ECCC RECOMMENDATIONS - VOLUME 3 PART IV [Issue 2]

TESTING PRACTICES FOR CREEP CRACK INITIATION

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TESTING PRACTICES FOR CREEP CRACK INITIATION

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ABSTRACT

ECCC Recommendations Volume 3 Part IV provides guidance on testing practice for the determination of creep crack initiation data.

ECCC Recommendation Volume 3 Part IV user feedback is encouraged and should be sent to:

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CONTENT

1 OBJECTIVES

Creep crack initiation (CCI) tests are not standardised. Specimen types and test procedures have been developed based on existing standards and guidelines for quasi-static and cyclic tests to determine fracture mechanics parameters. Special test and evaluation techniques for creep crack initiation and creep crack growth have been applied. Testing practices and specimen types are reviewed. Testing and measuring techniques especially those for determination of crack initiation (e.g. Potential Drop) are reviewed. Test conditions are discussed.

This review document is based on the experiences gained from own testing practices and from available standards in elevated temperature fracture mechanics (e.g. ASTM). It summarizes experience from several testing laboratories within Europe, validity criteria for test results developed by the German Creep Crack Group W14 are included. The aim is to give advice on the testing and measurement of creep crack growth data, and comprises following recommendations:

- definition of mandatory data to be measured,
- definition of data to be evaluated,
- evaluation procedures for measuring data, definition of relevant influencing parameters and validity criteria.

This document should be read in conjunction with the document "Terms and Terminologies" [1].

2. SPECIMENS AND SPECIMEN PREPARATION

2.1 Specimen geometry

Fracture mechanics testing to investigate Creep Crack Initiation (CCI) as well as Creep Crack Growth (CCG) can be performed on specimens of any size and shape, provided the calibration functions for K, J or C*(t) are available. However, differently from other types of Fracture Mechanics test methods standards, like fatigue and fracture toughness testing, which consider the possibility of a number of specimen geometries (for which therefore the standard provides the K and J calibration functions to be used), in the only existing CCG testing standard (ASTM) only one geometry of specimen is considered, namely the Compact Tension specimen.

Due to industrial needs for other geometries, suitable to match the size, crack position, shape and the constraint of the actual component to be examined, and convenient to be sampled from small sections, other types of non standard specimens are sometimes used in creep cracking tests. A partly EC funded European project CRETE in the frame of FMP5 has addressed this topic [2]. A European Code of Practice is being published [3] extending the existing test method for CT geometry to the other non standardised types of specimens, as shown in Fig. 1.

So far the specimens most common in use are standard CT specimens, Fig. 2, usually with thickness B = 25 mm and width W = 50 mm. For CT-specimens a ratio of B/W = 0.5 is standardised. The recommended a_0/W ratio range is 0.45 - 0.55 [4]. For DENT specimens a_0/W-ratios from 0.2 to 0.4 are used, however, this specimen-type is not yet standardised.

2.2 Side grooving

The crack front will usually be curved and crack length needs to be averaged across the specimen. Without side grooves curvature "tunnelling" can be very severe and optical measurement may be difficult. With side grooves the included angle needs to be optimised for a given material. It may occur that the crack is longer at the grooves than across the remainder of the specimen (Fig. 3).

The total depth of side grooves is usually 20%, 10% on each side. For ductile steels a total reduction of up to 40% may be necessary. Groove angle less than 90 ° is allowed (typical: 40 - 60 °) [4]. Ideally, the depth and configuration of side-grooves should be optimised for a given testpiece geometry / material condition to give the required straight crack-front.

2.3 Crack starter

Basically two methods for crack starter are used:

a) fatigue pre-cracking and

b) electric discharge machined notch.

Fatigue pre-cracking is normally done at room temperature with the specimen in the finally heat treated condition. Such fatigue pre-cracking has to be performed according to the requirements of [5,6], but fatigue pre-cracking procedure cannot guarantee uniform crack front. This can be better achieved if crack starters are machined by using electro discharge method (EDM). Such a method provides better comparison of specimen geometries and test results between different laboratories.

If crack starters are machined by EDM it is necessary to produce a notch radius small enough to be comparable with a sharp fatigue crack. A notch width of 0.1 mm is recommended [4] and desirable but difficult to achieve. Notch widths less than 0.2 mm are acceptable for creep ductile materials where significant creep deformation occurs at the crack tip (blunting) before initiation of a creep crack. For creep brittle materials fatigue pre-cracking is the preferred method since it may result in more conservative initiation values.

Side grooves are normally machined after crack starters are made. Some laboratories are using pre-cracking after side grooves are produced and crack length is monitored by Potential Drop Method (see 2.2). It is also possible to perform pre-cracking in two stages (one before and one after machining the side grooves).

The influence of pre-cracking (fatigue versus electro discharge machining - EDM) has been examined in several projects. In these studies for creep ductile materials EDM is used for specimen preparation. Some fatigue pre-cracked specimens have been used in order to examine the influence of pre-cracking. A comparison of crack length on Cs25-specimens with eroded and pre-fatigued crack starters shows no significant difference in time to specific short crack length (Fig. 4).

The crack starter type has an influence on the crack initiation time. The influence gets smaller with further creep crack growth progress (Fig. 5) and is thereby dependent on creep crack initiation criterion to define technical crack initiation. This is observed for 1 to 12 CMV-steels with high rupture elongation during first few thousands of hours.

3 TEST TECHNIQUES

Two experimental approaches can be used to determine the creep crack behaviour (creep crack initiation and creep crack growth):

- Interrupted Test Method (ITM) and
- Continuous Test Method (CTM).

While the interrupted test method is inherently a multi-specimen approach, requiring information from a series of testpieces interrupted at various life fractions, the continuous test method may be implemented employing either a single-specimen or multi-specimen approach. Implementation of the continuous test method as part of a multi-specimen test strategy is not uncommon for the determination of CCI parameters.

During test, temperature and the applied load are controlled, and the load line displacement and crack development are monitored. The load line displacement comprises three components: elastic, plastic and creep, i.e.

$V_{tot} = V_e + V_p + V_c$

The elastic component of the load line displacement is usually significant and cannot be disregarded. For many ferritic materials, in particular at higher application temperatures in the creep regime, the instantaneous plastic component of the load line displacement is negligible and can be disregarded. For other materials, including austenitic stainless steels and some Ni-based alloys, the instantaneous plastic displacement component is significant and must be measured during loading.

3.1 Interrupted Test Method (ITM)

For each stress level, a series of up to 10 specimens are tested under the same loading conditions for example in a multi specimen machine (Fig. 6) [7]. After reaching predetermined time proportions from 10 to 80% of the estimated test duration time the specimens are unloaded. During each interruption the load line displacement V of all specimens is measured at room temperature by special ceramics measurement marks fixed at the specimen in the load line ($V = V_p + V_c$, with tolerance of $\Delta V = \pm 5\ \mu m$). One specimen is cooled in liquid nitrogen and brittle fractured. The use of cyclic loading to achieve further crack growth which can be distinguished by fractography is also permissible. The specimen crack length is fractographically determined [4]. A crack length measurement using unloading compliance [8] with an appropriate machine is possible. A typical result of a creep crack test by using ITM is shown in Fig. 7. The advantage of this testing method is that, as several specimens are used, the results provide a scatter band which is also an indication of material inhomogeneity.

The following steps have to be carried out during the *ITM-Procedure:*

- measurement of specimen dimensions
- assembly of specimen-row
- assembly of specimen-row in furnace
- The hold time at test-temperature before test start should be at least 2 hrs to ensure homogenous temperature distribution in the specimen. For large specimens the hold time may be longer.
- manual setting of load, continuously as fast as possible
- when the test is interrupted unload, take the specimens out of furnace in less than 0.5 hrs and leave the specimen-row to cool down to room temperature.

Measurements during test:

- load,
- temperature
- load line displacement during loading when it is necessary to determine the plastic part of load line displacement

Measurements during test interruption:

- load line displacement on all specimens ($V = V_p + V_c$)
- creep crack length on all specimens using unloading compliance [9] with appropriate machine to assist in planning next test interruptions
- creep crack length on the removed specimens, when broken open in liquid nitrogen or by fatigue post test cracking to improve accuracy of crack length measurements.

Post test measurement:

- final load line displacement ($V = V_p + V_c$)
- on each specimen creep crack length is evaluated by fractography

3.2 Continuous Test Method (CTM)

During the tests, continuous online measurement of the load line displacement is performed ($V = V_e + V_p + V_c$). This can be done using appropriate extensometer with Linear Variable Displacement Transducer (LVDT, Fig. 8), capacitive high temperature strain gauges, see Fig. 9 and Fig. 10 or non-contact optical methods e.g. laser scanner [10]. In addition the permanent load line displacement is measured after the test.

By using LVDT the transducer is placed outside the furnace. It is important to make the tube and rod from materials that are thermally stable and with the same coefficient of linear expansion.

Direct or alternating current potential drop (DCPD or ACPD) technique is used to monitor potential drop and later to calculate crack length. At the end of each test the potential drop signal must be calibrated with the final crack length optically measured on the fractured specimen. Potential drop methods are described in Annex I.

Using the continuous test technique the so-called "Compliance method" [11] is an alternative method to determine the creep crack growth (and as an approximation the creep crack initiation). During the creep test unloading to F_{min} (e.g. $F_{min} \geq 0.85\ F_{max}$) is performed regularly. Subsequently the specimen is reloaded to F_{max}, Fig. 11.

During the unloading-reloading procedure the compliance of the specimen is measured. It can be clearly seen that the variation of the compliance $C = \Delta v_{LLD}/\Delta F$ is dependent on crack length. An indication on the reliability of crack length determination from crack length may be obtained from the unloading after pre-cracking. Friction at the load pins effecting the compliance measurement has to be avoided.

The compliance indicated crack length should be checked against the final creep crack length measured after the test. In Fig. 12 good agreement of the crack length determined by potential drop and compliance techniques is shown. The compliance method is suitable to obtain information on creep crack growth. Creep crack initiation can be derived from creep crack growth data. By adapting the frequency of unloading procedures it is necessary to ensure that there is no influence of cyclic loading on the test result.

The following steps have to be carried out during the *CTM-Procedure:*

- specimen dimensions measurement
- PD instrumentation on the specimen
- specimen assembly in furnace
- PD circuit connect (in case of PD measurement)
- Extensometer and LVDT assembly
- specimen preload to 10% of test load
- heat the furnace to test temperature
- The hold time at test temperature before test start should be sufficiently long to ensure a homogenous temperature distribution in the specimen. The hold time must be adapted to specimen size. For CT1-specimen a hold time of 2 h is recommended.
- check proper extensometer function
- load the specimen to test load
- perform unloading procedures (in case of compliance technique)
- unload the specimen at the end of the test, shut down the heating and leave the specimen to cool down to room temperature.

Measurements during the test:

- load (incl. load up information as a function of load line displacement)
- temperature
- electric potential drop voltage
- total load line displacement ($V_{tot} = V_{el} + V_{pl} + V_c$)

Post test measurement:

- final load line displacement (V = Vpl + Vc)
- initial crack length and final creep crack length after the specimen is broken in liquid nitrogen outside the furnace
- determination of plastic part of loadline displacement

3.3 Load control

Load control should be in accordance with the following standards

<u>ITM in multi specimen machine:</u>

EN 10291 [12]

<u>CTM in single specimen machine:</u>

EN 10291, ASTM E4, ASTM E74

3.4 Temperature control

Temperature control should be in accordance with the following standards

<u>ITM in multi specimen machine:</u>

EN 10291, [12]

Temperature (°C)	Permissible tolerance (°C)
T ≤ 600	**± 3**
600 < T ≤ 800	**± 4**
800 < T ≤ 1000	**± 5**
1000 < T ≤ 1100	to be agreed

<u>CTM in single specimen machine:</u>

EN 10291, [12]

4 DETERMINATION OF CREEP CRACK INITIATION PARAMETERS

In principle the following parameters can be determined as creep crack initiation parameters. A complete list with definitions can be found in Vol. 2 Part V, details on the evaluation procedure are described in Vol. 7.

4.1 Definition of creep crack initiation

The creep crack initiation is defined by a technical creep crack initiation length $\Delta a_i = a_i - a_0$. It is possible to use a creep crack initiation length which is dependent on the geometry and size of specimens as $\Delta a_i = 0.004 \cdot W$ for CT- or $\Delta a_i = 0.01 \cdot W$ for DENT-specimens.

For CT25 specimens and larger specimens it is recommended to use a constant creep crack initiation length of $\Delta a_i = 0.5$ mm independent of geometry and size of specimens. The definition of a fixed crack length at initiation is advantageous in order to avoid the influence of spurious factors not related to crack advance. Dependent on the degree of brittleness and the grain size of the material investigated a constant creep crack initiation length of $\Delta a_i = 0.2$ mm can be chosen.

For the determination of fracture mechanics parameters C(t), C*, K_I and K_{cmat} at technical crack initiation see Annex II.

4.2 Crack Tip Opening Displacement

During the early part of test, the crack tip opening displacement (CTOD or δ) increases in direct proportion to the load line displacement with elastic, plastic and creep components, i.e.

$$\delta_{tot} = \delta_e + \delta_p + \delta_c$$

Creep crack initiation (the onset of creep cracking from a pre-existing defect) occurs on the attainment of a critical crack tip opening displacement, i.e. $\delta_{I,x}$ (where x is the creep crack initiation criterion, e.g. $x = \Delta a = 0.5$mm).

Following creep crack initiation, the development of δ_{tot} no longer reflects the development of V_{tot} and can reduce in magnitude [13]. $\delta_{I,x}$ for a growing crack is usually less than that for a growing crack.

Methods for monitoring CTOD (δ) and determining $\delta_{I,x}$ are given in Annex III.

4.3 *Creep Toughness* K^c_{mat}

Creep Toughness K^c_{mat} - a generic term for measures of resistance to crack initiation, see Annex IV.

4.4 *C*-Integral*

C*-Integral, a mathematical expression, a line or surface integral that encloses the crack front from one crack surface to the other, used to characterise the local stress-strain rate field at any instant from the crack front in a body subjected to extensive creep conditions [14], see also Annex II

4.5 *Stress Intensity Factor K*

Stress Intensity Factor K - the magnitude of the ideal crack tip stress field (a stress-field singularity) for mode I in a homogeneous, linear-elastic body [15]. At initiation according to the definition in 3.1 the parameter K_{Ii} is determined.

4.6 *J-Integral*

J-Integral, a mathematical expression, a line or surface integral that encloses the crack from one crack surface to the other, used to characterise the local-strain field around the crack front [8]. J-Integral is used for further calculations e.g. of K_{cmat} or C*.

4.7 *Nominal Stress σ_n and other stress parameters*

Nominal stress σ_n - in fracture testing, a measure of the stress on the net cross section calculated in a simplified manner and without taking into account stress gradients produced by discontinuities such as holes, grooves, fillets etc. [8]. Other characterising stress parameters are reference stresses (determined under assumption of plane stress or plane strain conditions using Mises or Tresca criterion for determination of equivalent stresses), the reference stress according to ASME, plastic net stress as defined by Siebel [16]. The reference stresses or plastic net stress, respectively may be determined in accordance to the evaluation procedures, see Vol. 7.

5. SPECIFIC REQUIREMENTS AND VALIDITY CRITERIA

5.1 *Ratio* $\dot{V}_C / \dot{V}$

If $\dot{V}_C/\dot{V} \geq 0.5$ for CT-specimens, the data are classified as being creep-ductile and the candidate crack growth rate relating parameters are C*(t). If $\dot{V}_C/\dot{V} \leq 0.25$ for which the data are classified as being creep-brittle the candidate parameter is K.

5.2 *Transition time*

The transition time t_T is defined by

$$t_T = \frac{K^2 \cdot \left(1 - \nu^2\right)}{E \cdot (1+n) \cdot C^*(t_T)}$$

where n is the creep exponent in

$d\varepsilon/dt = A \cdot \sigma^n$.

Data for which the time exceeds transition time are correlated by C*.

5.3 *Validity Criteria for the Parameter C**

The validity of the parameter C* is restricted to the crack tip displacement δ_t which is small compared to the specimen geometry ($\delta_t \leq a/50$). The following validity criteria can be derived from that for the parameter C* :

a/50 > v/[1+3a/(W-a)] for CT or Cs- specimens,

Using the same approach criteria for DENT specimens have been determined for 1CMV-steel, see Annex V.

5.4 *Further validity requirements*

As defined for linear elastic fracture mechanics, a similar criterion limiting maximum load taking into account time dependent material behaviour is recommended. The failure of specimens loaded in such a way that the plastic net stress σ_{npl} at crack initiation is higher than the creep rupture strength (at the time of crack initiation) is due to ligament damage. Specimens for which

$$\frac{\sigma_{npl}}{R_{u/ti/T}} > 1$$

should be excluded for the determination of fracture mechanics parameters. Similar consideration should be given to the value of the reference stress.

6. REPORT

The report should contain the following information:

1) Test material data
2) Specimen type and dimensions
3) Pre cracking
    - fatigue pre cracking: temperature, frequency of loading, number of cycles
    - EDM: root radius, length of the notch
4) Test data:
    - load
    - test temperature
    - environment
5) Test method
    - ITM
    - CTM
6) Crack length
    - ACPD
    - DCPD
7) Load line displacement
8) Validity criteria

7 REFERENCES

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[2] Development and Harmonisation of Creep Crack Growth Testing for Industrial Specimens – CRETE – A Route to a European Code of Practice", GRD2-2000-30021

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[5] ISO 12737 (1996): Metallic materials - Determination of plane-stain fracture toughness

[6] ASTM E 399 (1990): Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials

[7] Kloos, K.H., J. Granacher, A. Scholz, R. Tscheuschner: Prüfung metallischer Werkstoffe bei hohen Temperaturen, Teil 1 bis 4, Materialprüfung 30 (1988) S. 93/98, 151/151, 202/204, 255/230.

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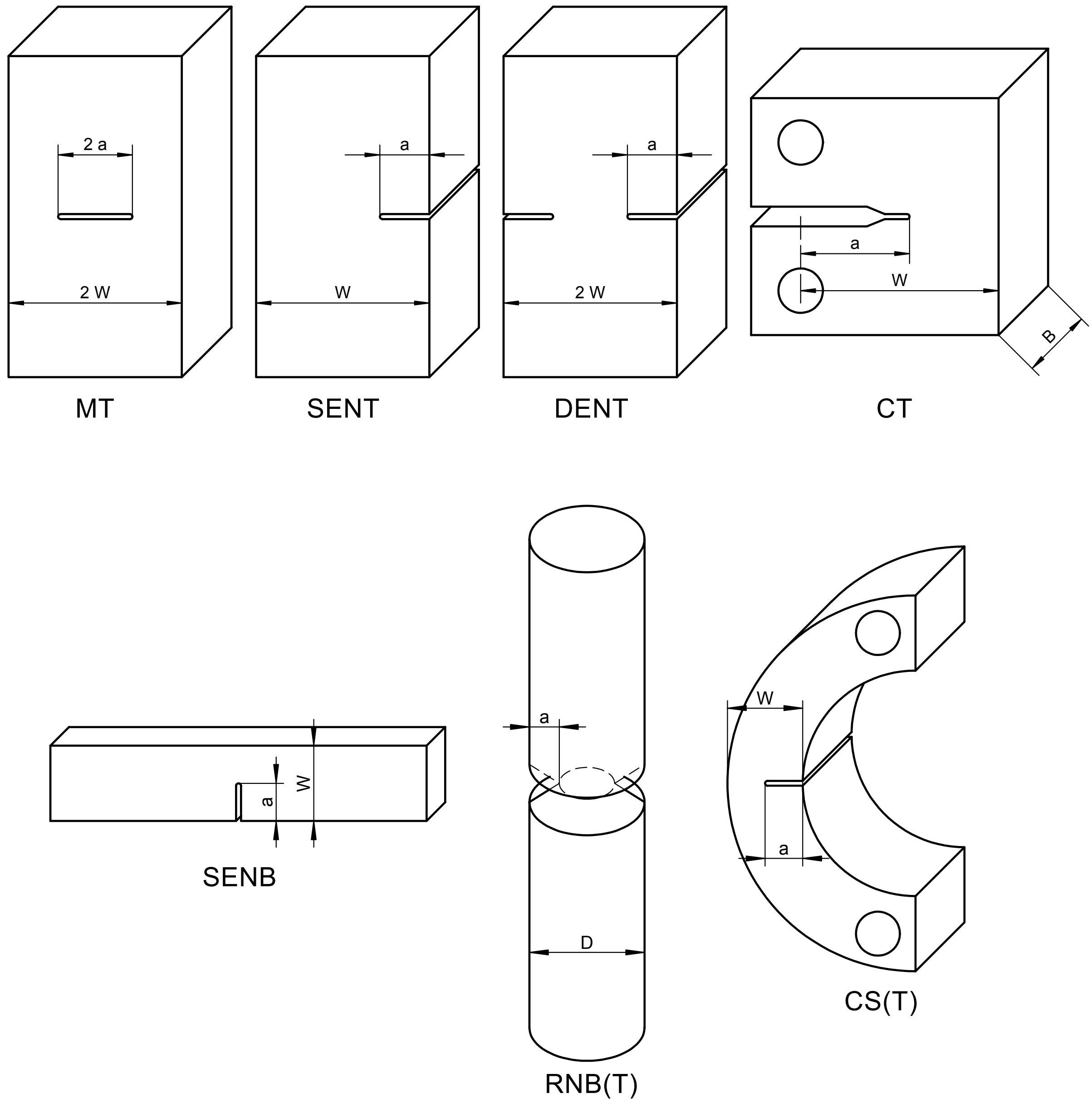
FIGURES AND TABLES



	B (mm)	a_0 (mm)	W (mm)
Mid-Crack **T**ension	12.5	3.5	25
Single **E**dge **N**otched **T**ension	12.5	5	25
Double **E**dge **N**otched **T**ension	12.5	3.5	25
Compact **T**ension	25	27.5	50
Single **E**dge **N**otched **B**ending	12.5	5	25
Round **N**otch **B**ar **T**ension	12.5	1.25	-
C-**S**hape **T**ension	25	5	25

Fig. 1. Geometries and dimensions of typical specimens

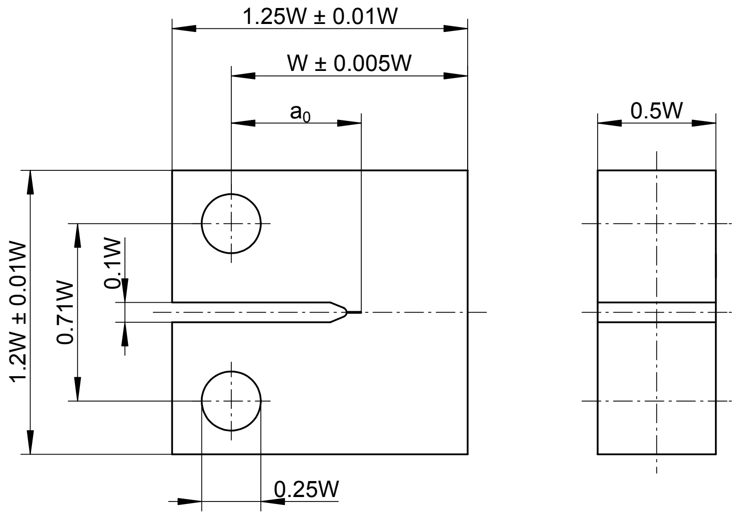


Fig. 2. Standard CT-Specimen

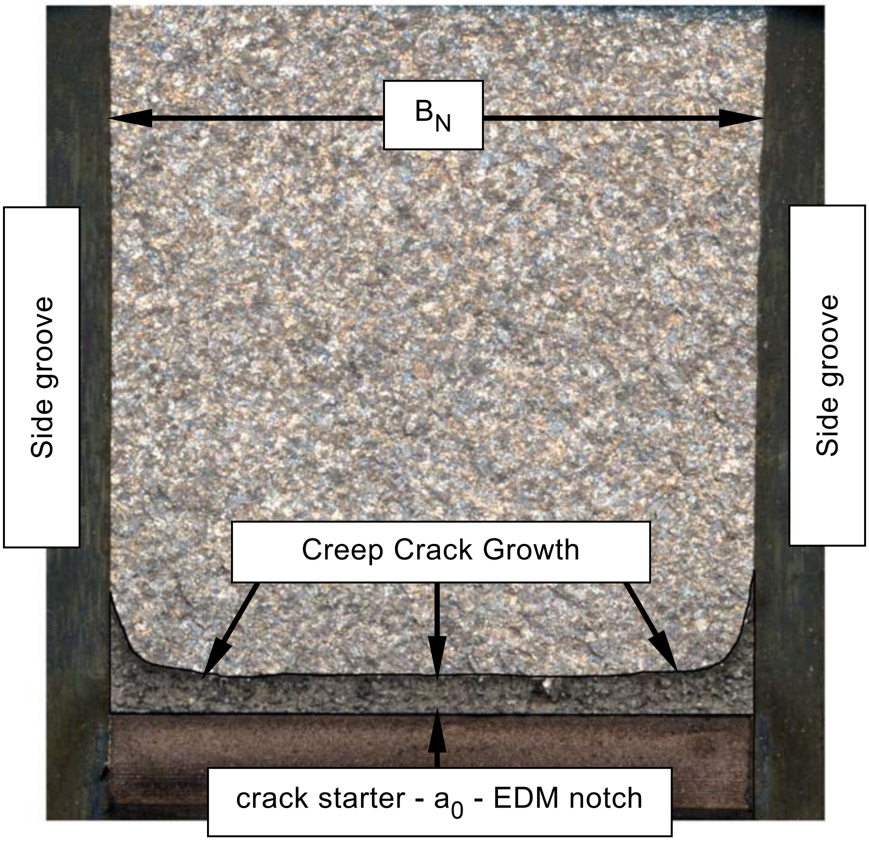


Fig. 3. Crack front on a side grooved CT-Specimen

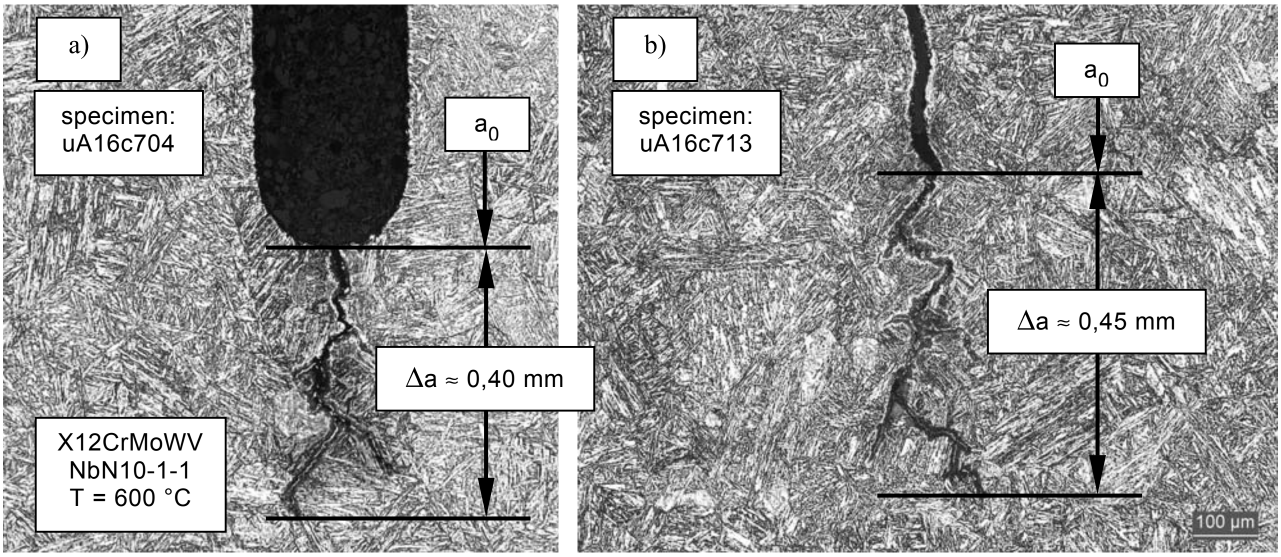


Fig. 4. Comparison of early CCG on Cs25-specimens with EDM notch (a) and fatigue pre-crack (b), 10CMV-steel, t = 1 344 h, 600 °C

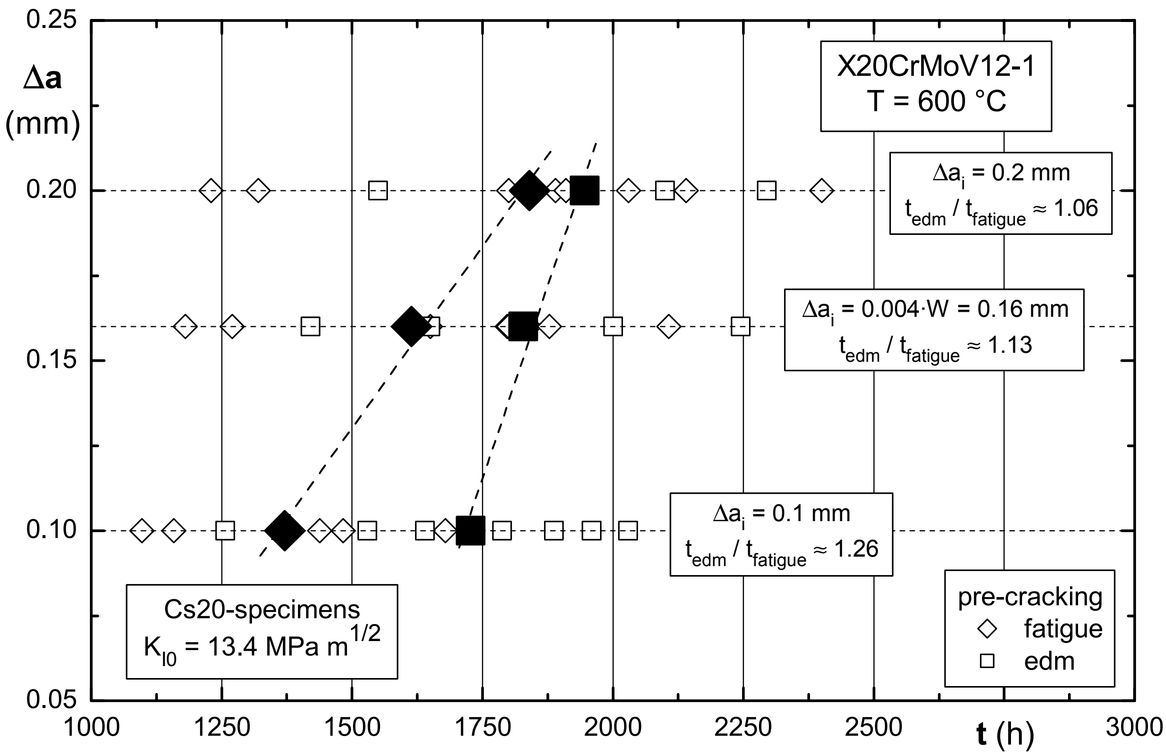
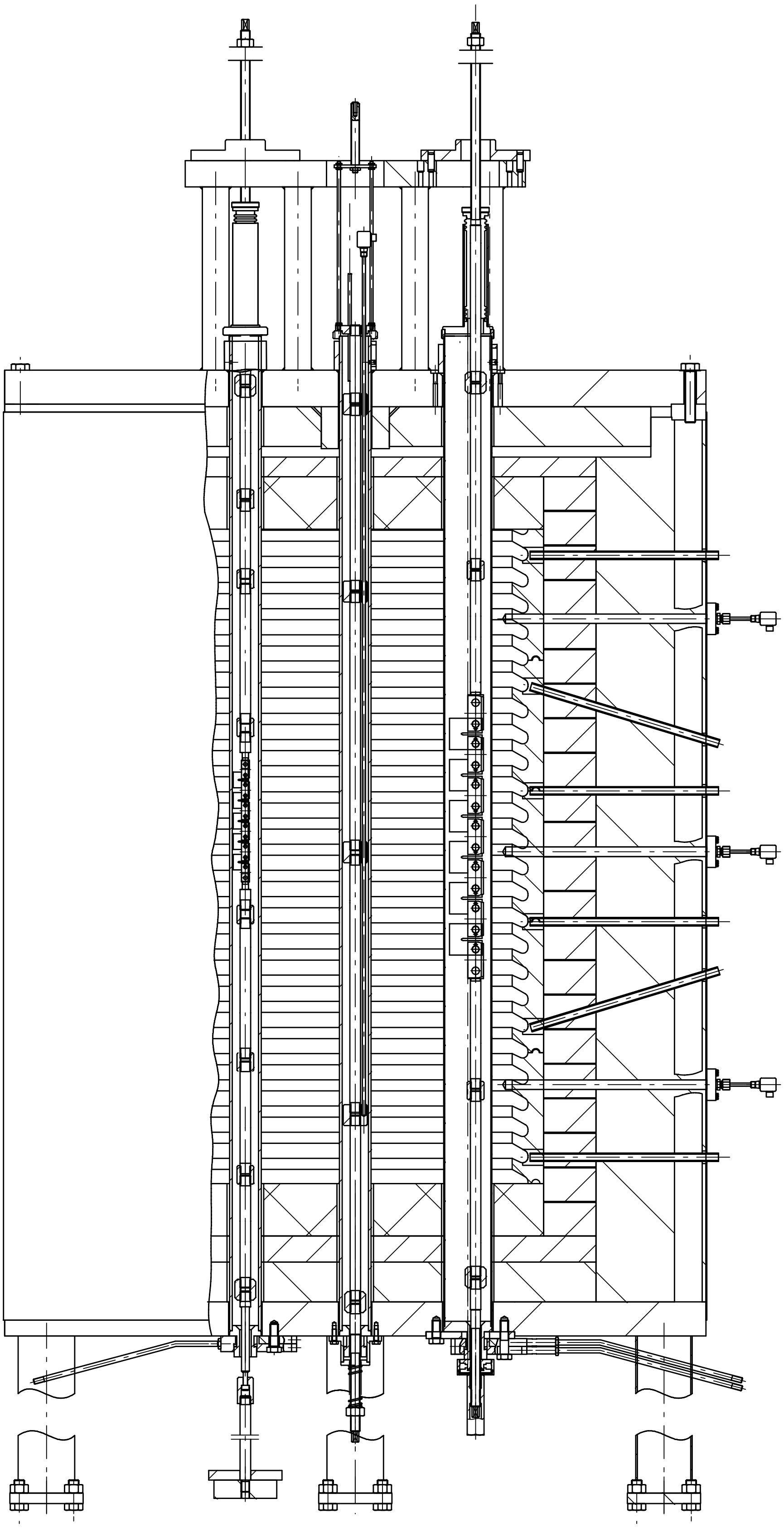


Fig. 5. Comparison of early CCG on Cs20-specimens with EDM notch and fatigue pre-crack, 12CMV-steel, 600 °C



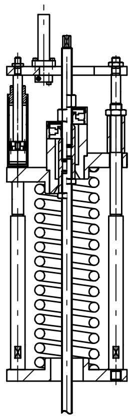


Fig. 6. Multi Specimen Machine, [7]

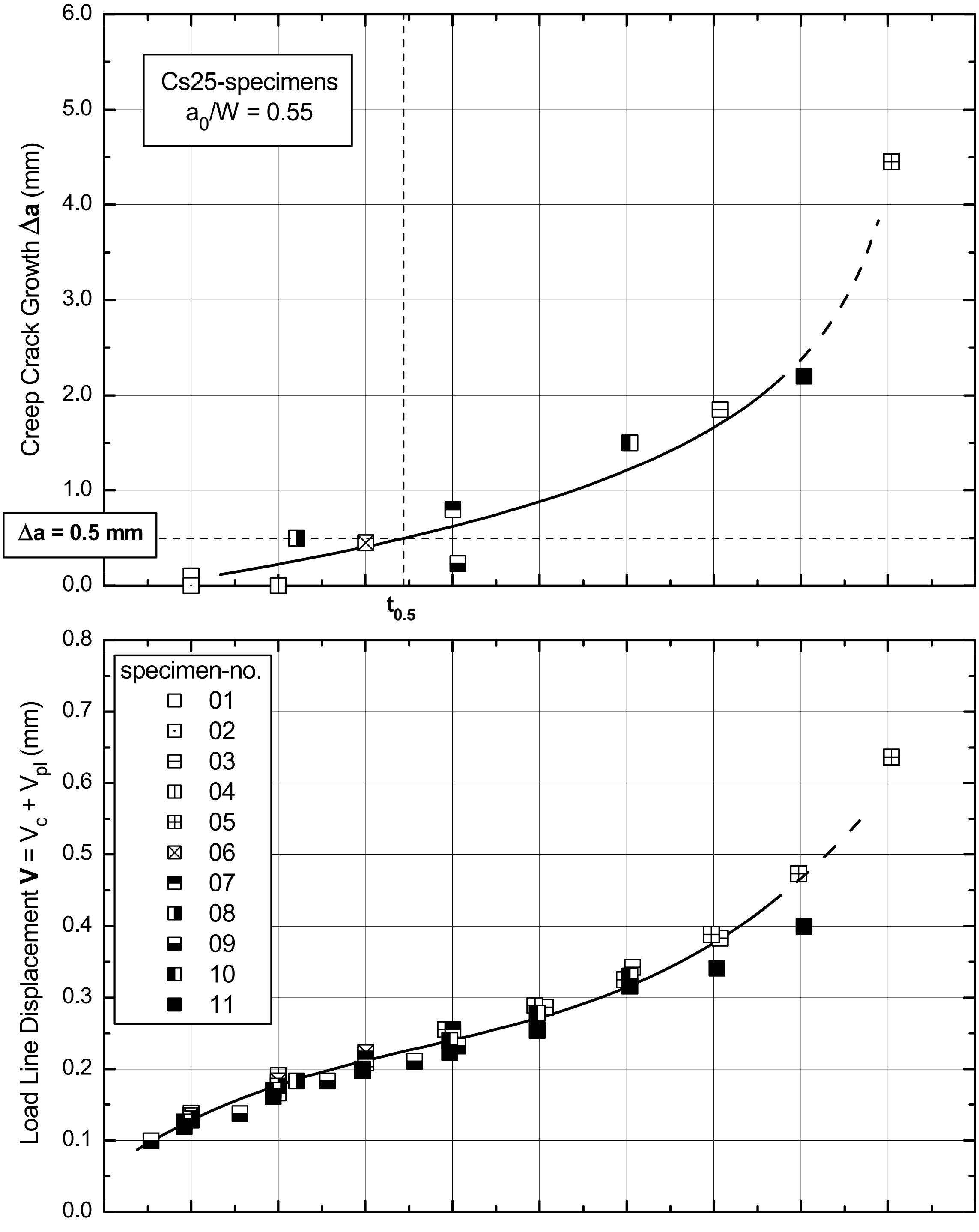


Fig. 7. Typical Presentation of Creep Crack Growth Test by using ITM, 1CMV-steel, 550 °C (IfWD)

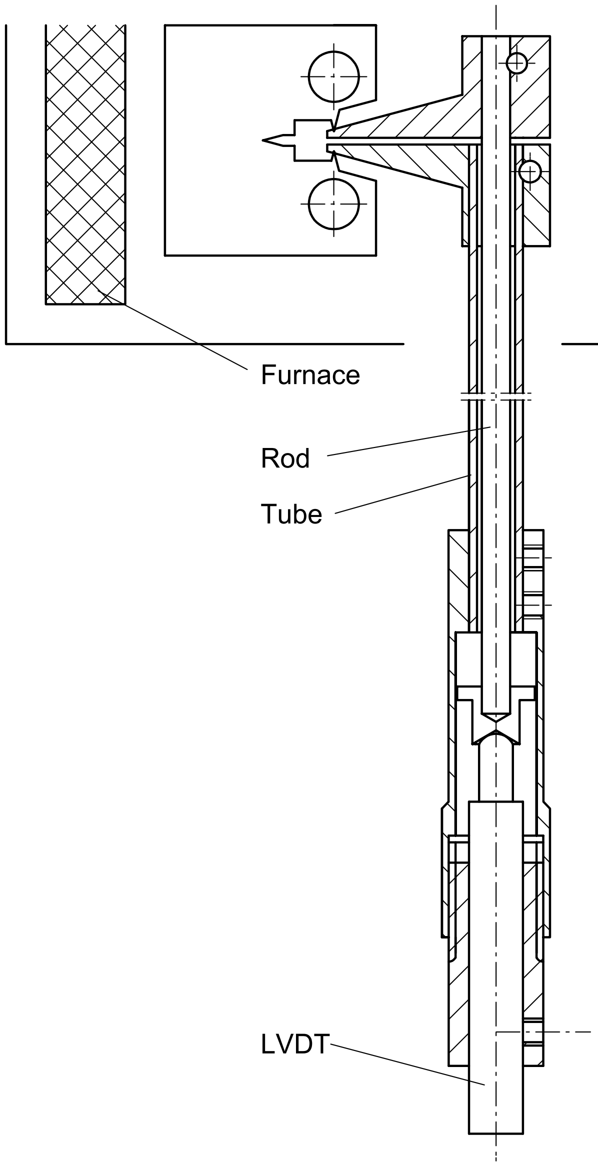
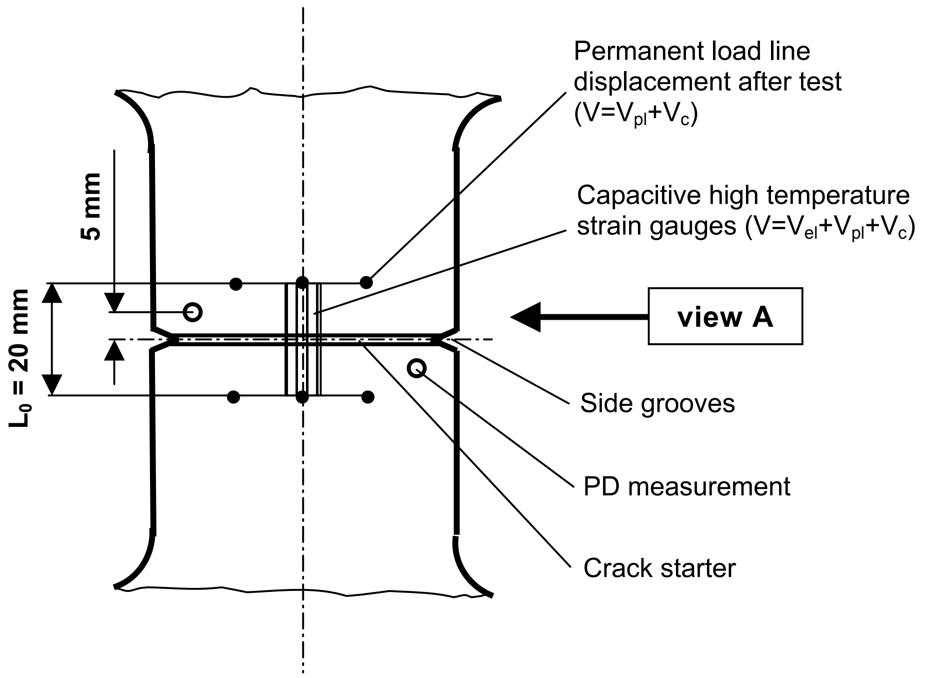


Fig. 8. Extensometer for load line deflection measurement on a CT-specimen



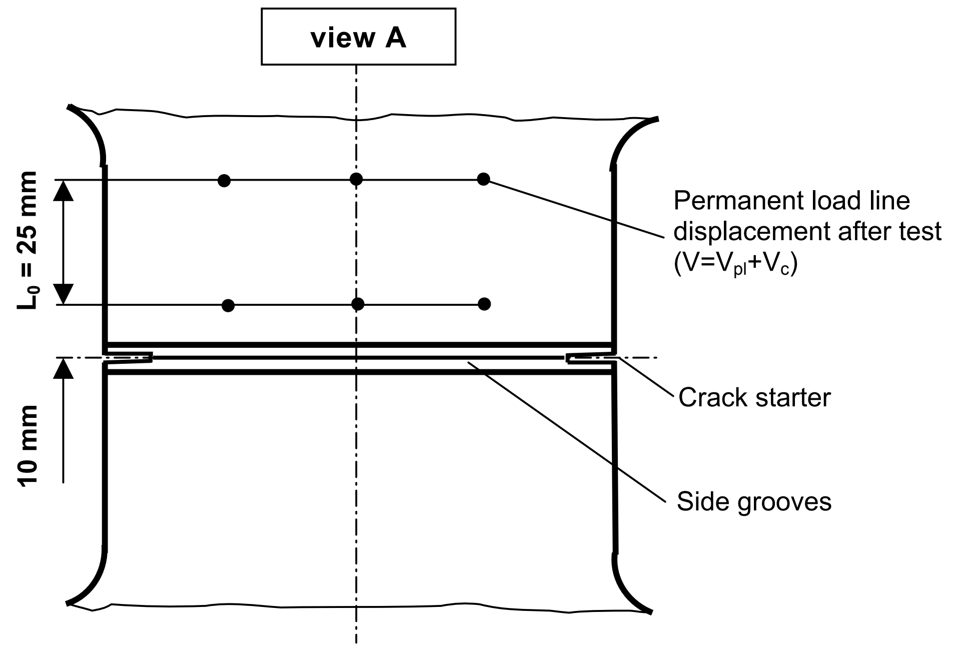


Fig. 9. Displacement (v) measurement using capacitive gauges for DENT60 specimens

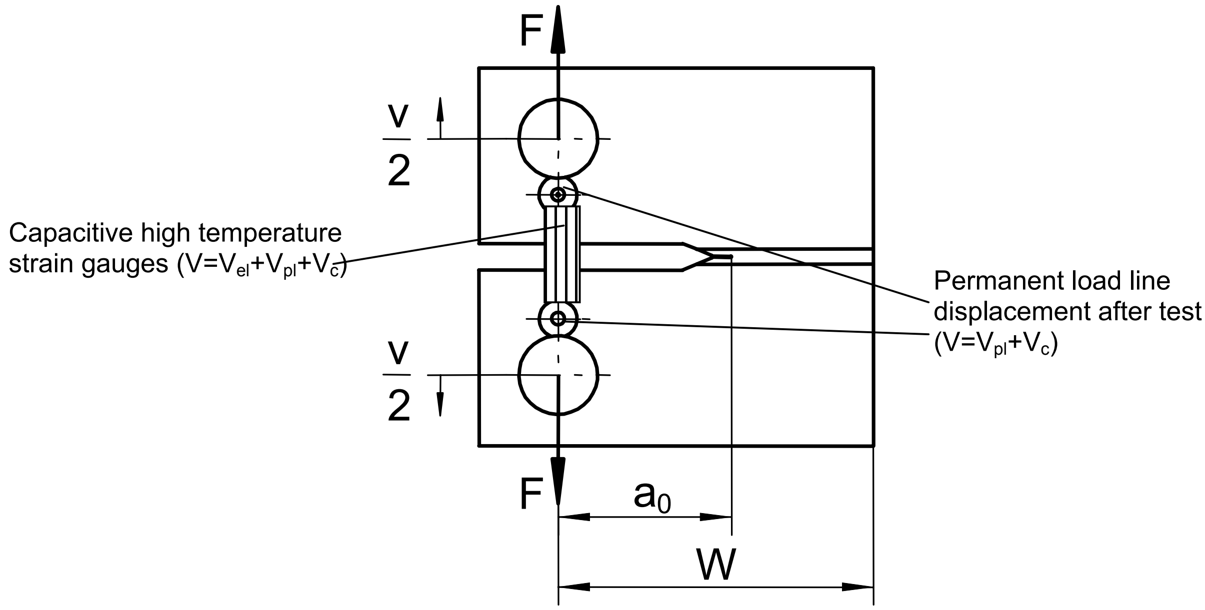


Fig. 10. Displacement (v) measurement using capacitive gauges for CT specimens

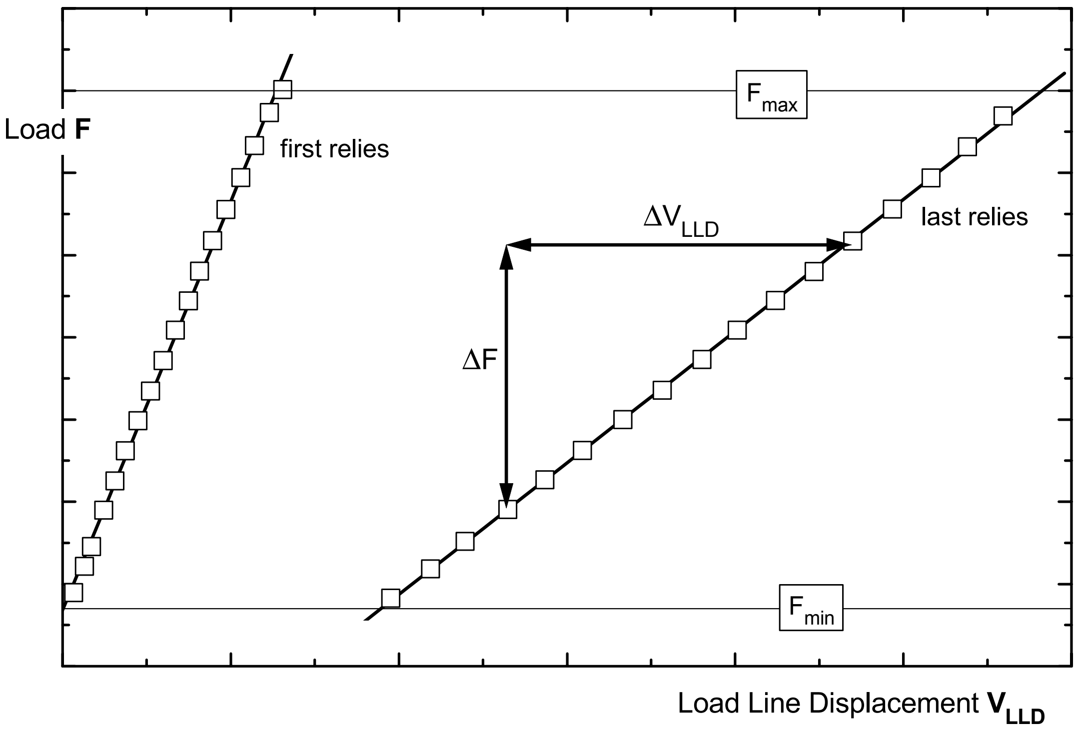


Fig. 11.

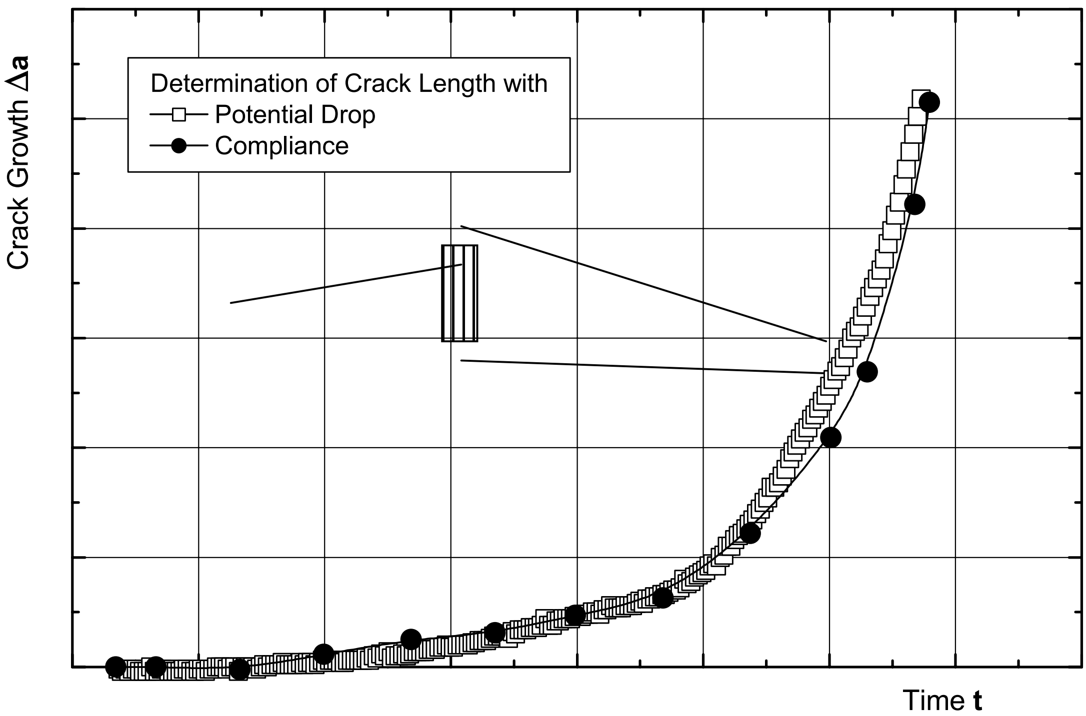


Fig. 12. Comparison of crack length measurement methods (Compliance & PD) /17/

ANNEX I Potential drop measurements

Basic Principle

AC-PD-System:

An AC current (1 A) with a frequency of approximately 460 Hz is fed to the specimen. Due to the skin effect, the current is flowing in a thin surface layer. If the crack opens, the current path is enlarged and the resistance increases, leading to a voltage drop due to the crack. It has been shown that the potential drop (≈ 1 mV) is proportional to crack length. One pair of electrodes is spot welded across the notch. The signal is input into a Lock-In-amplifier via transformer. The data are logged by a PC. Fig. 1 and 2 show typical results for the potential and the corresponding crack growth.

DC-PD-System:

The DC System is identical, except that:

- no skin effect is operating
- PD-signals are microvolts so needing strong amplfication
- No twisting is needed for current and PD wirings

A special version, called reversing DC Electrical PD method was developed in order to improve accuracy and eliminate e.m.f. potentials [1, 2].

Calibration

The proportionality factor between the physical crack length and the voltage drop can be determined after each test. For this purpose the specimen has to be broken under liquid nitrogen or by fatigue in order to evaluate the crack area. Due to the brittle fracture mode the fatigue/creep crack can be identified and measured in order to determine the aforementioned factor.

Attachment and Operation

By using the PD four electrical connections are required to be made to the specimens, two current and two voltage. It is important to obtain a good electrical contact between leads and specimen and it is usual to use spot welded or screwed connections in this respect. For a CT-specimen and ACPD the connections should be made as shown in Fig. 3. The current leads should be positioned such that the current path enclosed the crack. The voltage sensing leads should be positioned symmetrically about the crack site and between the current connections. The connections shown in Fig. 3 are used at IfW Darmstadt. A typical result of a creep crack test by using ITM with ACPD for crack length measuring and LVDT for Load Line Displacement measuring is shown in Fig. 4. For a CT-specimen and DCPD the connections should be made as shown in Fig. 5. If the time of crack initiation has to be determined, an alternative probe positioning e.g. like Fig. 6 can raise the sensitivity. A reference signal should be used to determine effects due to possible fluctuations due to temperature and other influences.

The PD record may be in one of four types as depicted in Fig. 7 of [3]. It depends on the material, loading and specimen geometry and size. The critical issue in PD measurements hence the determination of the CCI and CCG is determination of V_o that is particularly important for CCI. Therefore, V_o values are schematically depicted in Fig.2 proved applicable to a range of materials and specimen geometries [3].

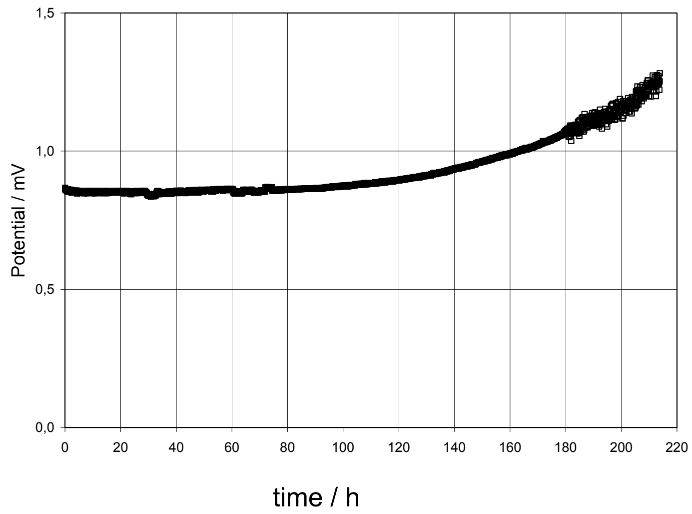


Fig. 1. Potential

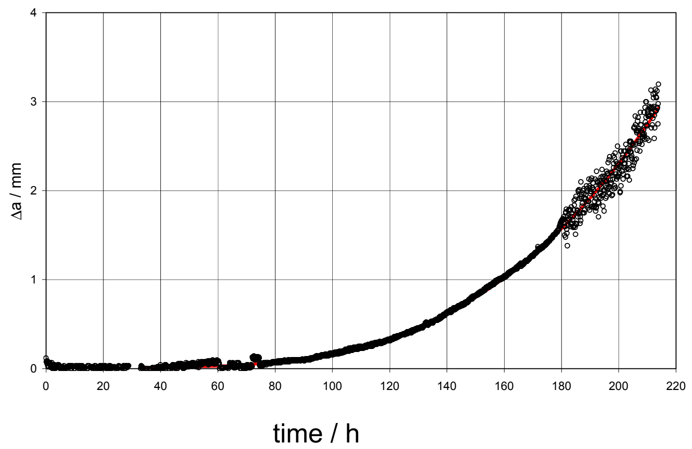


Fig. 2. Crack growth

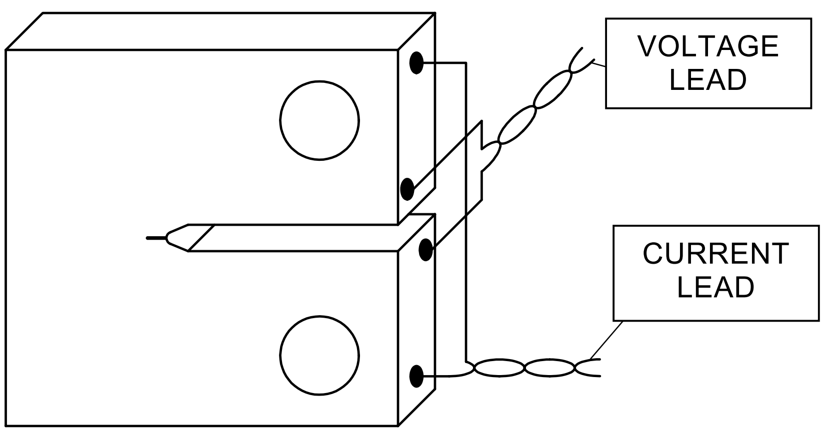


Fig. 3.
ACPD connection locations on a CT-specimen, IfWD

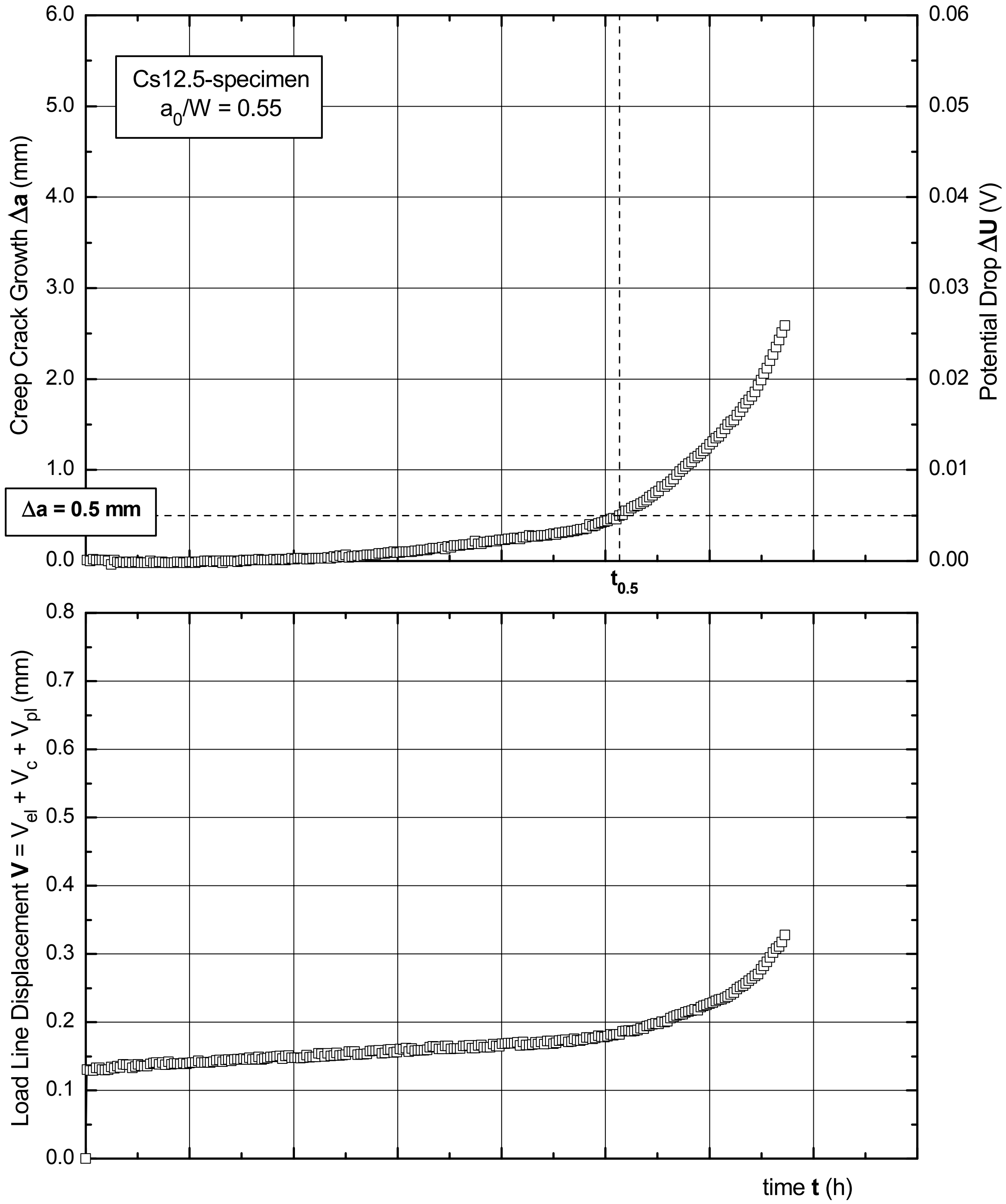


Fig. 4. Typical presentation of Creep Crack Growth Test by using CTM, crack length measured by ACPD, load line displacement measured by LVDT, Ni-base alloy, 600 °C, IfWD

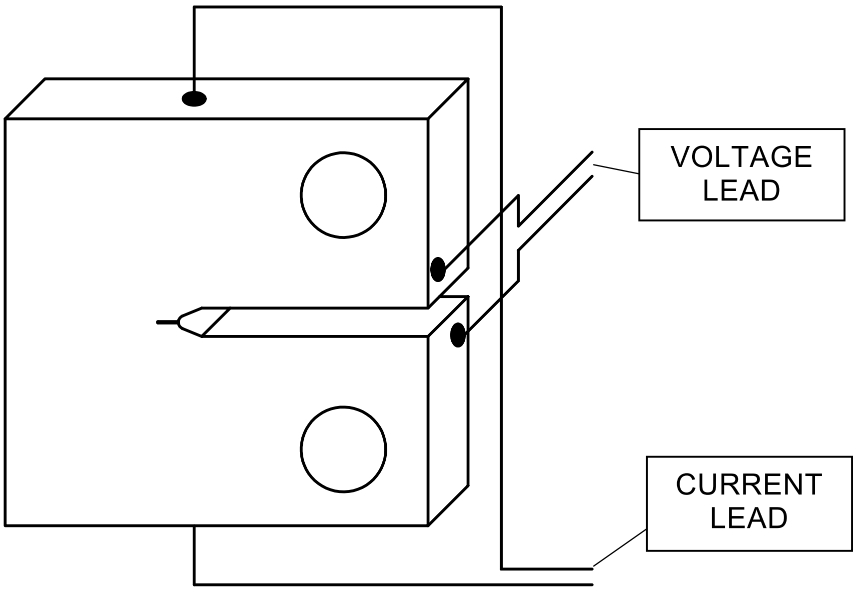


Fig. 5. DCPD connection (used for crack growth determination)

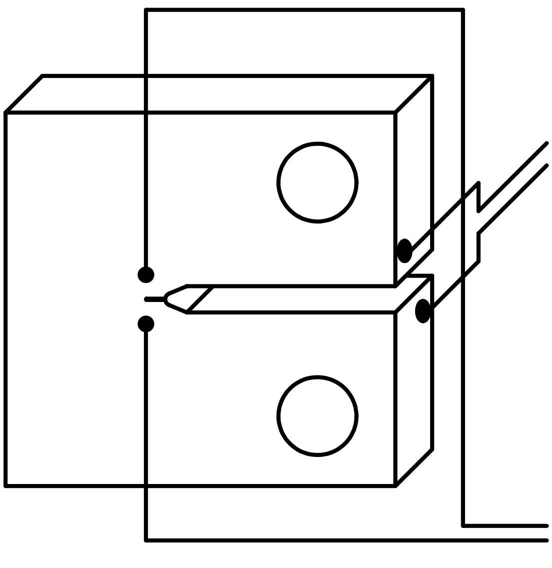


Figure 6: DCPD connection for determination of crack initiation

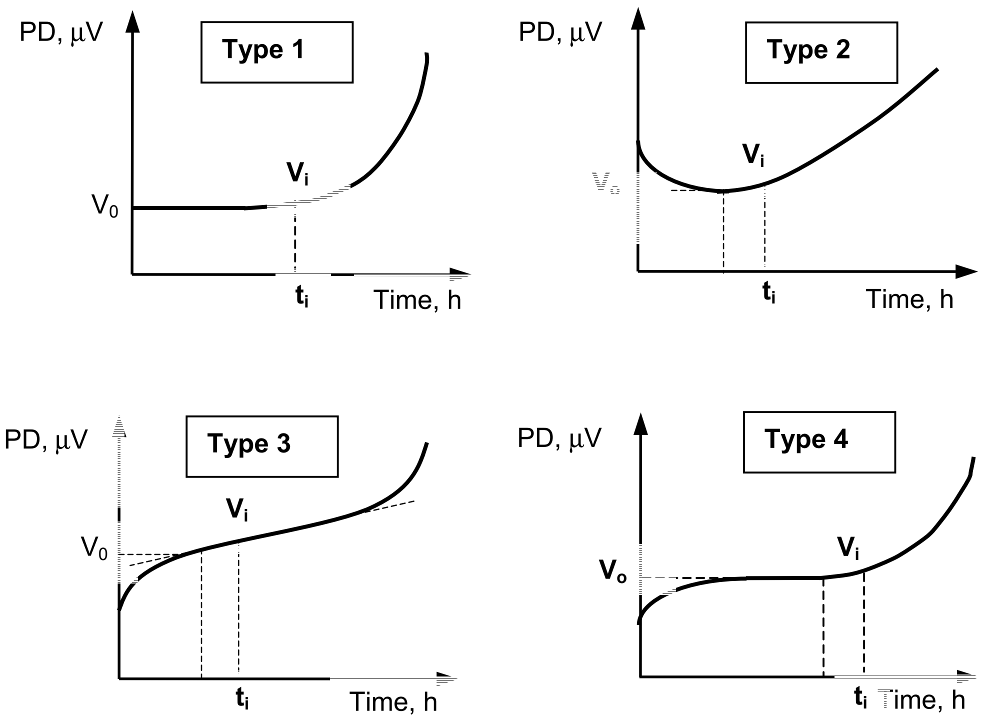


Figure 7: Types of PD records from testing various specimen geometries. (3)

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ANNEX 2 DESCRIPTION OF CREEP CRACK INITIATION BEHAVIOUR WITH DIFFERENT DEFINITIONS OF CREEP CRACK INITIATION LENGTH

F. Mueller (IfWD)

The creep crack initiation is defined by a technical creep crack initiation length $\Delta a_i = a_i - a_0$. The creep crack initiation length is dependent on material, ductility and grain size. It is possible to use a creep crack initiation length which is dependent on the geometry and size of specimens as $\Delta a_i = 0.004 \cdot W$ for CT- or $\Delta a_i = 0.01 \cdot W$ for DENT-specimens. Further it is possible to use a constant creep crack initiation length of $\Delta a_i = 0.2$ or 0.5 mm independent of geometry and size of specimens.

The needed creep crack initiation dates are obtained from the measured crack length vs. time curves (Fig. 1) and load line displacement vs. time curves (Fig. 2). From these curves and corresponding load information the creep crack initiation parameters are determined. Here only the parameter C* and the stress intensity factor K_I are considered for CT-specimens. The parameter C* can be determined approximately [Kie87]:

$$C^* = \dot{V}_c \cdot \frac{P}{B_n \cdot (W - a)} \cdot 2$$

with

$\dot{V}_c$ ... load line displacement rate due to creep alone,

B_n ... specimen net thickness,

W ... width,

a ... crack length,

P ... applied load.

The stress intensity factor is [Fet97]:

$$K_I = \frac{P}{\sqrt{B \cdot B_n \cdot W} \cdot (1 - a/W)^{3/2}} \cdot (2 + (a/W)) \cdot f(a/W)$$

with:

$$f(a/W) = 0{,}886 + 4{,}64 \cdot (a/W) - 13{,}32 \cdot (a/W)^2 + 14{,}72 \cdot (a/W)^3 - 5{,}6 \cdot (a/W)^4 \ .$$

In case of use of the above-mentioned parameters to the description of the creep crack initiation the dependences are represented in Figs. 3 and 4. The creep crack initiation take place for the creep crack length 0.2 mm earlier than for 0.5 mm. However, this difference is much greater for the K_I - representation than for the C* - representation. In use of the parameter C* to the description of the creep crack initiation it can happen that the results for 0.5 mm appear earlier than for 0.2 mm. Cause is the inadequate description of the creep behaviour in the early stage of creep. This phenomenon (so-called "Tail", [Lai98]) can be seen in Figs. 5 and 6. For Δa_i = 0.2 mm there is a greater C*-value than for Δa_i = 0.5 mm. Further the creep crack initiation occurs under scatter. For materials with high ductility (A_u > 10 %) it is useful to describe the creep crack initiation with the parameter C* for both crack extensions in a common diagram. For this case the lower scatter band limit must be used.

By using the creep toughness $K_{c\ mat}$ [Ecc04] to describe the creep crack initiation (Fig. 7) the creep crack initiation take place for the creep crack length 0.2 mm earlier than for 0.5 mm.

For a small scale creep region the recommended fracture mechanics parameter is C_t [Ast00]. There are only small differences (Fig. 8) in comparison to C*-parameter (Fig. 3).

To transfer the creep crack initiation results of small scale specimens to components it is important/needed to use large scale specimens (Fig. 9 and Fig. 10). In different investigations it was found that the creep crack initiation occurs later with large scale specimens rather than with small scale specimens [Ewa03]. This could be observed by using the C*-parameter as well as stress intensity factor K_I .

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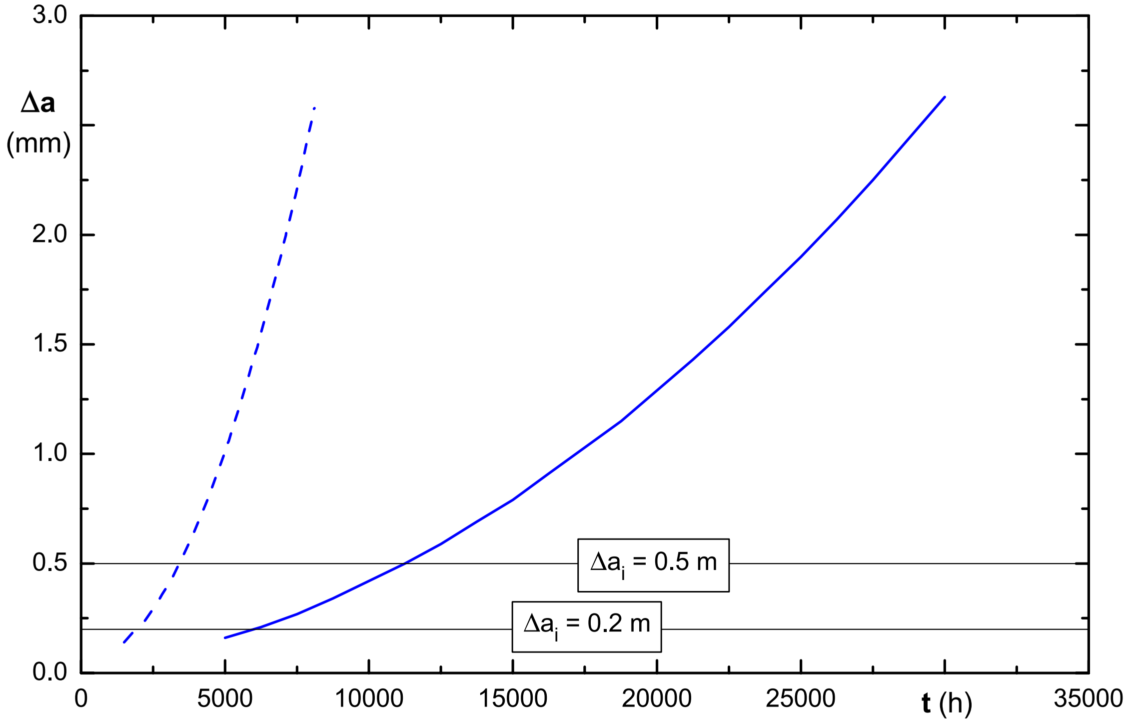

Fig. 1. Typical result of Creep Crack Growth Tests on CT-specimens, creep crack length vs. time, 1CMV @ 550 °C

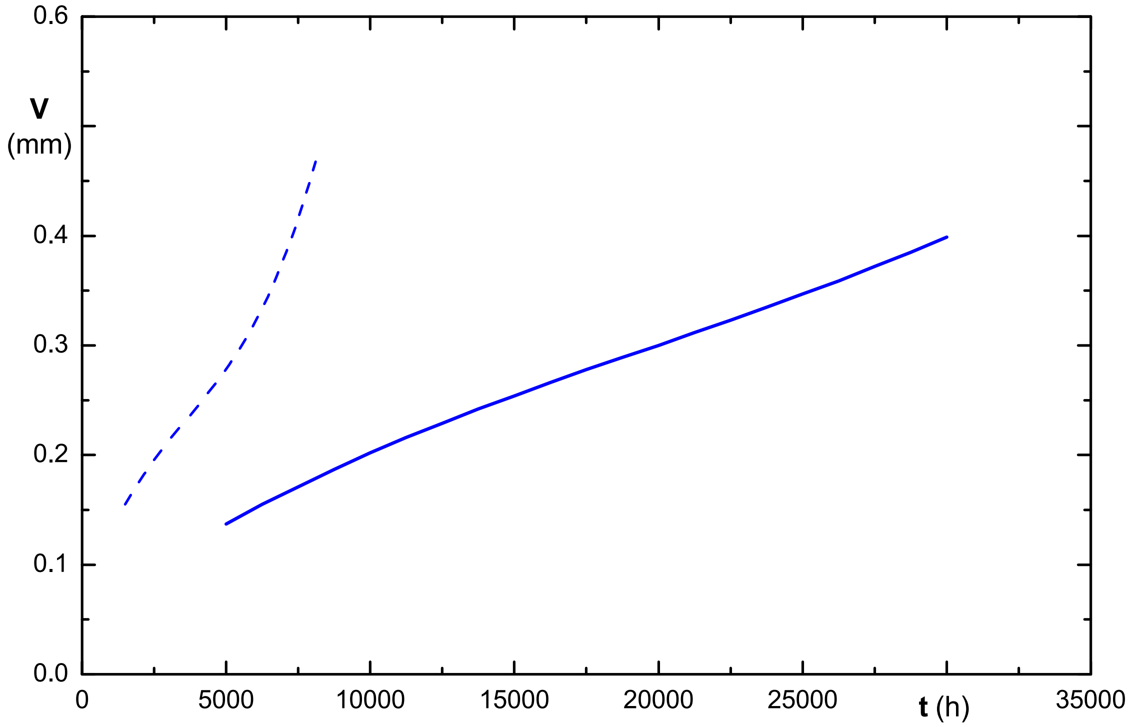

Fig. 2. Typical result of Creep Crack Growth Tests on CT-specimens, load line displacement vs. time, 1CMV @ 550 °C

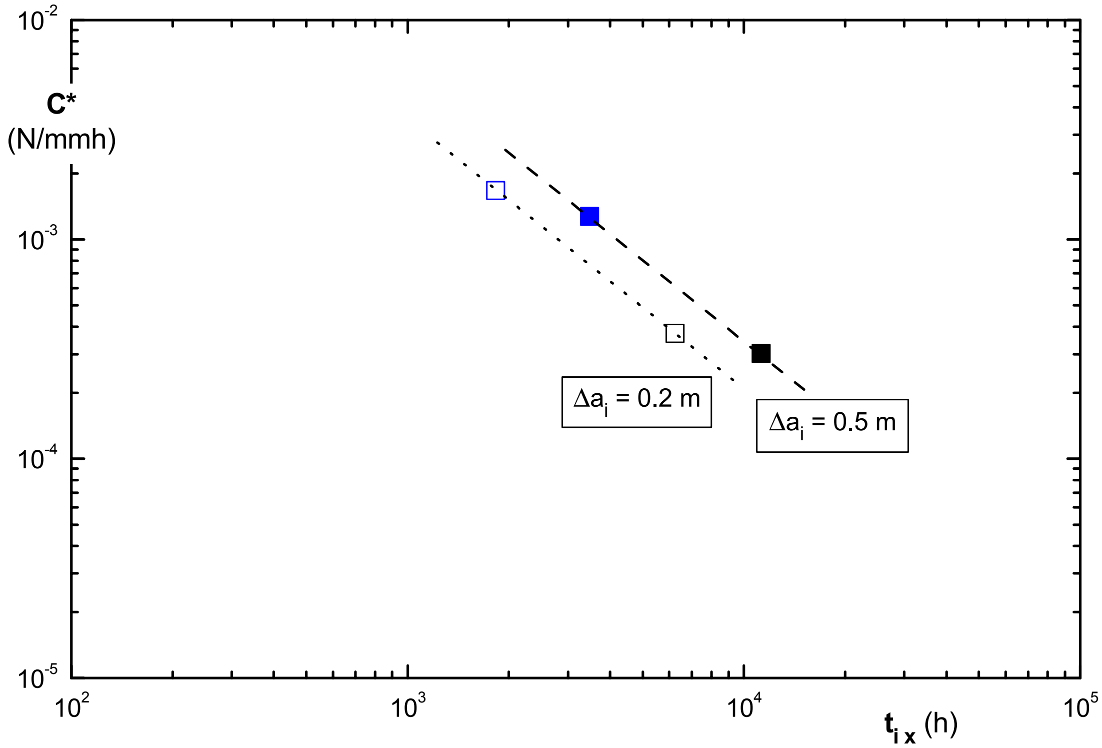

Fig. 3. Typical representation for description of creep crack initiation, Parameter C* vs. creep crack initiation time, 1CMV @ 550 °C

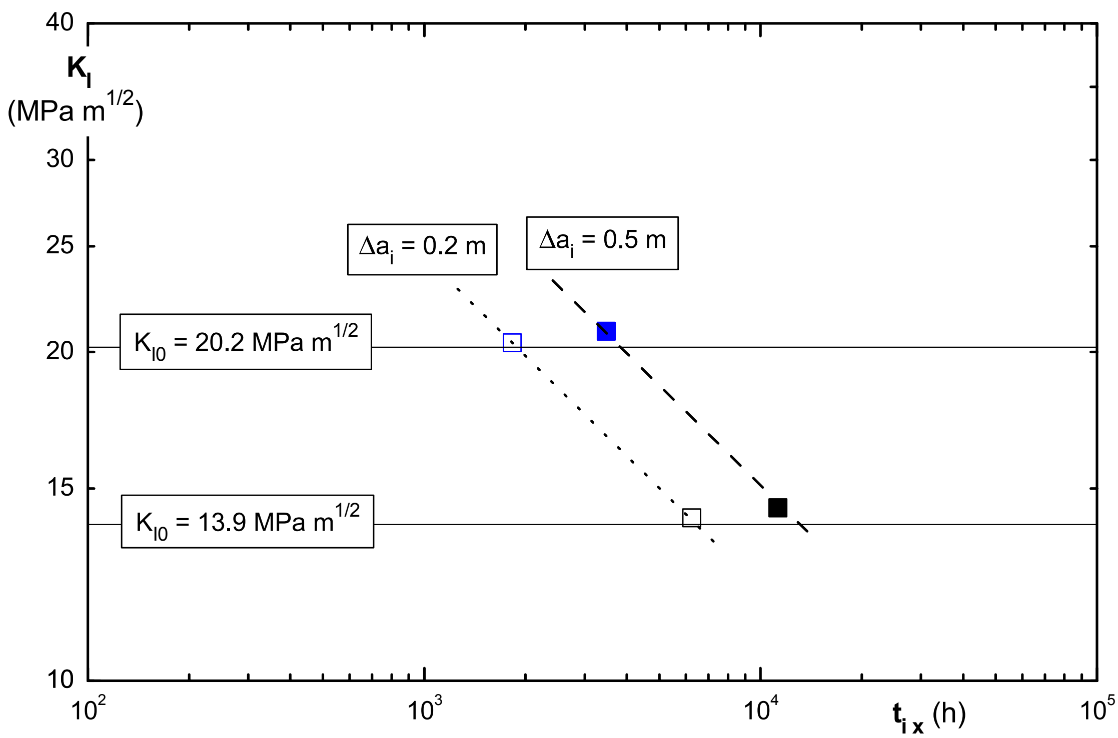

Fig. 4. Typical representation for description of creep crack initiation, stress intensity factor K_I vs. creep crack initiation time, 1CMV @ 550 °C

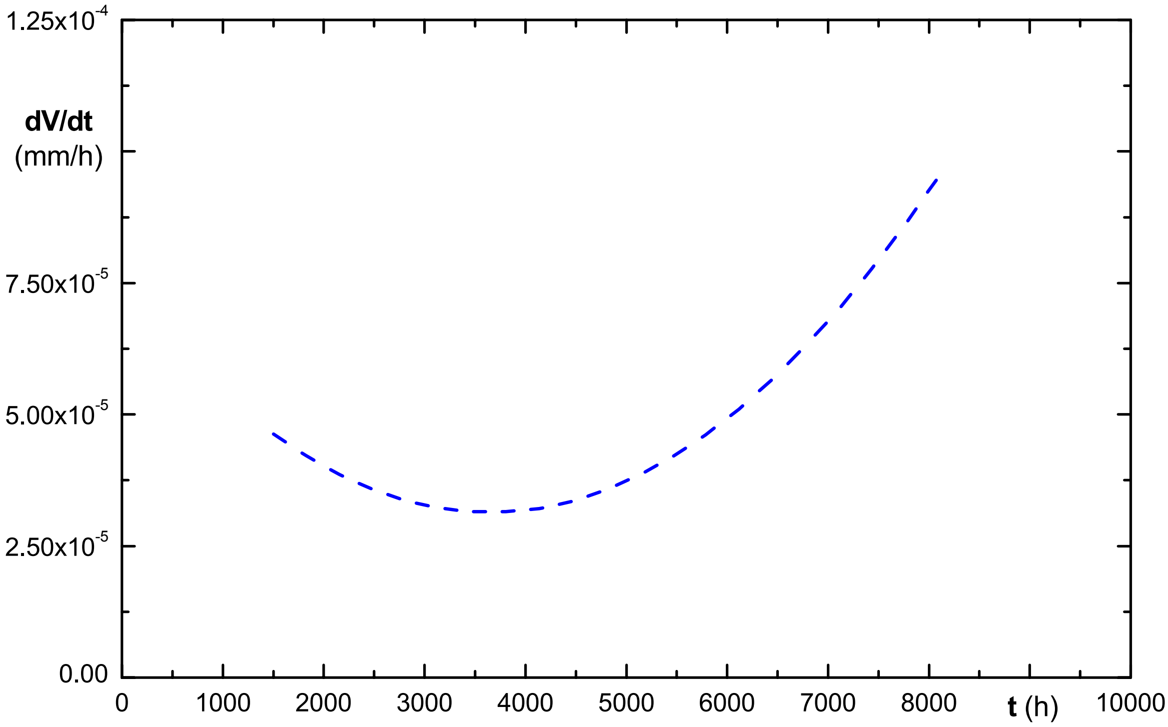

Fig. 5. Typical development of the load line displacement rate vs. time, 1CMV @ 550 °C

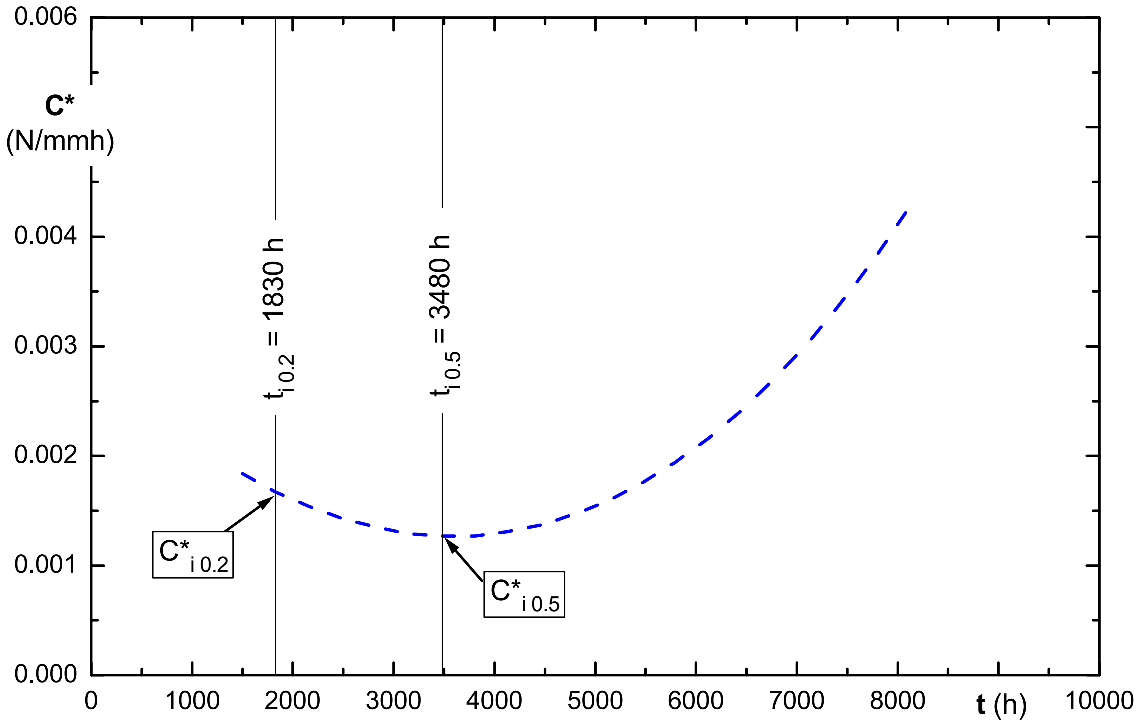

Fig. 6. Typical development of the parameter C* vs. time, 1CMV @ 550 °C

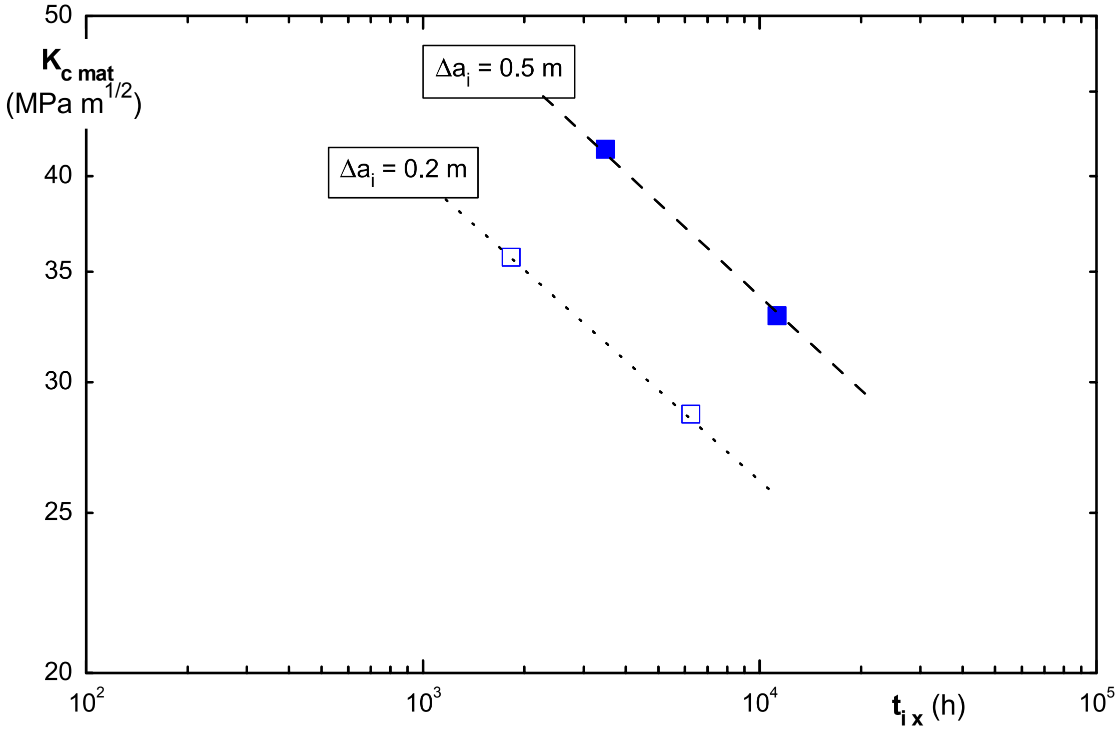

Fig. 7. Typical representation for description of creep crack initiation, creep toughness $K_{c\ mat}$ vs. creep crack initiation time, 1CMV @ 550 °C

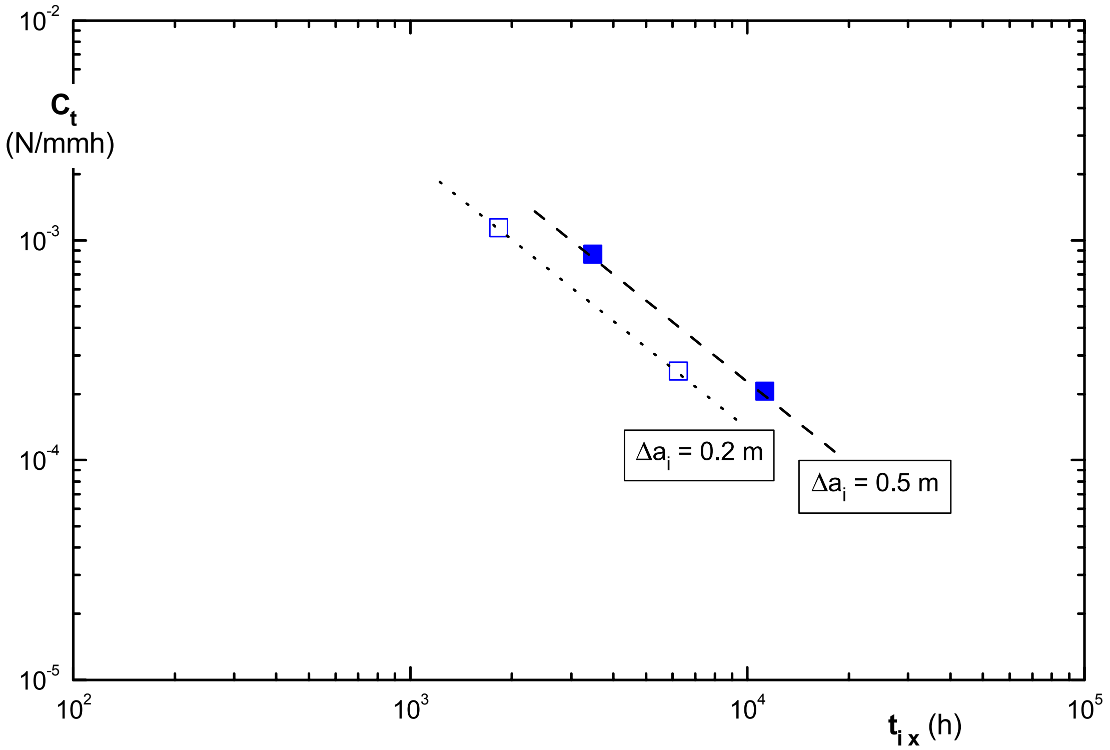

Fig. 8. Typical representation for description of creep crack initiation, Parameter C* vs. creep crack initiation time, 1CMV @ 550 °C

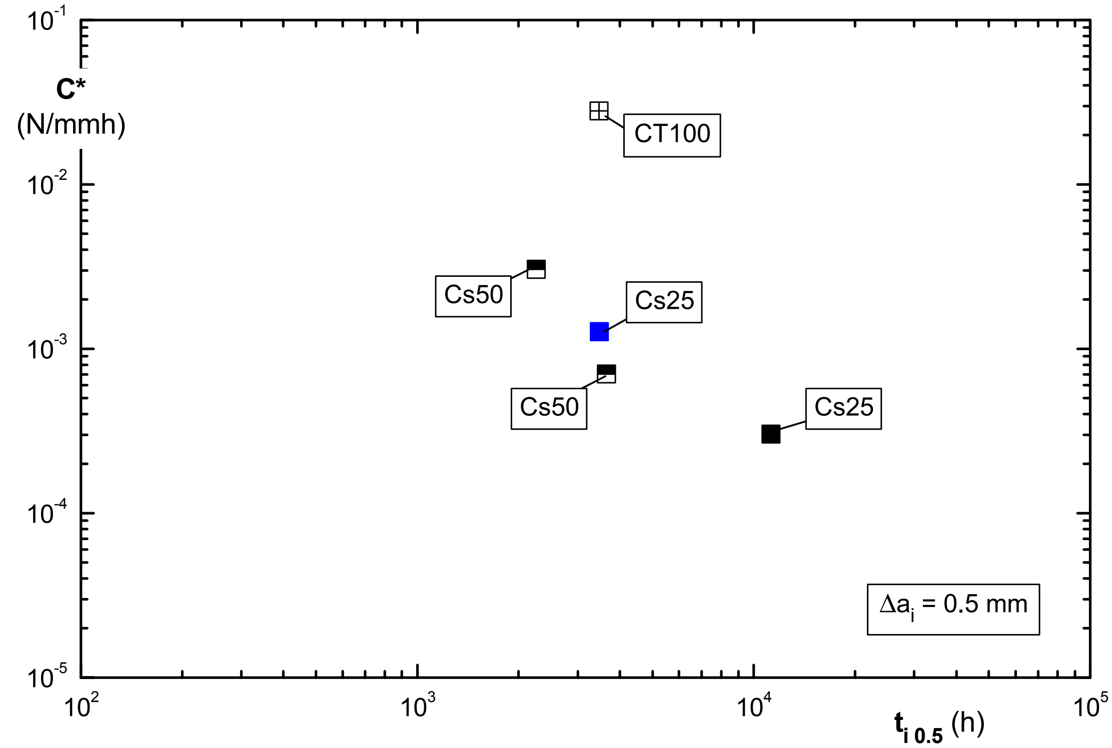

Fig. 9. Typical representation for description of creep crack initiation, Parameter C* vs. creep crack initiation time, 1CMV @ 550 °C

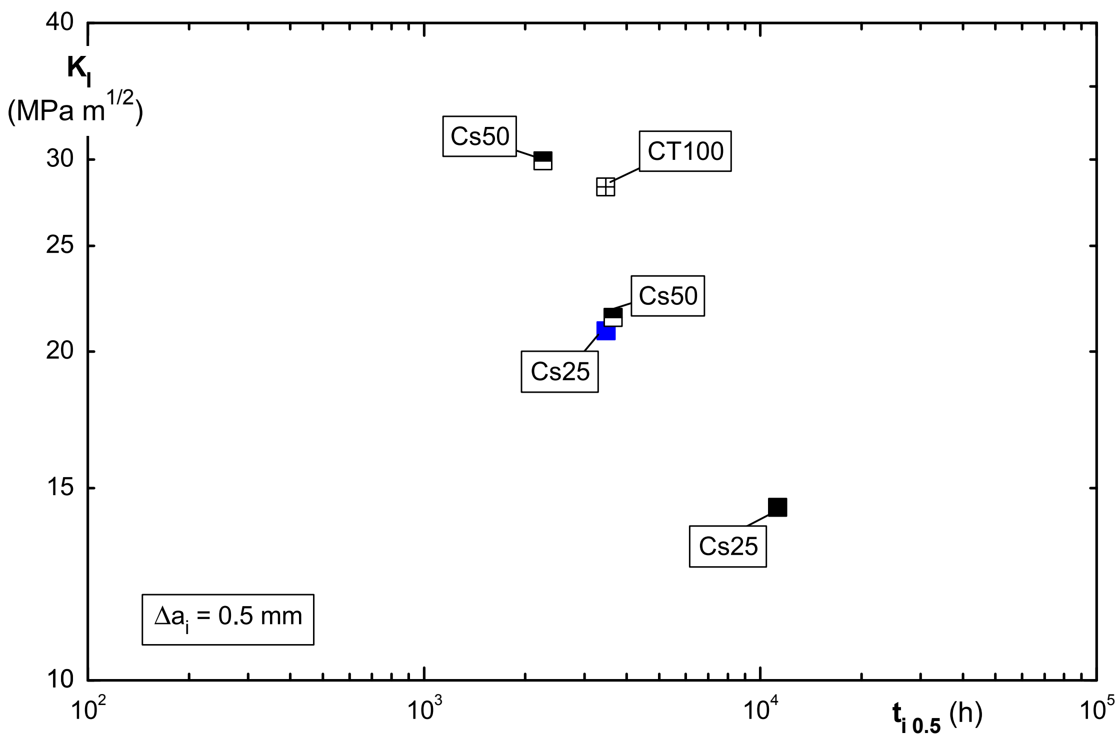

Fig. 10. Typical representation for description of creep crack initiation, stress intensity factor K_I vs. creep crack initiation time, 1CMV @ 550 °C

ANNEX 3

DETERMINATION OF CRITICAL CRACK TIP OPENING DISPLACMENT

S R Holdsworth, ALSTOM Power, UK

B Dogan, GKSS, Germany

Introduction

$\delta_{i,x}$ is the critical crack tip opening displacement responsible for the onset of creep crack propagation from a pre-existing defect, for a given crack initiation criterion (defined by *x*, e.g. $x = \Delta a = 0.5$mm) [1,2]. The parameter may be used in the following equation to determine crack initiation time.

$$t_{i,x} = \{\delta_{i,x}/C^*\}^{n/(n+1)}.D^{-1/n+1} - 1/\left[E.D.(\sigma_{ref})^{n-1}\right]$$

where $\dot{\varepsilon}_c = D.\sigma^n$ [1,3].

Two approaches are described to determine the crack tip opening displacement. Both rely to some extent on a knowledge of the position of the deformation hinge-point of the testpiece. In this respect, they are usually only practical up to the development of early crack extension since the position of the hinge-point will shift with increasing crack size. The first approach involves determination of the deformation hinge point and its use to analytically convert load line displacement to δ_c[4]. The second involves the direct measurement of δ_c by metallographic observation on the testpiece side-surfaces (e.g. [5]).

Hinge Point Method

In CCI/CCG tests, it is usual only to continuously monitor load line displacement. However a proven technique to determine $\delta_c(t)$ from $V_c(t)$ is available [4]. The approach requires for a series of hardness indent pairs to be placed either side of the notch and pre-crack of the virgin testpiece. The spacing between each pair of indents is measured prior to the start and at the end of a test interrupted prior to or ideally close to crack initiation. These measurements are used to establish the position of the hinge point with respect to the crack tip (i.e. $W - D' - a_o$)[1] and to confirm that the relationship between displacement and distance from the load line is linear (Fig. 1). The position of the hinge point is dependent on geometrical constraint and material ductility.

With this information, crack opening displacement is determined from the load line displacement (Fig. 2), i.e.

$$\delta_c(t) = V_c(t).\frac{(W - D' - a_o)}{(W - D')}$$

The critical crack tip opening displacement is determined from the $\delta_c(t)$ record at the onset of cracking, as defined by the crack initiation criterion, *x*.

[1] *D*' is distance of hinge point from back face in a CT testpiece. Other terminology is as given in Volume 2 Part IV

Metallographic Observation

The alternative approach is to measure δ_c directly by metallographic observation on the testpiece side-surfaces. The application of this procedure for off-line inspection during test is only possible with testpieces without side grooves.[2] After unloading and withdrawal from the furnace, one (or both) testpiece side-face(s) is locally ground and polished to a ≤6μm finish. The opening at the crack tip is then measured optically (e.g. Fig. 3).

In order to minimise subjectivity, the measurement of δ is made a standard distance from the origin of the radius of curvature formed by the initial crack opening on loading. The standard measurement distance is determined by constructing lines from the origin of the radius of curvature at 45° to the centre line through the crack (Fig. 3).

Practical Considerations

The two approaches are complementary and are often used in combination. For example, δ_c values determined by the Hinge Point method can be verified by metallographic observation during post test inspection. At this stage, the measurement can be made on a mid-plane section through the crack if the testpiece is side-grooved.

References

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[2] Post test, measurements by metallographic observation can be made on mid-plane sections of side-grooved testpieces

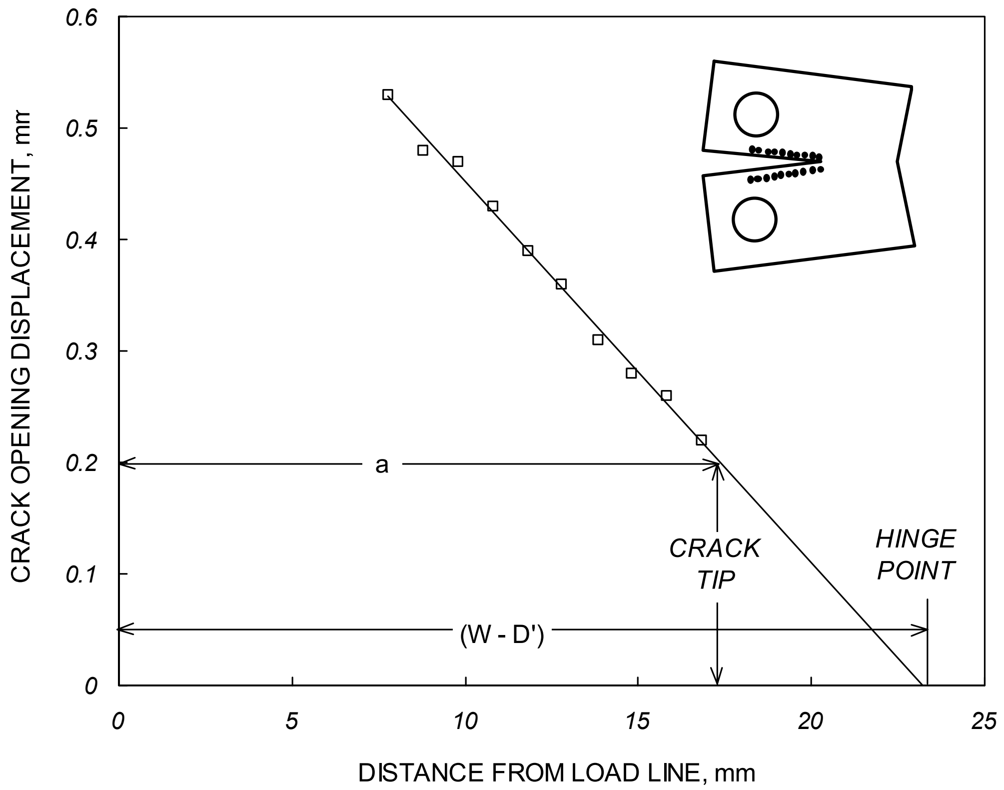

Fig. 1 Variation of crack opening displacement with distance from the load line

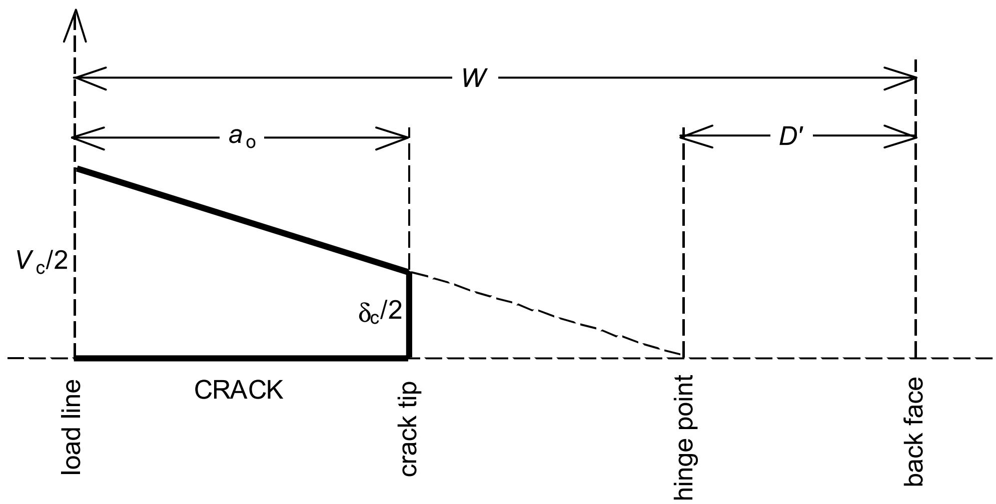

Fig. 2 Dimensional relationship between δ_c and V_c

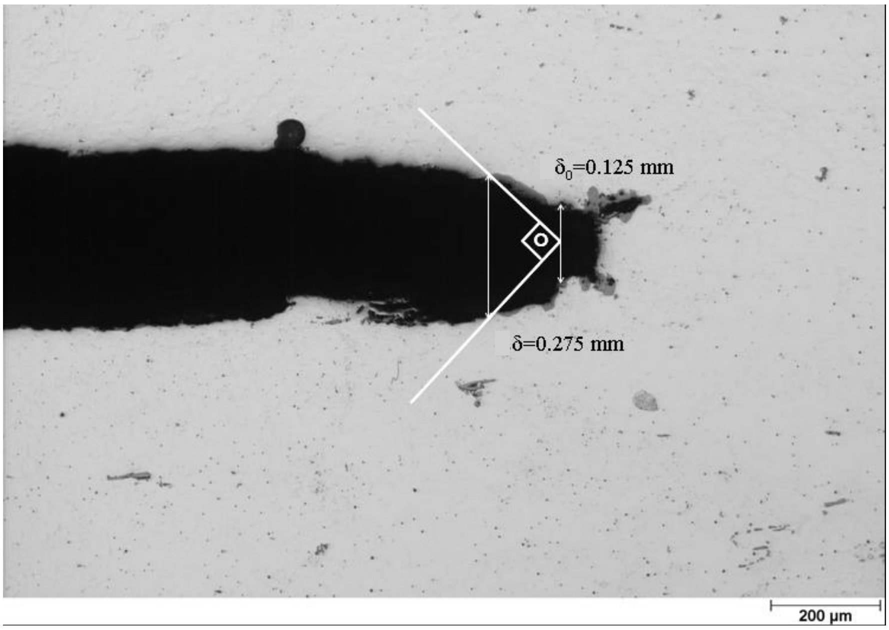

Fig. 3 Metallographic measurement of δ

ANNEX 4 Determination of K^c_{mat}

Dave Dean, British Energy, UK

A central feature of the TDFAD approach is the definition of an appropriate creep toughness which, when used in conjunction with the failure assessment diagram, ensures that crack growth in the assessment period is less than a value Δa. Creep toughness values may be estimated indirectly from conventional creep crack initiation and growth data or evaluated directly from experimental load versus displacement information [A4.1]. This section describes the latter direct approach for evaluating creep toughness values.

Direct approaches for determining creep toughness based on experimental load-displacement data can be based on methods used to derive critical J-integral and hence the material toughness, K_{mat}, given in low temperature fracture toughness standards [A4.3-5]. Consider a load-controlled creep crack growth test conducted on a standard compact tension (CT) specimen resulting in a typical load-displacement trace of the form shown in Fig. A4.1. If it is assumed that the amount of crack growth in the test, Δa, is small, the total displacement, V, may be conveniently partitioned into elastic, plastic and creep components, denoted V_e, V_p and V_c, respectively, where

$$V = V_e + V_p + V_c \tag{A4.1}$$

Similarly, the total area under the load-displacement curve, U_T, may be conveniently partitioned into elastic, plastic and creep components, denoted U_e, U_p and U_c respectively where

$$U_T = U_e + U_p + U_c \tag{A4.2}$$

The ESIS fracture toughness testing procedure [A4.3] evaluates experimental total J values, U_T, using the following relationship based on the total area under the load-displacement curve

$$J_T = \frac{\eta \cdot U_T}{B_n \cdot (W - a_0)} \tag{A4.3}$$

where W is the specimen width, a_0 is the initial crack length, B_n is the net specimen thickness and

$$\eta = 2 + 0.522 \cdot (1 - a_0/W) \tag{A4.4}$$

for CT specimens.

The British Standard [A4.4] and ASTM [A4.5] fracture toughness testing procedures adopt an alternative approach for estimating the elastic J value, J_e. This results in the following modified expression for experimental total J values

$$J_T = \frac{K^2}{E'} + \frac{\eta \cdot (U_T - U_e)}{B_n \cdot (W - a_0)} \tag{A4.5}$$

where K is the stress intensity factor and $E' = E$ for plane stress and $E' = E/(1-\nu^2)$ for plane strain conditions.

Values of creep toughness, K^c_{mat}, may then be derived from creep crack growth tests as a function of crack growth increment, Δa, using

$$K^{c}_{mat} = \sqrt{E' \cdot J_T} \tag{A4.6}$$

in conjunction with equation (A4.3) or (A4.5). Thus,

$$K^{c}_{mat} = \left[\frac{E' \cdot \eta \cdot U_T}{B_n \cdot (W - a_0)} \right]^{1/2} \tag{A4.7}$$

based on the ESIS fracture toughness testing procedure [A4.3] method for evaluating J_T.

However, it is considered that the British Standard [A4.4] and ASTM [A4.5] approaches for deriving the elastic contribution to J based on K^2/E' are more robust than the ESIS approach based on U_e, which implicitly assumes that the initial portion of the load-displacement curve accurately reflects the elastic compliance of the specimen. The following expression for direct evaluation of creep toughness from experimental load-displacement information has therefore been proposed

$$K^{c}_{mat} = \left[K^2 + \frac{E' \cdot \eta}{B_n \cdot (W - a_0)} \cdot \left(U_p + \frac{n}{n+1} \cdot U_c \right) \right]^{1/2} \tag{A4.8}$$

where the factor n/(n+1) is required for consistency with standard creep crack growth testing procedures [A2.11] as U_c is defined here as

$$U_c = P \cdot \Delta_c \tag{A4.9}$$

where P is the applied load. Therefore equation (A4.6) can alternatively be expressed as

$$K^{c}_{mat} = \left[K^2 + \frac{E' \cdot \eta \cdot U_p}{B_n \cdot (W - a_0)} + \left(\frac{n}{n+1} \cdot \frac{E' \cdot \eta \cdot P \cdot \Delta_c}{B_n \cdot (W - a_0)} \right) \right]^{1/2} \tag{A4.10}$$

which only differs from the equation (A8.4) of Appendix A8 of R5 Volume 4 [A4.1] in the use of $E' = E/(1-\nu^2)$ rather than E and the inclusion of an additional second term in equation (A4.10) to incorporate the effects of plasticity during loading. Equation (A4.10) is the recommended expression for detemining the creep toughness, K^{c}_{mat}. In order to accurately determine creep toughness values experimentally, it is necessary to monitor load-line displacement during the loading phase of tests to allow U_p to be evaluated.

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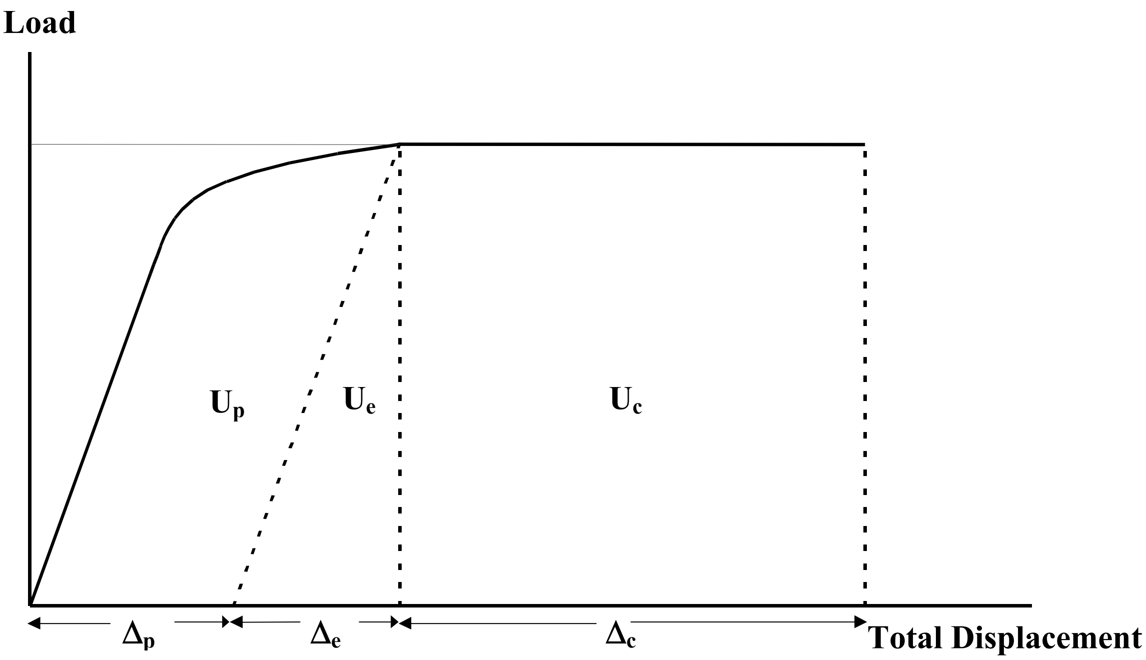

Figure A4.1 Schematic Load-Displacement Behaviour for a Constant Load Creep Crack Growth Test

ANNEX 5: Validity criteria for the Parameter C*

J. Granacher, T.S. Mao, F. Mueller, IfW Darmstadt, Germany

Before a crack starts to grow, its tip is blunted by creep flow of the surrounding material. For the computation of the parameter C* in specimens the crack is treated mathematically as if it was sharp. Following Wang, Shih & Needleman (1990), the validity of the parameter C* is restricted to the crack tip opening displacement δ_t which is small compared to the specimen geometry ($\delta_t \leq a/50$).

In a sensitivity study the parameter C* was determined on two different specimen types (CT and DENT) for three crack tip radii (r_0 = 0.0 mm, r_0 = 0.1 mm "as eroded crack start notch" and r_0 = 0.2 mm "as eroded and blunted crack notch") with the program ABAQUS. Further the FE-calculations were performed for a crack start notch r_0 = 0.1 mm and a technical crack initiation length as well as for a crack start notch r_0 = 0.2 mm and a technical crack initiation length. The results of the FE-calculations are influenced by the crack tip radii (Figure 1) and the integration path (Figure 2). This influence disappears outside the zone $4 \cdot r_0$. The C_{FE}*-values are path independent for the eroded crack start notch (r_0 = 0.1 mm and r_0 = 0.2 mm) with the technical crack initiation length. They agree well to the C_{FE}*-values calculated for r_0 = 0.0 mm, i.e., the parameter C* is capable to describe stress and strain fields in the vicinity of the crack tip after a technical crack initiation.

Furthermore, this study yielded the result that the crack tip opening displacement δ_t of DENT-specimens is much smaller than the load line displacement v. In a usual range of a_0/W = 0.2 and 0.4 it can be assumed that $\delta_t \leq v/2.2$ for DENT9-specimens (Figure 3), $\delta_t \leq v/2.4$ for DENT18-specimens (Figure 4) and $\delta_t \leq v/2.7$ for DENT60-specimens(Figure 5).

The following validity criteria for the parameter C* have been determined:

$\delta_t \leq a/50$ with

$\delta_t = v/[1+3a/(W-a)]$ for CT or Cs- specimens,

$\delta_t = v/2,2$ for DENT9 or Ds9 - specimens,

$\delta_t = v/2,4$ for DENT18 or Ds18 - specimens,

$\delta_t = v/2,7$ for DENT60 or Ds60 - specimens.

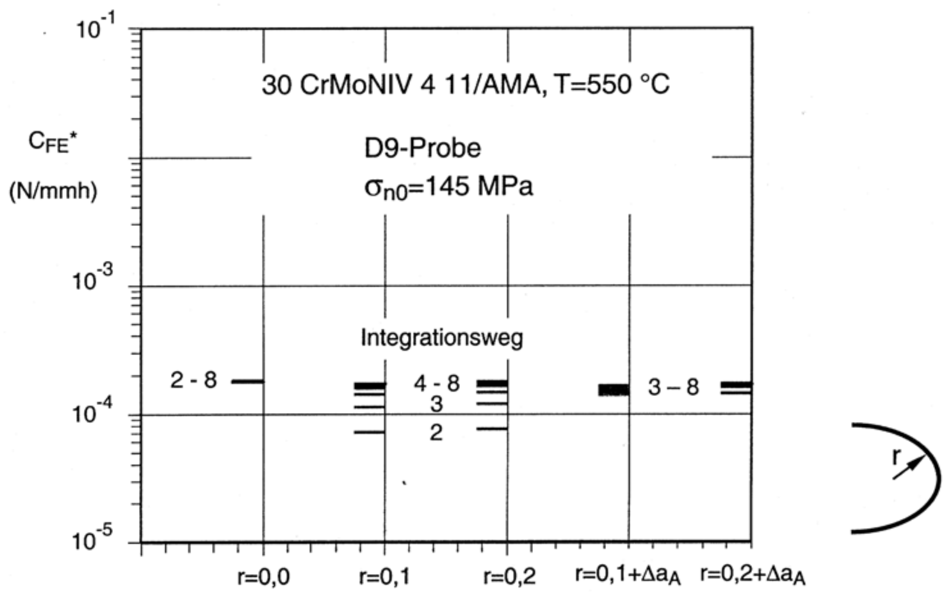

Figure 1. C_{FE}*-values calculated for different crack tip radii

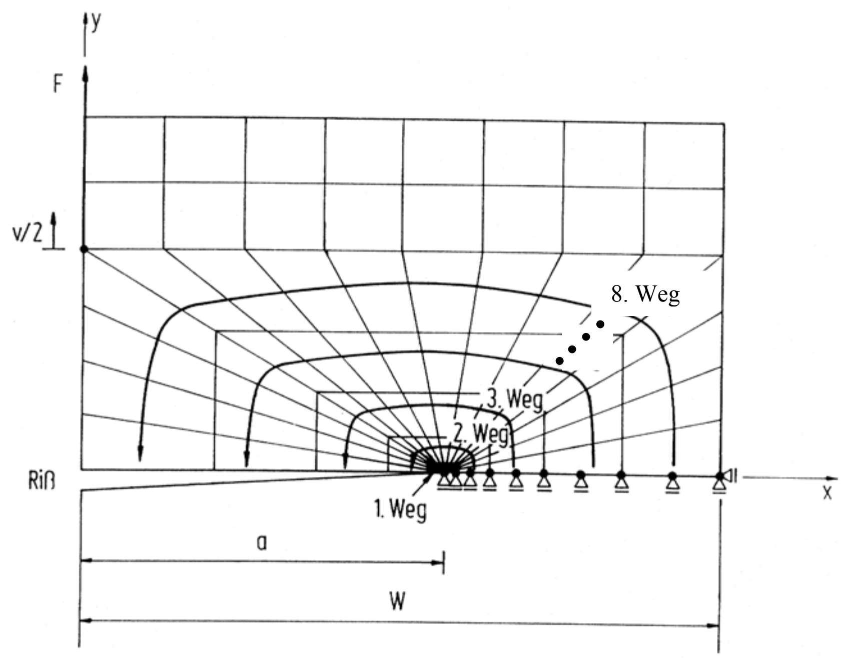

Figure 2. 2D-discretization of a CT-specimen with 8 integration paths

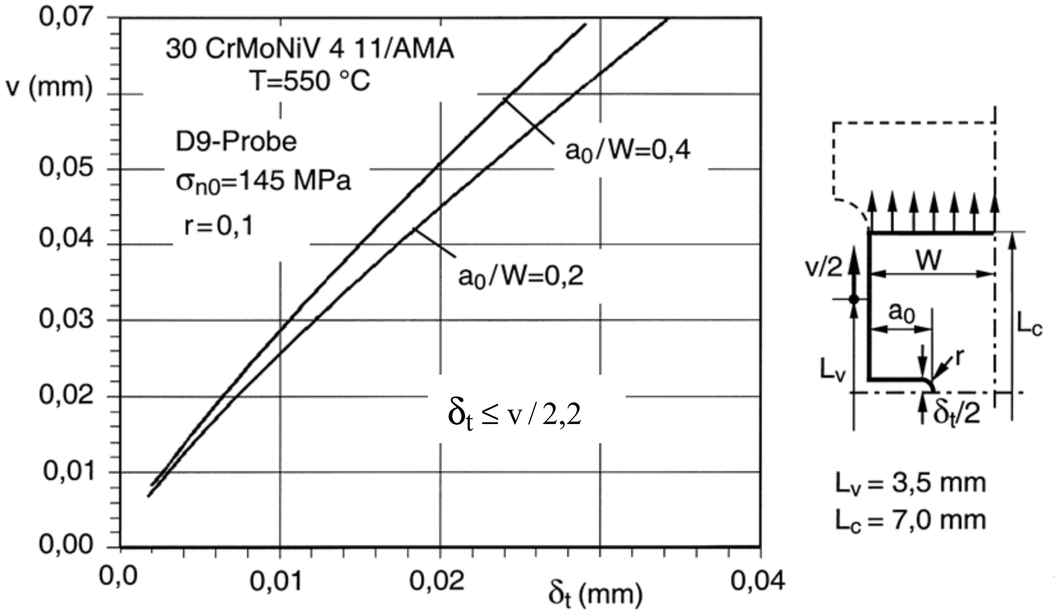

Figure 3. Comparison between the load line displacement v and the crack tip opening displacement δ_t of specimens DENT9

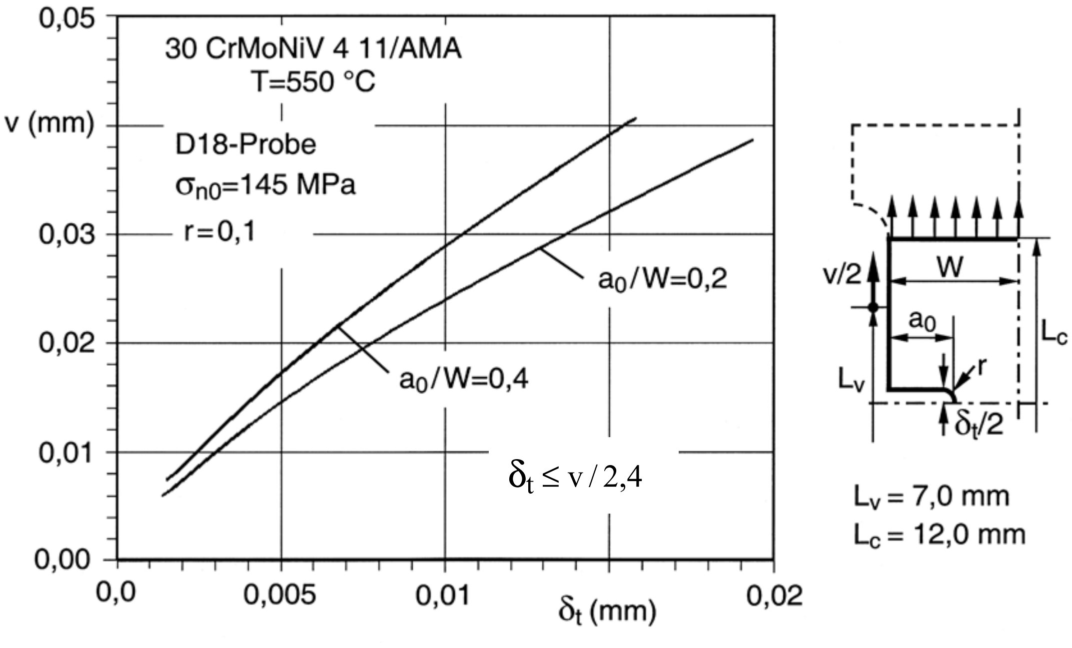

Figure 4. Comparison between the load line displacement v and the crack tip opening displacement δ_t of specimens DENT18

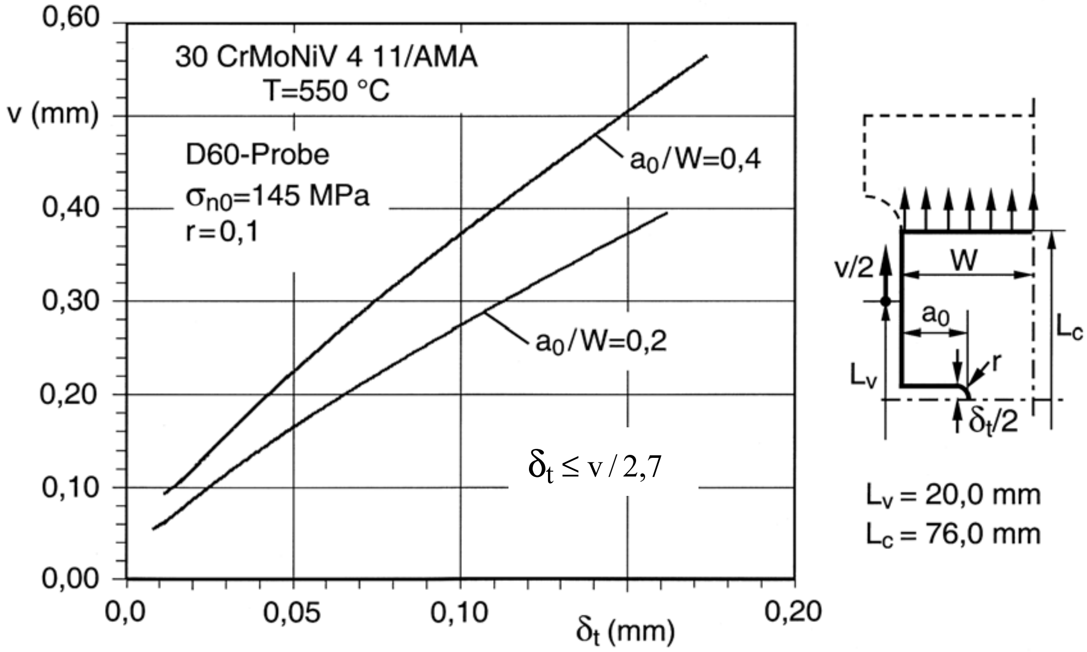

Figure 5. Comparison between the load line displacement v and the crack tip opening displacement δ_t of specimens DENT60