aspects concerning crack growth are directly affected by the stress/strain history of the crack tip material, such as : crack closure [1], the character of plastic flow during increasing load [2], and the local material strain hardening [3].

A different crack growth behaviour should be expected if the residual stress/strain system around the crack tip is removed by a new heat treatment. A number of systematic fatigue crack growth tests with intermediate heat treatments has been carried out to explore this question. The tests were performed on specimens of the 2024-T3 Al-alloy, tested under constant-amplitude loading with periodic blocks of overloads. It was expected that intermediate heat treatments can eliminate the retardation effects of the overloads.

Constant-amplitude loading was applied in two fatigue tests to obtain reference data. In another three tests, the same baseline loading was periodically interrupted by overload blocks of ten cycles (Fig.1). New heat treatments (T4) were carried out during intermediate stops of the fatigue tests in order to remove the residual stress/strain system in the crack tip zone. The intention was:

- to study the crack growth behaviour in fresh crack tip material without residual stress/strain,
- to see whether the overload retardation still occurs when the residual plastic deformation of the overload is removed, and
- to observe how the crack growth situation is re-established after a new heat treatment.

The transitional crack growth behaviour after a new heat treatment was also studied in a scanning electron microscope (SEM), by observations on the fatigue crack surface . First, experimental details are given, followed by an evaluation of the crack growth results.

2. Experimental details

All tests were carried out on central cracked specimens of 6.35 mm 2024-T3 bare Al-alloy. The specimen width is 100 mm. The original heat treatment of the material was T351. The mechanical properties of the material are S_U = 469 MPa, $S_{0.2}$ = 324 MPa, δ = 20 %. A computer controlled servo-hydraulic testing machine was used to carry out the fatigue tests in a laboratory air environment. The frequency of the cyclic load varied between 3 and 7 Hz. The macroscopic crack length was measured by the d.c. electro-potential drop technique [4]. Crack growth data are presented in the next section. Full records of the data can be found in [5].

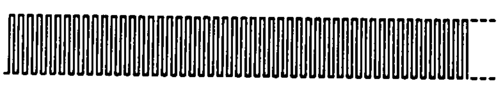
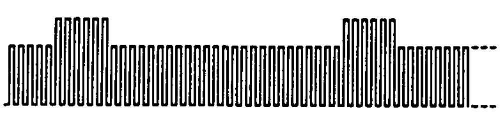
load sequence	test No.	a(mm) at intermediate heat treatments				
	A1	7.25				
	A2	10	12.5	16.4	22.8	29
	B1	7.25				
	B2	10.3	14	19.2	25.5	
	B3	7	10	12.5	15.5	

Table 1. Fatigue tests and crack lengths at which an intermediate heat treatment was applied.

A list of the fatigue tests is given in table 1. A constant-amplitude (CA) loading with S_{max} = 80 MPa and S_{min} = 4 MPa (R = 0.05) was used in two tests. In the other variable-amplitude (VA) tests, the same baseline loading was periodically interrupted after every 1000 cycles, in order to insert blocks of 10 overload cycles with S_{OL} = 120 MPa (Fig.1).

Intermediate heat treatments (T4) were applied to remove the residual stress around the crack tip. Raju et al. [6] already demonstrated that a high temperature exposure can fully remove the retardation effect of a peak load applied to sheet specimens of the 2014 alloy. The maximum exposure temperature in [6] was 250°C. The precipitation hardening is then lost, or at least reduced. Therefore, a full precipitation heat treatment was adopted in the present investigation.

The T4 heat treatment involves a 495 °C solution heat treatment for 60 minutes, followed by water quenching and room temperature aging. In tests A1 and B1 only one T4 heat treatment was applied. In the other tests the T4 heat treatment was carried out four or five times at different crack lengths. The locations (i.e. the corresponding crack length) of the intermediate heat treatments are listed in table 1. After an intermediate heat treatment the fatigue tests was resumed, starting with the 1000 baseline cycles.

TEST RESULTS

General crack growth behaviour

The macroscopic crack growth curves of the CA tests (tests A1 and A2) are presented in Figure 2. In test A1 only one new heat treatment was carried out at a = 7.25 mm. In test A2 four extra intermediate heat treatments were applied at larger crack lengths (Table 1). After a horizontal shift of the data points of test A2 the results practically coincide with the crack growth curve of test A1. In other words, an obvious influence of the intermediate heat treatments on the macroscopic crack growth curve can not be observed. The heat treatments left some kind of a heat tinting colour on the fatigue fracture surface, which apparently did not affect the subsequent crack growth.

The crack growth curves of the three tests with overload blocks (tests B1, B2 and B3) are presented in Figure 3. In test B1 only one heat treatment was carried out, viz. at a = 7.25 mm. In tests B2 and B3 four heat treatments were applied at different crack lengths (Table 1). The crack growth rates in the VA blocks are shown in Figure 4, which also includes measurements of the CA tests. The graph shows that the crack rate in the tests with overloads was much lower than in the CA tests. Apparently, a significant retardation has occurred. However, this is not true for the crack growth rate in the first baseline load block after an intermediate heat treatment (points • in Fig.4). In those baseline load cycles the growth rate is practically the same as in the CA tests. Apparently, a heat treatment fully eliminates the retardation effect of OL cycles, which occurred before the heat treatment, but one batch of OL cycles after the heat treatment is sufficient to restore the retardation effect.

Additional results of measurements in the electron microscope are given in Figure 5. It shows the average crack growth rate in the overload cycles and in the baseline cycles after the overload cycles. The results are compared to CA data. It appears that the crack growth rate during the overload cycles agrees with the CA results, whereas the growth rate in the baseline cycles (except for the 1st block after the heat treatment) is about 5 to 10 times lower than in the CA tests. The retarded crack growth behaviour is rapidly re-established after applying new overloads. The latter observation is also illustrated in Figure 3 by the horizontal shift of the test data of specimens B2 and B3. After the horizontal shifts the results practically coincide with the results of specimen B1, which had seen only one additional heat treatment.

Microscopic observations on striation spacings

Base line cycles in the first block after a new heat treatment

It is quite remarkable that the intermediate heat treatments did not obliterate the microscopic features (e.g. striations) on the fatigue fracture surface, even after five heat treatments.

After each new heat treatment, the fatigue test was continued with the CA baseline loading. The crack surface created during the first 10 to 20 cycles usually appears to be irregular, see Figure 6. In most cases a large white band can be found in the irregular region, but it does not always appear immediately after the new heat treatment. Sometimes it is preceded by a flat region as shown in Figure 6. The white band might be related to changes of the crack growth path. At some locations along the crack front the crack growth path changed immediately after the new heat treatment, while at other locations it changed after several baseline load cycles to form a new coherently interconnected crack front. At low values of the crack length, changes of the crack path occur almost along the entire crack front, whereas it occurs less frequently at a larger crack length.

In most cases the striation of the very first baseline cycle after the new heat treatment could not be observed, due to the irregular fracture surface. However, occasionally it could be indicated, and then the spacing was found to be larger than those of subsequent cycles.

A regular striation pattern with an approximately constant striation spacing was usually found ahead of the irregular region. The da/dN values measured from the striation pattern do agree rather well with the scatter band of the macroscopic data of the CA tests.

Overload cycles

The first overload block after a new heat treatment occurred after approximately 1000 baseline load cycles. Striation patterns of the overload cycles can easily be observed on the crack surface. As systematically observed in previous work [7,8] the first striation is significantly wider than the other ones (giant striation). The crack increments of the following overload cycles are approximately constant and in agreement with the data found in other overload blocks, see Figure 7. It indicates that the normal conditions for crack growth in the overload cycles are restored already in the first overload block.

Baseline cycles after new overloads

As pointed out before, the crack growth rate in the baseline load cycles directly after a new heat treatment is constant and unretarded. However, as soon as the specimen after a new heat treatment has seen the first block of overload cycles, then the well known retardation does occur again. Occasionally, striations could be seen immediately after the first overload block in the baseline area. Spacings measured for this striations are indicated in Figure 8 (•). Due to delayed retardation the crack growth rate decreases further and the striations can no longer be distinguished. The average da/dN in a baseline load block can be estimated by measuring the spacing between the striation patterns of the overload blocks. The average crack growth rates in the base line blocks (o in Fig.8) are much lower, which confirms that delayed crack growth occurs in the baseline load block.

DISCUSSION

Two remarkable observations have been made:

(1) A new heat treatment fully eliminates the crack growth retardation of previous overload cycles.

(2) The very first block of overload cycles completely restores (delayed) crack growth retardation.

The observations are schematically illustrated in Figure 9 by a qualitative comparison of observed crack growth rates (= striation spacings) with crack growth rates in CA-tests. The comparison shows whether accelerations or retardations do occur.

Another observation is that the first overload cycle of a block of ten overload cycles gives a larger striation, which is in agreement with previous work [7,8]. The same is true for the first cycle of the baseline loading, directly after the intermediate heat treatment, although this observation is partly obscured by some initially irregular crack extension after the new heat treatment. Afterwards the crack growth rate in the baseline cycles is similar to the growth rate in CA tests. This rapid stabilization to the nominal load cycle condition is also remarkable.

The overload cycles have induced (delayed) crack growth retardation. Under the present experimental conditions, it must primarily be associated with crack tip plastic deformation (plasticity induced crack closure, Elber mechanism). After the overload cycles the crack tip plastic zone has been extended in the loading direction, which leaves residual compressive stresses at the crack tip after unloading. If the crack growth into this zone it requires a higher stress (increased S_{op}) to open the crack tip, which is essential for further crack extension. The lower ΔS_{eff} accounts for the crack growth retardation. Apparently the solution heat treatment at 495 °C is sufficient to fully remove the retardation, and thus the plastic deformations and the associated residual stress. That is not surprising, because at such a high temperature the precipitation and the inhomogeneous strain hardening will be fully removed. Dislocation movements are easily possible at the solution heat treatment temperature, the material becomes very soft and any residual stress will vanish. Subsequent quenching and aging will lead to a homogenous material structure. Crack growth after the heat treatment thus starts in the original material with no reminiscences of plastic deformation of the load history before the heat treatment. In the very first baseline cycle crack extension is associated with plastic deformation in virgin material (see Fig.10a). In terms of De Koning et al [2,9] it is called primary plastic deformation. However, already in the second and in subsequent cycles, crack tip plastic deformation mainly occurs in plastic zones of previous cycles, which by De Koning is referred to as secondary plastic deformation. It mainly occurs in strain hardened material, and not in virgin material. Only shortly before $S = S_{max}$ a small amount of primary plastic deformation will occur (Fig.10a). As suggested by De Koning and Dougherty [9] the crack extension law associated with secondary plastic deformation inside an existing plastic zone is different from that associated with primary plastic deformation. The latter is supposed to have the character of ductile tearing in view of the primary plastic flow. Consequently, a larger crack increment is expected if more primary plastic deformation is involved during the crack extension process. That explains why the striation of the first baseline cycle after the heat treatment, if it could be observed, was wider than for the subsequent baseline cycles. The same arguments apply to the larger striation of the first cycle of the overload block (giant striation) as discussed already in [8]. It is illustrated in Fig.10b.

The first overload block after an intermediate heat treatment does restore the characteristic delayed retardation behaviour during the baseline cycles. This is another indication that the load history memory of the material is largely depending on the last dominant cycles of the load history. In such a way the present results provide conclusive evidence for the evaluation of prediction models for fatigue crack growth under variable-amplitude loading. History effects depend on crack tip plasticity of previous cycles. The intermediate heat treatments did erase history effects, but subsequent load cycles immediately introduce history effects again. It indicates that crack growth prediction models must consider cycle-by-cycle variations of crack tip plasticity induced history effects. The observations emphasize that a prediction model must also discriminate between primary and secondary plastic deformation, which contribute different amounts of crack extension.

SUMMARY AND CONCLUSIONS

Crack growth fatigue tests were carried out on 2024-T3 Al-alloy specimens (t = 6.35 mm) at a baseline cyclic load of S_{max} = 80 MPa and S_{min} = 4 MPa. Blocks of 10 overload cycles (S_{max} = 120 MPa, same S_{min}) were periodically applied after every 1000 baseline cycles. The fatigue tests were interrupted for intermediate heat treatments (T4, 495°C solution heat treatment, water quench, natural aging). A summary of the findings is given below.

1. The blocks of overload cycles introduced the characteristic delayed crack growth retardation. The first overload cycle of a block caused a larger striation than the other ones.
2. An intermediate heat treatment fully erased the effect of overloads applied before the heat treatment. Immediately after an intermediate heat treatment some irregular crack extension occurred during a small number of cycles . Indications of an increased crack extension in the very first cycle after the heat treatment were obtained.
3. Crack growth after an intermediate heat treatment rapidly stabilized to the behaviour of the material without that heat treatment. After the first block of overload cycles crack growth retardation was restored again.
4. The above observations can be explained by considering that crack extension, associated with primary crack tip plastic deformation (in virgin material) is more effective than crack extension associated with secondary crack tip plastic deformation (in existing plastic zones). The present results on load history effects provide conclusive information for the evaluation of cycle-by-cycle prediction models on fatigue crack growth under variable-amplitude loading.

REFERENCES

1. W.Elber (1971), The significance of fatigue crack closure. *ASTM STP 486*, pp.230-242.
2. D.J.Dougherty, A.U. de Koning and B.M.Hillberry (1990), Modelling high crack growth rates under variable amplitude loading. In: Advances in fatigue lifetime predictive techniques, ASTM STP, to be published.
3. N.A.Fleck (1985), Fatigue crack growth due to periodic underloads and overloads. *Acta Metallurgica* **33**, 1339-1354.
4. A.Burgers and P.D.Kempen (1980), Automatic crack length measurements by the electrical potential drop method with computer control. Delft Univ. of Tech., Rep. LR-309.
5. M.R.Ling (1990), Compilation of test data and fractographic measurements on fatigue crack growth in tests with intermediate heat treatments. Delft Univ. of Tech., Fac. of Aerospace Eng., Doc. B2-91-xx.
6. K.N.Raju, V.Ningiah and B.V.S.Rao (1972), Effect of exposure to elevated temperatures on delay in crack growth due to a high stress cycle. *Int. J. of Fracture Mech.* **8**, 99-102.
7. M.R.Ling and J.Schijve (1990), Fractographic analysis of fatigue crack growth under two-blocks loading in 2024-T3 sheet specimens. Delft Univ. of Tech., Rep. LR-628.
8. M.R.Ling and J.Schijve (1990), Effects of blocks of overloads and underloads on fatigue crack growth in 2024-T351 sheet specimens. Fractographic analysis and crack closure predictions. Delft Univ. of Tech., Rep. LR-629.
9. A.U. de Koning and D.J.Dougherty (1989), Prediction of low and high crack growth rates under constant and variable amplitude loading. In *Fatigue Crack Growth Under Variable Amplitude Loading*, pp.208-217., Elsevier Applied Science.

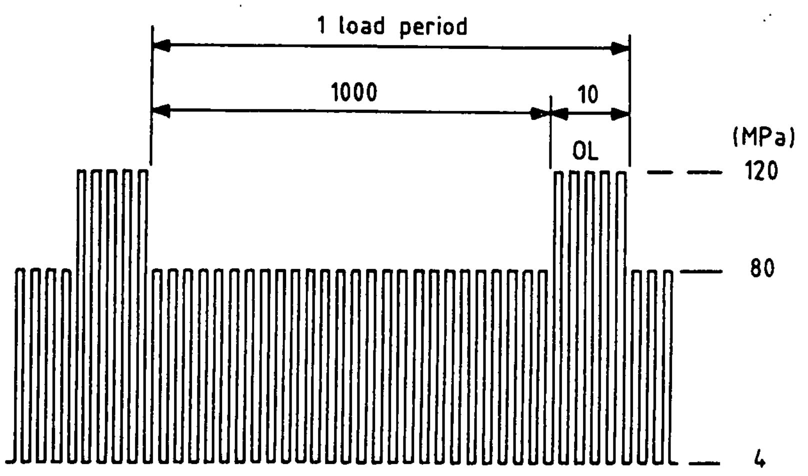


Fig. 1: The load sequence in the tests with periodic blocks of overload cycles.

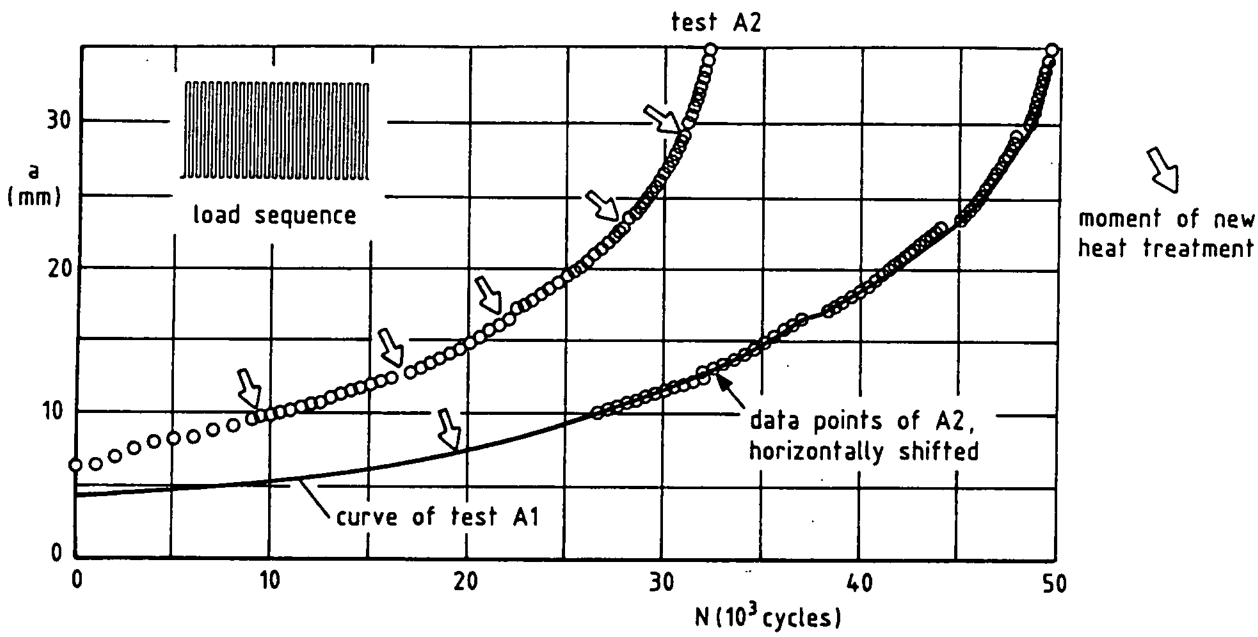


Fig. 2 : Macroscopic crack growth curves for the constant-amplitude baseline loading.

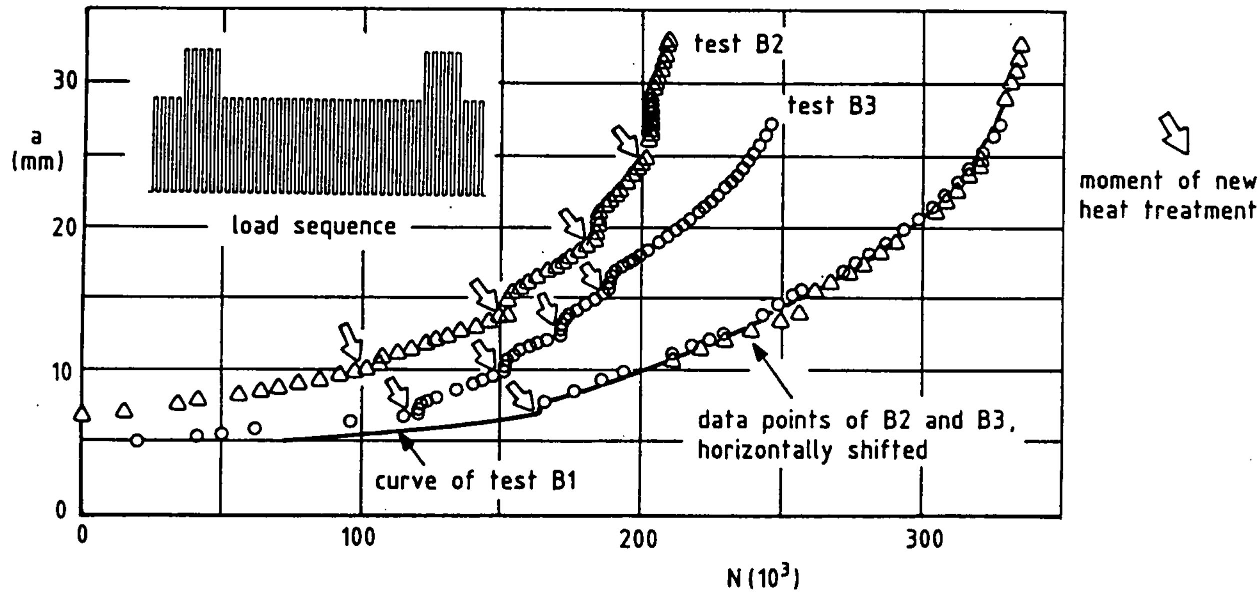


Fig. 3 : The macroscopic crack growth curves for the variable-amplitude loading.

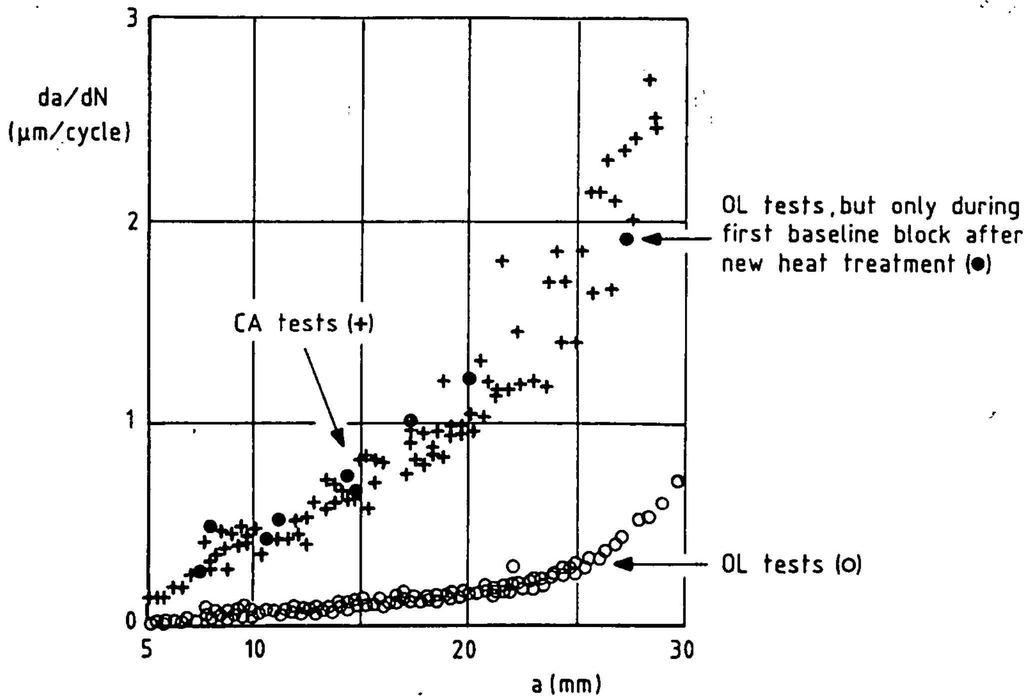


Fig. 4 : Macroscopic da/dN results in tests with and without overload blocks.

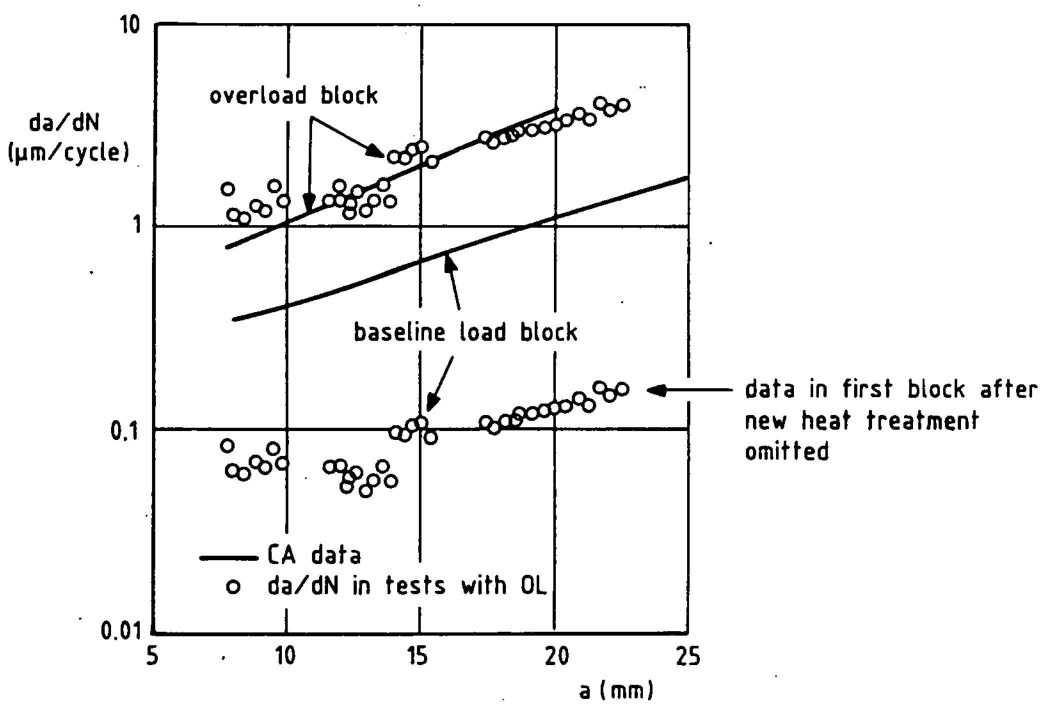


Fig. 5: Comparison of the average da/dN in the load blocks of the VA tests with the CA data. Results of microscopic measurements.

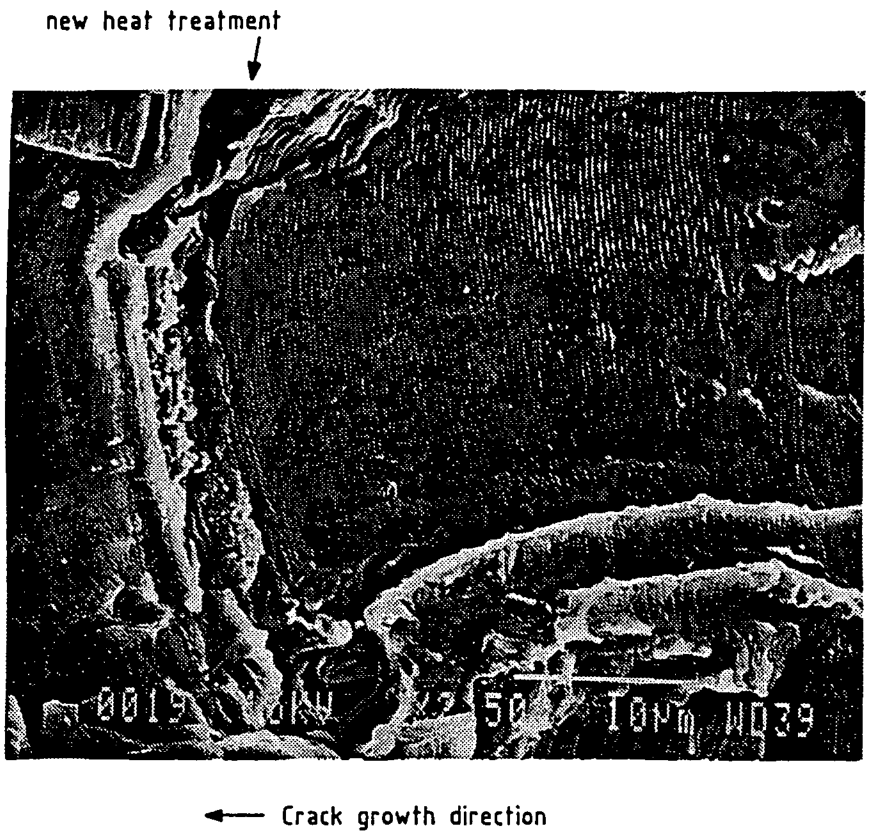


Fig. 6: Fatigue fracture surface and effect of an intermediate heat treatment.
Specimen A2, a = 10 mm (SEM, 2500 x, tilt angle 20°)

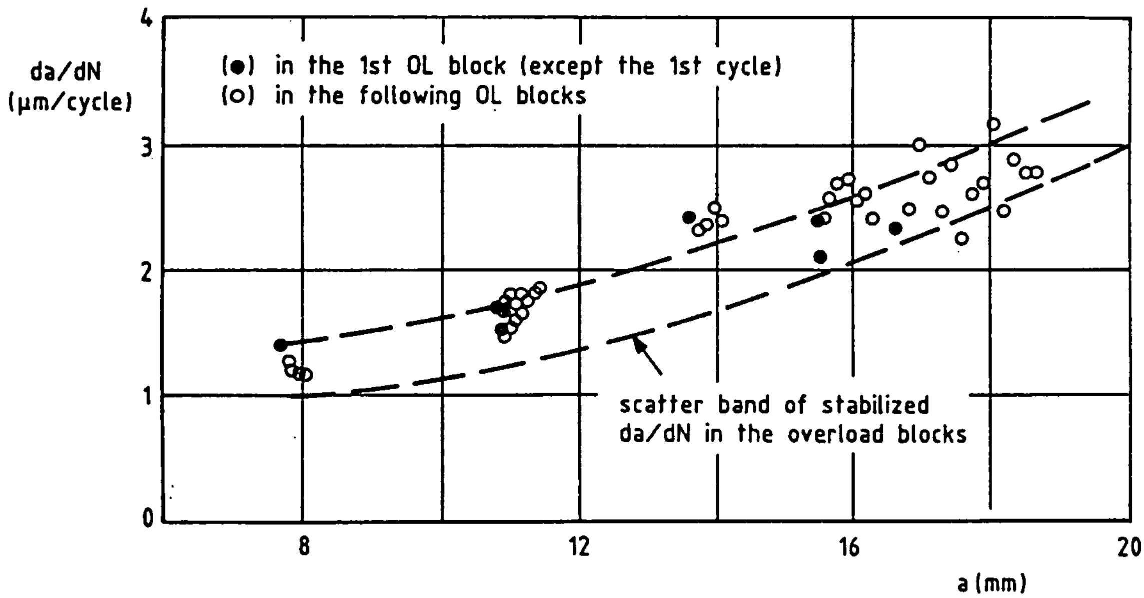


Fig. 7: The microscopically measured da/dN in the overload blocks after a new heat treatment (except for the first overload cycle).

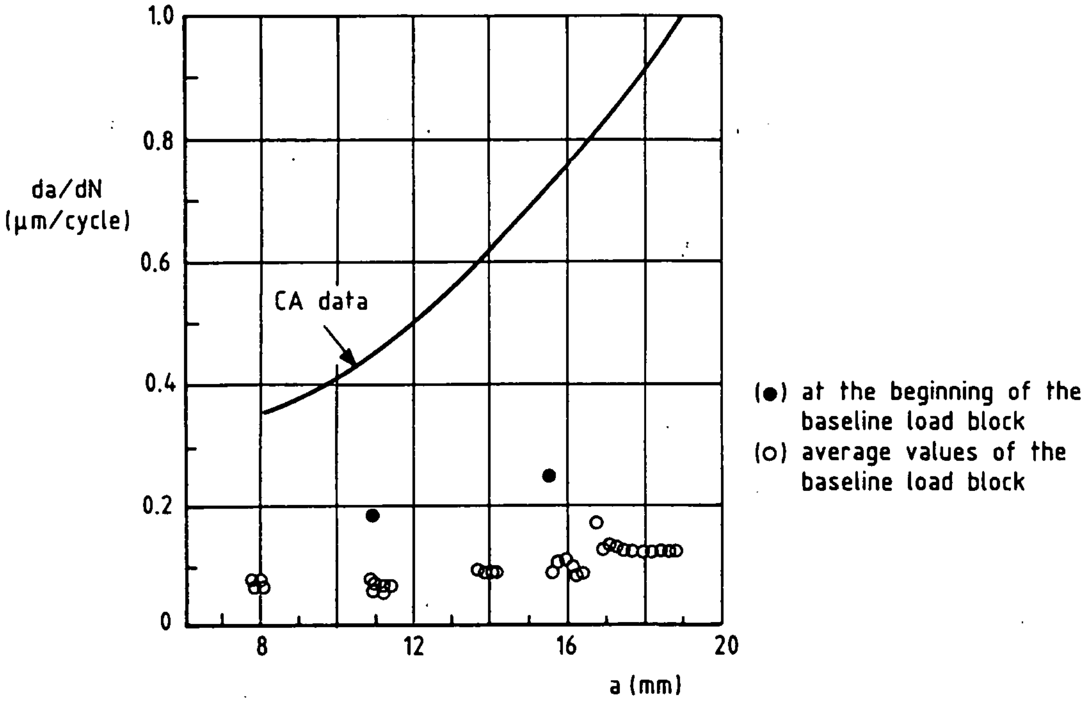


Fig. 8 : Microscopically measured da/dN in the baseline load blocks after applying new overloads on new heat treated material.

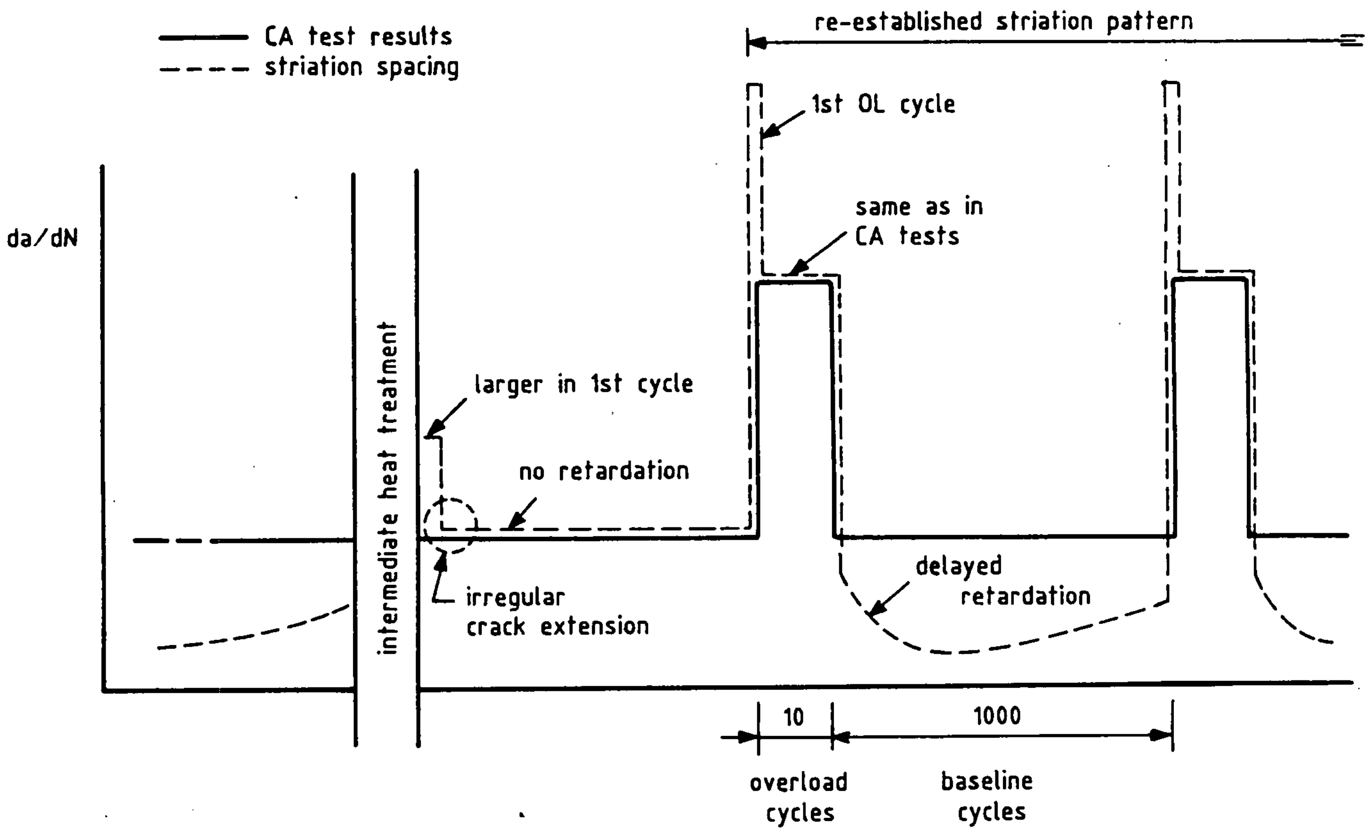


Fig. 9 : Schematic picture of observed fractographic trends.

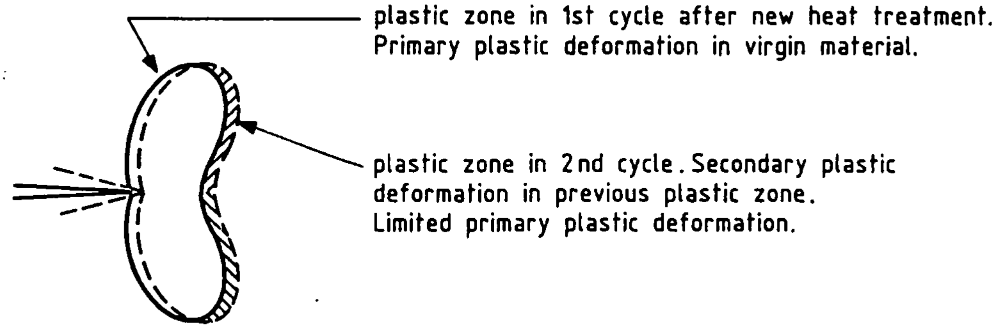


Fig. 10a

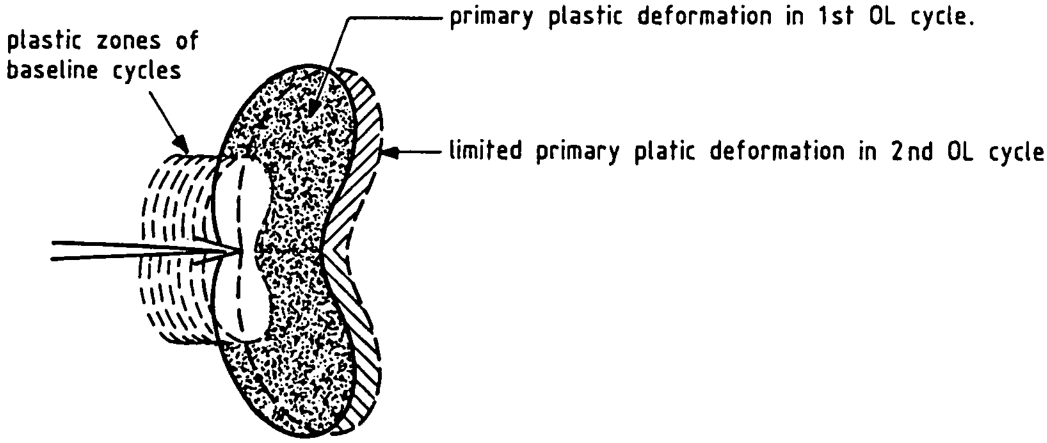


Fig. 10b

Fig. 10 : Primary plastic deformation in virgin material.

Rapport 651

60141070695

912577