Evaluation of Creep-Fatigue Crack Growth in HTR Components

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1. AIM

The assessment of crack growth in components at high temperatures usually is based on the consideration of pure creep crack growth (CCG) and/or pure fatigue crack growth (FCG). The problem of describing pure CCG and pure FCG and the transferability to components can be solved under certain presuppositions. However the real conditions for a component in operation are much more complicated. One of the reasons for this is the superposition of creep crack growth and fatigue crack growth. Therefore it is necessary to evaluate the mechanisms of interaction between these two phenomena [1].

The interaction of CCG and FCG becomes obvious by the influence of one of the following parameters on the crack growth rate:

- frequency,
- loading- and unloading time,
- hold time in FCG-tests or cyclic unloadings in CCG-tests,
- ratio of maximum and minimum load during a load cycle.

The aim of the present work was to find a mathematical description for the interaction of CCG and FCG based on a damage accumulation rule. As a presupposition for the description of the interaction phenomena, equations for the description of pure CCG and pure FCG are mandatory. It must be possible to describe the damage accumulation by means of these rather simple loading cases.

2. TESTING TECHNIQUES

The standard type of testing specimen for the experiments was the 1"CT-specimen according to ASTM-E399 [2]. For CCG-tests and the interaction tests the specimens were provided with 20% side groves. All experiments have been performed at 700°C. The R-value (minimum load/ maximum load) was 0.05.

3. REFERENCE TESTS (PURE CCG AND FCG)

A large collection of results of pure CCG- and FCG-tests is given in [3] and [4] respectively. As a reference for the interaction experiments only the data for the same production lot were considered.

In the Paris regime of the da/dN vs. ΔK_I-curve pure FCG experiments at 700°C can be described by the equation:

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$$da/dN = 2.3 \cdot 10^{-8} \text{ mm/cycle } \Delta K_I^{3.3} \text{ (MPa m}^{1/2}) \quad (1)$$

Pure CCG experiments can be described either by the energy rate integral C* or by the linearelastic stress intensity factor K_I. The criteria which of both parameters should be used, is given by Riedel's characteristic time t_1 [5]:

$$t_1 = \frac{K_I^2 \ (1 - \nu^2)}{(n+1) \ C^* \ E} \quad (2)$$

(ν: Poisson's ratio, n: creep exponent, E: Young's modulus).

For pure CCG tests the experimental time t is always large compared to t_1 and hence C*-controlled crack growth must be assumed. The following law was derived at 700°C:

$$da/dt = 1.5 \cdot 10^{-8} \text{ m/s} \quad C^{*0.8} \text{ (W/m}^2) \quad (3)$$

(a: crack length, t: time). In this paper, for most experiments the CCG phases are larger than t_1, but in some of the experiments the hold times are comparatively short. For these cases a description by means of K_I was of relevance:

$$da/dt = 7.7 \cdot 10^{-16} \text{ m/s } K_I^{4.7} \text{ (MPa m}^{1/2}) \quad (4)$$

4. INTERACTION OF CCG AND FCG

4.1 FCG with hold times

FCG tests with hold times are relatively simple experiments to study the influence of the interaction of CCG and FCG. Here only one parameter has to be changed; and with increasing hold time the influence of CCG becomes more and more obvious.

Experiments with hold times between 30 seconds and 4 hours have been carried out. The times for the loading ramps and the unloading ramps respectively were 1 sec.

The tests can be considered as FCG experiments with constant load periods at load maximum or as CCG experiments with periodic unloadings (cp. Fig. 1). According to the point of view two methods of evaluation are possible:

(i) Evaluation as a CCG-test:
- da/dt is calculated as the total crack increment in a load cycle divided by the hold time at maximum load,
- loading and unloading phases give no contribution to the CCG, they are short (>0.5 Hz) compared to the hold time, so pure FCG is assumed during loading and unloading.

(ii) Evaluation as a FCG-test:
- da/dN is the total crack increment per load cycle.

4.1.1 Evaluation as a CCG-test

In fig. 2 the hold time experiments are compared to pure CCG experiments. The crack propagation rate da/dt is plotted versus the energy rate integral C*. The experiments with short hold times show a larger amount of crack growth per second. This is due to a higher number of cycles per time interval. On the other hand, the large number of cycles causes a great amount of elastic crack opening. This leads to high values of C* combined with high crack growth rates.

With increasing hold time, the portion of CCG increases. For hold times of 32 minutes and more, the cyclic portion is negligible and the situation is similar to pure CCG (cp. fig. 2). This behaviour becomes more obvious, if the crack propagation rate is plotted versus the hold time at a fixed stress intensity factor of K_{Imax} = 25 MPa $m^{1/2}$ (cp. fig. 3). At short times the cyclic portion dominates, with increasing hold time the cyclic influence diminishes, and for $t_h \rightarrow \infty$ the creep crack growth rate of pure CCG experiments is reached.

If the crack propagation rate da/dt is plotted versus K_I, the influence of hold times becomes stronger as in the C*-plot (cp. fig. 4). Large hold times give a larger portion of CCG.

4.1.2 Evaluation as a FCG-test

If the crack propagation rate da/dN is plotted vs. the cyclic stress intensity factor ΔK_I, the tendency is reverse to the one in the da/dt vs. K_I plot (cp. fig. 5). With increasing hold time the crack propagation rate is increased. This is due to the fact, that more time is available for the creep induced crack growth during a load cycle, compared to a short hold time.

For those tests with the shortest hold times (t_h = 30 sec) the portion of fatigue dominates, as only little time is available for creep induced crack growth. This is expressed by the fact, that the Paris-line of these tests is very near to the Paris-line of pure FCG experiments. But even for the very short hold times they do not coincide totally.

4.1.3. Metallographical description

Fig. 6 compares the fracture surfaces of pure CCG-and FCG-experiments with those of hold time tests. As for the performed experiments the experimental time was limited by the crack opening displacement, the total amount of crack growth decreases with hold time. The micrographs of fig. 7 show the propagation of cracks for experiments with different hold times. For pure FCG transcrystalline crack propagation is found, for pure CCG intercrystalline crack propagation dominates. With the increase of hold time, a tendency for the formation of micro cracks and for intercrystalline fracture is found. Furthermore for long hold times a more severe damage of structure occurs near the initial crack front (cp. fig. 6 and 7). This is more obvious for longer hold times and for pure CCG.

4.2 Variation of the loading rate

With increasing loading and unloading time during a FCG experiment, the portion of CCG during these phases should become more relevant. To study the influence of the loading rate, experiments with load ramps of 4 minutes and 8 minutes have been carried out. After the maximum load was reached, the load was reduced to zero immediately (cp. fig. 8).

An evaluation of the experiments was performed on the base of the cyclic stress intensity factor ΔK_I. In fig. 9 the results are compared to those of pure FCG experiments. The crack growth rate in the tests with a loading rate of 4 minutes is approximately five times as high as in the pure FCG tests. This is caused by the creep induced crack growth during the loading phase. On the other hand, only little increase of the crack growth rate is found between loading rates of 4 and 8 minutes.

By comparing the results of chapter 4.1 and chapter 4.2, it is found that the crack increment per cycle is much more increased by a hold time than by the length of the load ramp. This is due to the length of loading at high stress levels which favour the CCG. In the ramp tests, the high stress levels do not last the whole period as in the hold time experiments.

5. LINEAR DAMAGE ACCUMULATION

The calculation of crack growth under stress, can be performed on the base of K_I, C^* (CCG) and ΔK_I.

The stress intensity factor is calculated from the well-known equation

$$K_I = \sigma \sqrt{\pi}\, a \quad Y \tag{5}$$

(σ: stress, a: crack length, Y: function of geometry). Hence only the load and the original crack length must be known for the calculation of crack propagation by means of equ. (1) and (4) respectively.

The crack growth as a function of C^* can be calculated from equation (3). In principle C^* can be taken from one of the two following equations:

$$C^* = B\ a\ \sigma_{net}{}^{n+1}\ g_1\ (a/W,\ n) \tag{6}$$

$$C^* = 2\ \dot{V}\ \sigma_{net}{}^{n+1} \tag{7}$$

(B: constant of Norton's creep law, σ_{net}: net section stress, g_1 (a/W, n): function given in the EPRI handbook [6], $\dot{V}$: crack opening displacement rate). However it is very complicated to calculate the crack opening displacement rate, and therefore only equation (6) can be used for the C^* calculation.

5.1 Hold time experiments

It was tried to describe the crack growth in the hold time experiments on the base of a linear damage accumulation rule. The model assumes, that the crack increment Δa per loading cycle consists of an amount of CCG and an amount of FCG. The CCG-portion Δa_{ccg} is produced during the constant load at load maximum, and the FCG-portion Δa_{fcg} during the loading and unloading phase.

$$\Delta a = \Delta a_{ccg} + \Delta a_{fcg} \tag{8}$$

Then the total amount of crack growth during the test is:

$$a_{tot} = \sum_{i}^{N} (\Delta a_{ccg} + \Delta a_{fcg}) \tag{9}$$

(N: total number of cycles during the test), where

$$\Delta a_{ccg} = (da/dt)\Big|_{a_i} \cdot t_h; \qquad \Delta a_{ccg} = (da/dN)\Big|_{a_i + \Delta a_{ccg}} \cdot \Delta N \tag{10}$$

(a_i: crack length during the i_{th} cycle, t_h: load time)

With equ. (1), (3) and (4) a general expression for the crack increment in the i^{th} cycle can be given:

$$a_{tot} = A\ K_I(a_i)^n\ t_h + B\ \Delta K_I(a_i + \Delta a_{ccg})^m\ \Delta N \tag{11}$$

$$= D\ C^*(a_i)^q\ t_h + B\ \Delta K_I(a_i + \Delta a_{ccg})^m\ \Delta N \tag{12}$$

(A, B, D, n, m, q are constants).

To validate the quality of crack length calculation, the relative error is used. It is expressed by the difference of calculated and experimental final crack lengths divided by the crack propagation during the test. The final crack length was calculated on the base of mean values of the pure CCG- and pure FCG-experiments. The material laws for the calculation of crack propagation are equ. 1 and 3 (ΔK_I, K_I) or equ. 1 and 4 (ΔK_I, C^*) respectively.

If the crack growth is calculated only on the base of the stress intensity factor (K_I ΔK_I), the crack growth is strongly underestimated (up to 60%). The calculation on the base of C^* and ΔK_I gives positive and negative deviations. For short hold times the negative deviations become larger, but for hold times ≥ 4 minutes the deviations are -38% and +27%. From the fact, that by the calculation on the base of C^* and ΔK_I the experimental results sometimes are overestimated and sometimes are underestimated, it can be assumed that this is a valid calculation method.

For the statistical confirmation of this assumption however, a great number of experiments must be performed. But more information on the validity can be gained, if the crack propagation is not calculated from the mean curves of pure CCG and pure FCG, but from their upper and lower border. These curves are given by:

upper borders:

$$\begin{aligned} da/dt &= 1.6 \cdot 10^{-8}\ m/s \cdot C^{*0.8}\ (W/m^2) \\ da/dN &= 4.0 \cdot 10^{-8}\ mm/cycle \cdot \Delta K_I^{3.0}\ (MPa\ m^{1/2}) \end{aligned} \tag{13}$$

lower borders:

$$\begin{aligned} da/dt &= 8.0 \cdot 10^{-9}\ m/s \cdot C^{*0.8}\ (W/m^2) \\ da/dN &= 1.2 \cdot 10^{-8}\ mm/cycle \cdot \Delta K_I^{3.0}\ (MPa\ m^{1/2}) \end{aligned} \tag{14}$$

The calculations on the base of the lower borders systematically underestimate the crack propagation, as the calculations on the base of the upper borders systematically overestimates the crack propagation [1]. Therefore the calculation of crack propagation on the base of the lower borders of pure CCG- and FCG-curves leads to a conservative result.

5.2 Variation of loading rate

Some experiments were carried out with saw tooth shaped loading cycles. The loading time was 4 and 8 minutes. The CCG during the loading was considered in a similar way as in the hold time experiments, but now a number of load levels were assumed during the increase of load. Therefore the crack growth in each load cycle caused by CCG is given by (cp. fig. 8)

$$a_{CCG} = \sum_{i=1}^{j} \Delta a_{CCGi} \tag{15}$$

Where Δa_{CCGi} is the crack increment during the i^{th} step of calculation.

Opposite to the hold time experiments, the calculation on upper limits (equ. 15) is not conservative. Therefore the assumed concept is not suitable for the description of slow loading experiments.

The reason for the failure is assumed to be in the validity of the C* laws. The latter were derived for constant loads under the assumption of power law creep, as in our case the load steadily increases during each load cycle. Therefore the presuppositions of the C* integral are violated. But a calculation by means of the linearelastic K_I is not conservative either. On the other hand, a calculation under the assumption of only the maximum load during the whole cycle is extremely conservative. But this seems to be the only way out at the moment.

6. CONCLUSIONS

- FCG tests have been carried out with hold times between 30 seconds and 4 hours. Experiments with hold times of more than 32 minutes lead to results similar of pure CCG-tests.
- FCG-tests with hold times at load maximum show larger crack propagation rates as pure FCG- and pure CCG-tests. The increase of the crack propagation rate with hold times is an expression of the CCG on the FCG.
- The crack growth rate per cycle is increased if the duration for the loading ramp is increased from 4 to 8 minutes.
- A linear damage accumulation rule was used to give a mathematical description for the interaction of CCG and FCG.
- A linear damage accumulation rule can be used to describe the crack propagation in FCG-experiments with hold times. The calculation is based on the laws for pure FCG (da/dN vs. ΔK_I) and pure CCG (da/dt vs. C*). If the lower borders of pure CCG- and FCG-experiments are used, the results are conservative.
- Some experiments with saw tooth shaped loading cycles and different load step rates were performed. The attempt to apply the linear damage accumulation rule to these experiments by considering the CCG during the load increase was negative.

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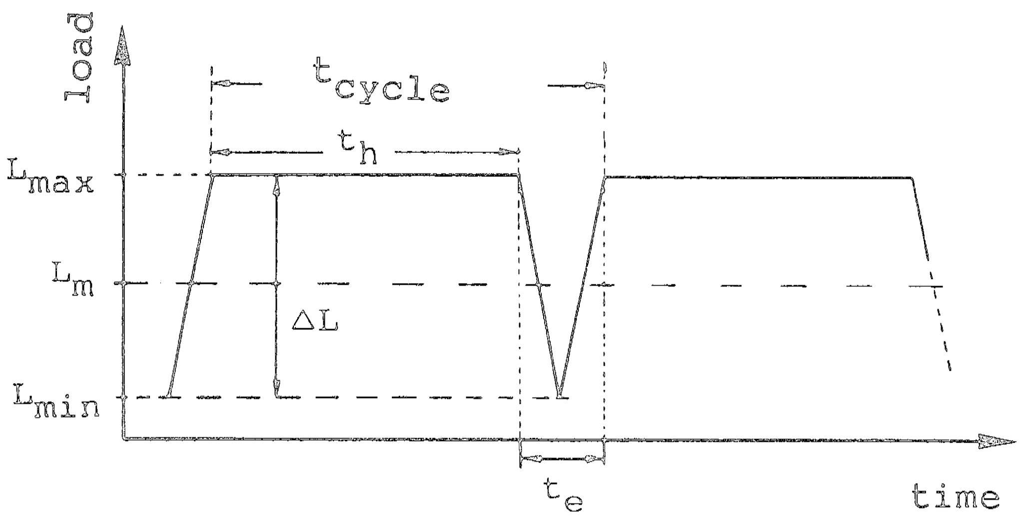

Fig. 1: Loading diagram for FCG experiments with hold times

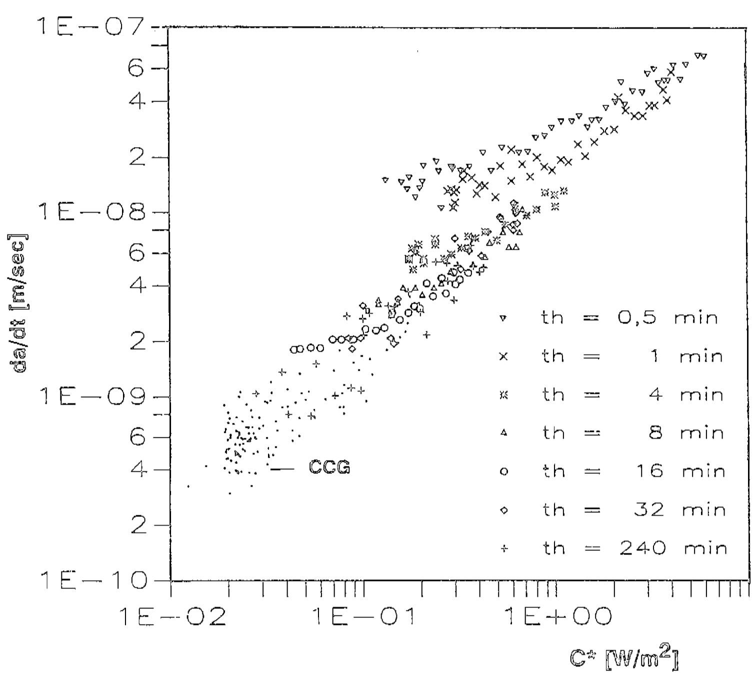

Fig. 2: Hold time experiments and pure CCG experiments (CCG-evaluation with C*-parameter)

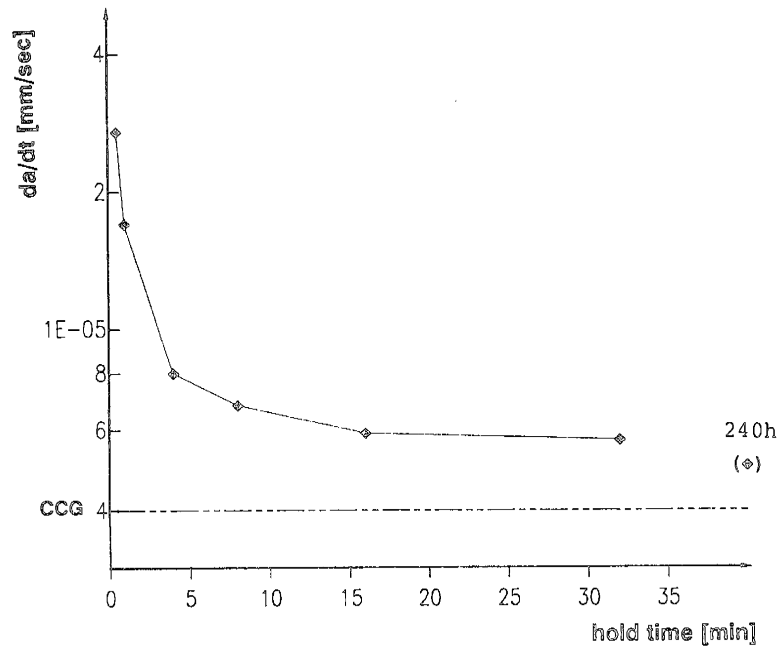

Fig. 3: Influence of hold times on the crack propagation rate ($K_{I\ max}$ = 25 MPam$^{1/2}$)

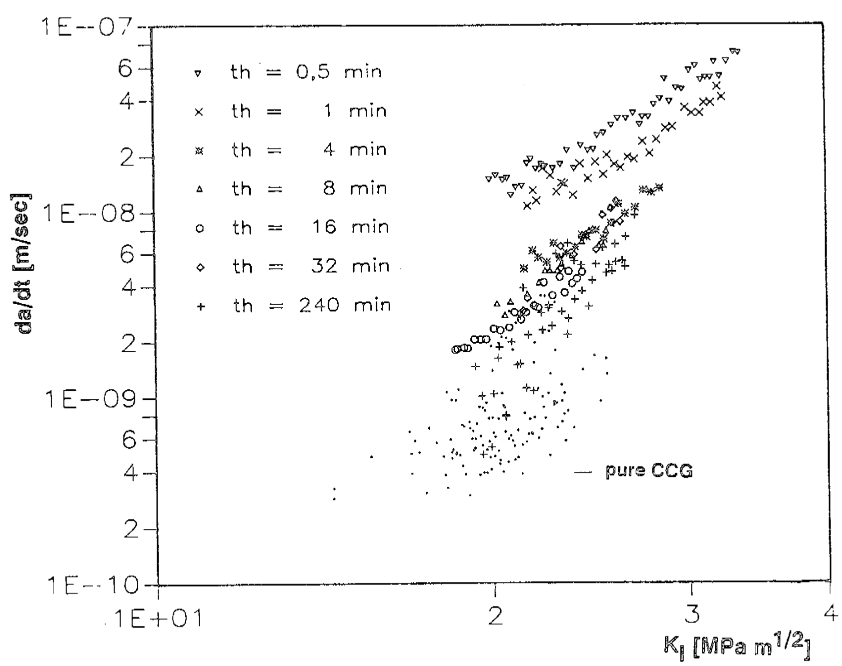

Fig. 4: Hold time experiments and pure CCG experiments (CCG-evaluation with K_I-parameter)

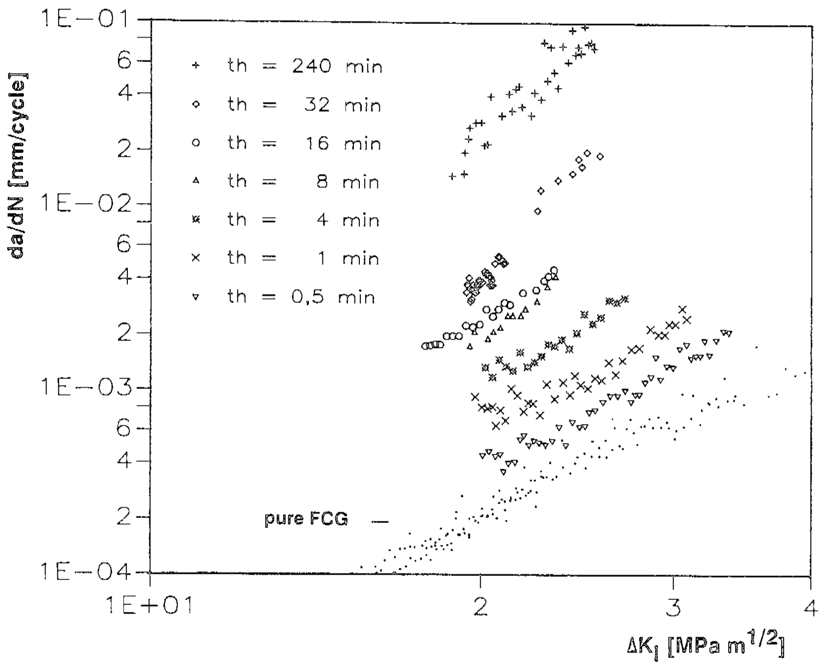

Fig. 5: Hold time experiments and pure FCG experiments (FCG-evaluation)

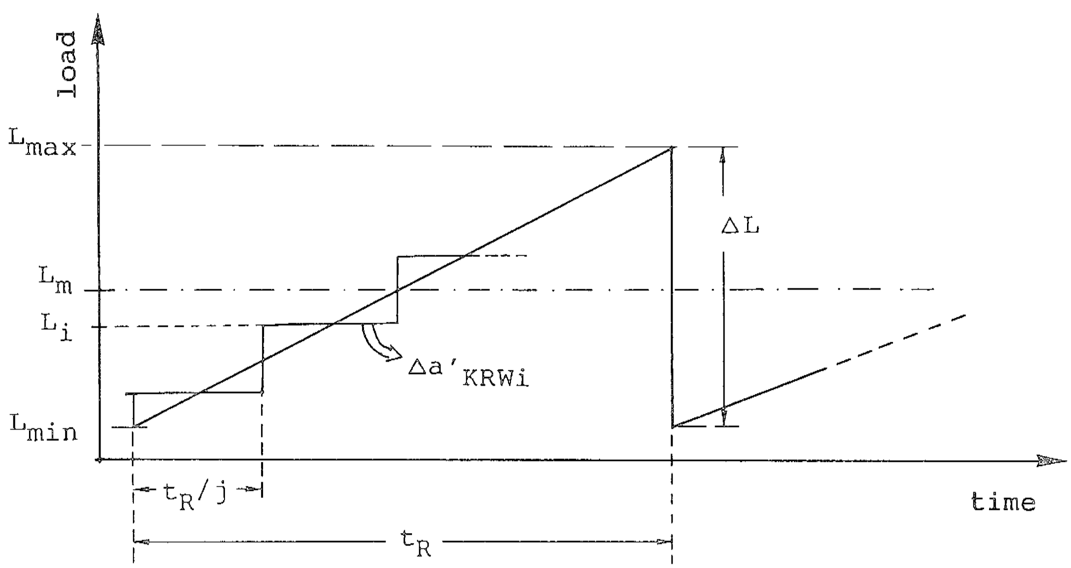

Fig. 8: Scheme of calculation for experiments with variable loading rate

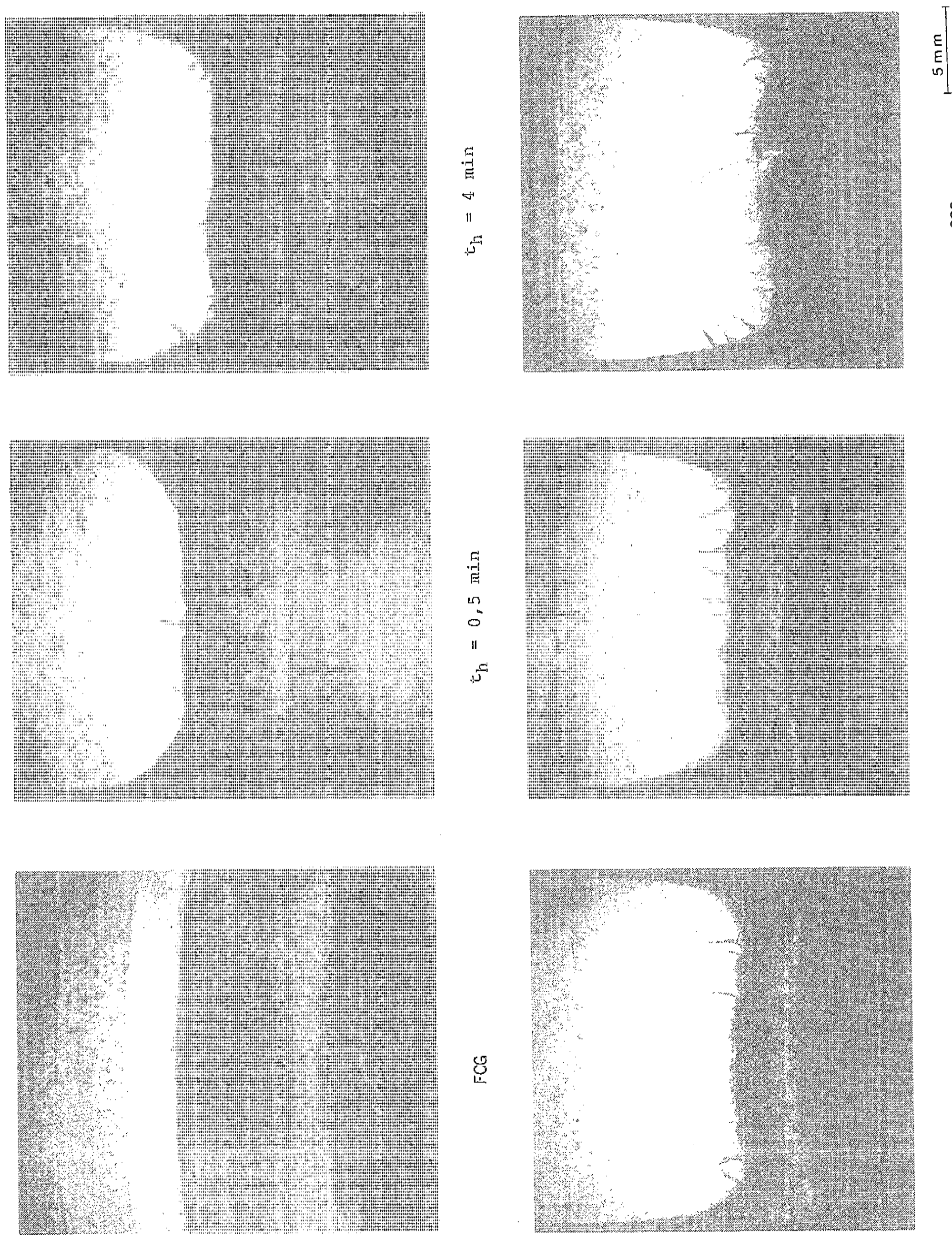

Fig. 6: Fracture surfaces of FCG-experiments with hold times and a CCG experiment

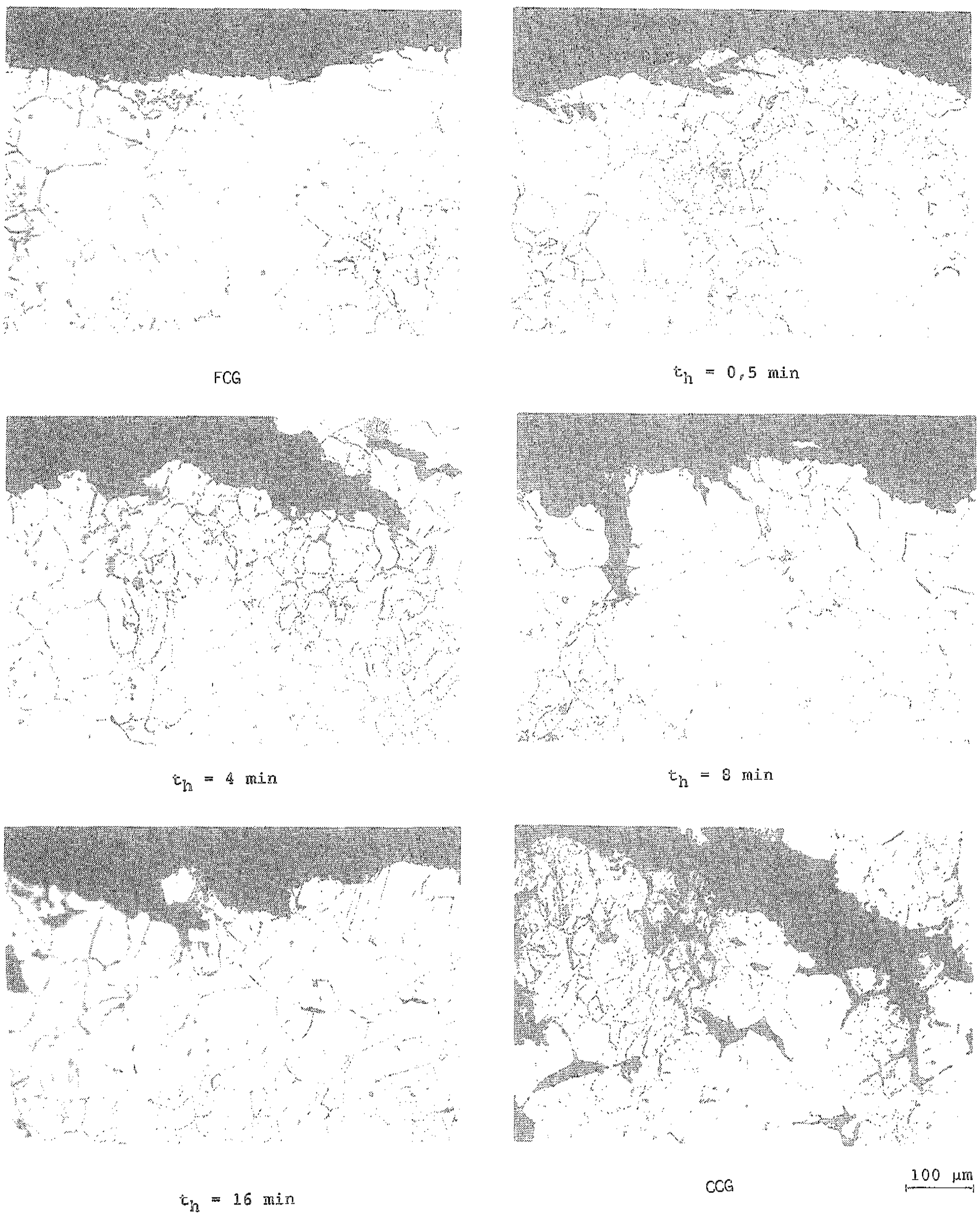

Fig. 7: Micrographs perpendicular to the crack front, for FCG-experiments with hold times

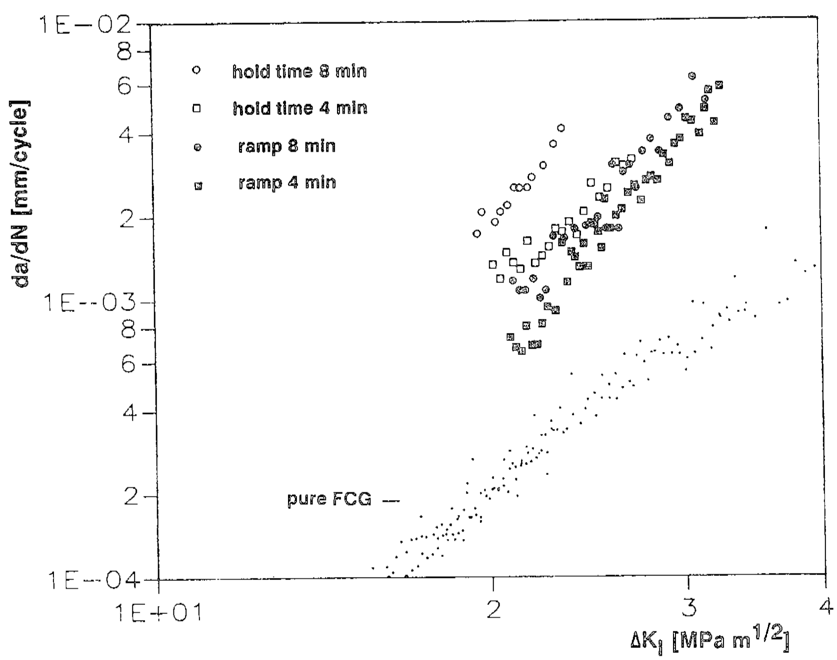

Fig. 9: Experiments with loading rates of 4 and 8 minutes compared to pure FCG- and hold time tests (FCG-evaluation)

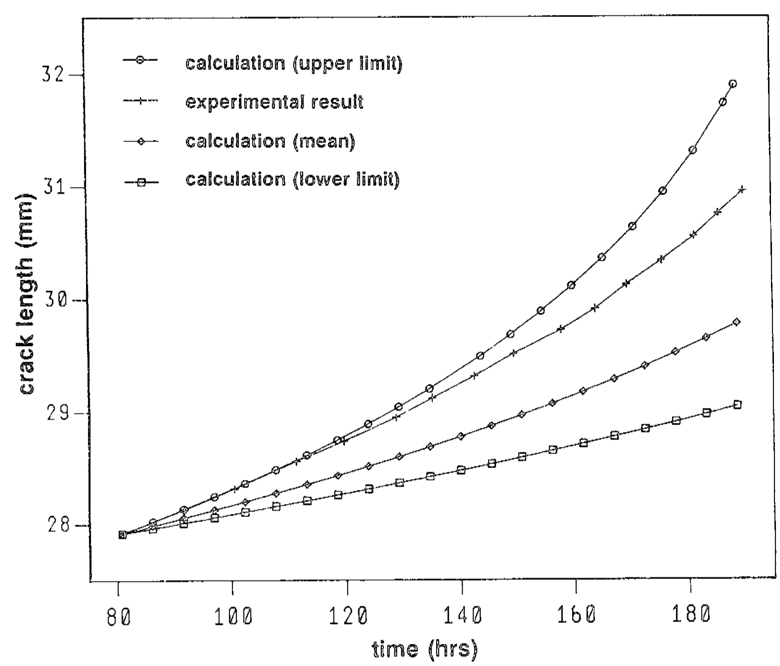

Fig. 10: Crack growth in a hold time experiment compared to the calculated crack growth. Calculation based on the results of pure CCG- and FCG-tests (mean values, upper and lower limit values).