Standards for Creep-Fatigue Crack Initiation and Crack Growth Testing of Metallic Materials

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Abstract

There is an international collaborative effort led by Electric Power Research Institute, EPRI, USA to address an industrial need for a verified standard accepted internationally. Such a standard will replace the currently used mostly in house codes, those used at academic institutions and by industry.

The present paper will report on the state-of-the-art in the subject field and current status of the draft standards for creep-fatigue crack initiation and crack growth of metallic materials prepared for submission to ASTM E8 Committees.

Introduction

The industrial need for harmonized procedures for material testing and data analysis covers testing for materials development, design of components for engineering applications and defect assessment of in-service components for lifing. The available codes for high temperature crack growth testing and characterization of materials are limited in scope and international acceptance. The most widely used standard for creep crack growth testing of metallic materials [1] is mainly addressing compact tension, C(T), type specimens testing. Therefore, the outstanding need for characterization of industrial specimens is being worked on in an international Creep-Fatigue experts group of EPRI[2] that will serve for harmonization of testing and defect tolerance assessment of components. Recent reviews of high temperature defect assessment procedures [3] and significance of creep in defect assessment procedures for low to high temperature [4] emphasize the need for reliable crack growth data. The British Standard document BS 7910 [5] contains some specialized data for creep crack growth assessment, whereas, the R5 [6] procedure does not supply elevated temperature data, except where specifically used to validate the procedures.

Furthermore, the characterization of defect shapes and sizes is an essential part of the analysis for defects detected during in service inspection. The BS 7910 [5], R5 [6] and A16 [7] procedures describe methodologies for crack shape characterization. The minimum detectable crack size will affect the subsequent calculations and therefore improvements in detection techniques will assist in improved life estimation procedures. Within the context of Fast Breeder Reactor assessments, a 'long' crack is considered greater than 1 mm in depth. 'Short' cracks may initiate and, up to a certain critical depth, arrest, yet their average growth rate would still be greater than predicted by linear elastic fracture mechanics [8]. The guidelines are presented for experimental determination and analysis of Creep Fatigue Crack Initiation and Growth (CFCI-G) rate data including an application example.

2. CFCI-G Testing of Industrial Specimens

The reader is assumed to be familiar with materials behaviour, materials testing and data assessment together with basic knowledge of high temperature fracture mechanics.

2.1 Scope and Use

The specific aim of the CFCI-G Standards document is to provide recommendations and guidance for a harmonized procedure for measuring and analyzing Creep Fatigue Crack Initiation (CFCI) and CFCG characteristics using a wide range of industrial fracture mechanics specimen geometries. It will allow user laboratories with limited test material to carry out validated tests on different test geometries [9].

2.2 Specimens

The novel aspect of the presented CoP is the inclusion of component relevant industrial specimen geometries [9]. It covers testing and analysis of CCG in metallic materials at elevated temperature using six different cracked geometries [Fig. 1], that have been validated in [2].

The choice of specimen should reflect a number of factors such as [10]: availability and the size of material for testing, material creep ductility and stress sensitivity, capacity of the test rig. The emphasis is put on:

-Type of loading under consideration (tension, bending, tension/bending),

-Compatibility with size and stress state of the specimen with the component under investigation.

It is likely that not all conditions can be satisfied at any one time. The appropriate decision will need expert advice in the relevant field or industry.

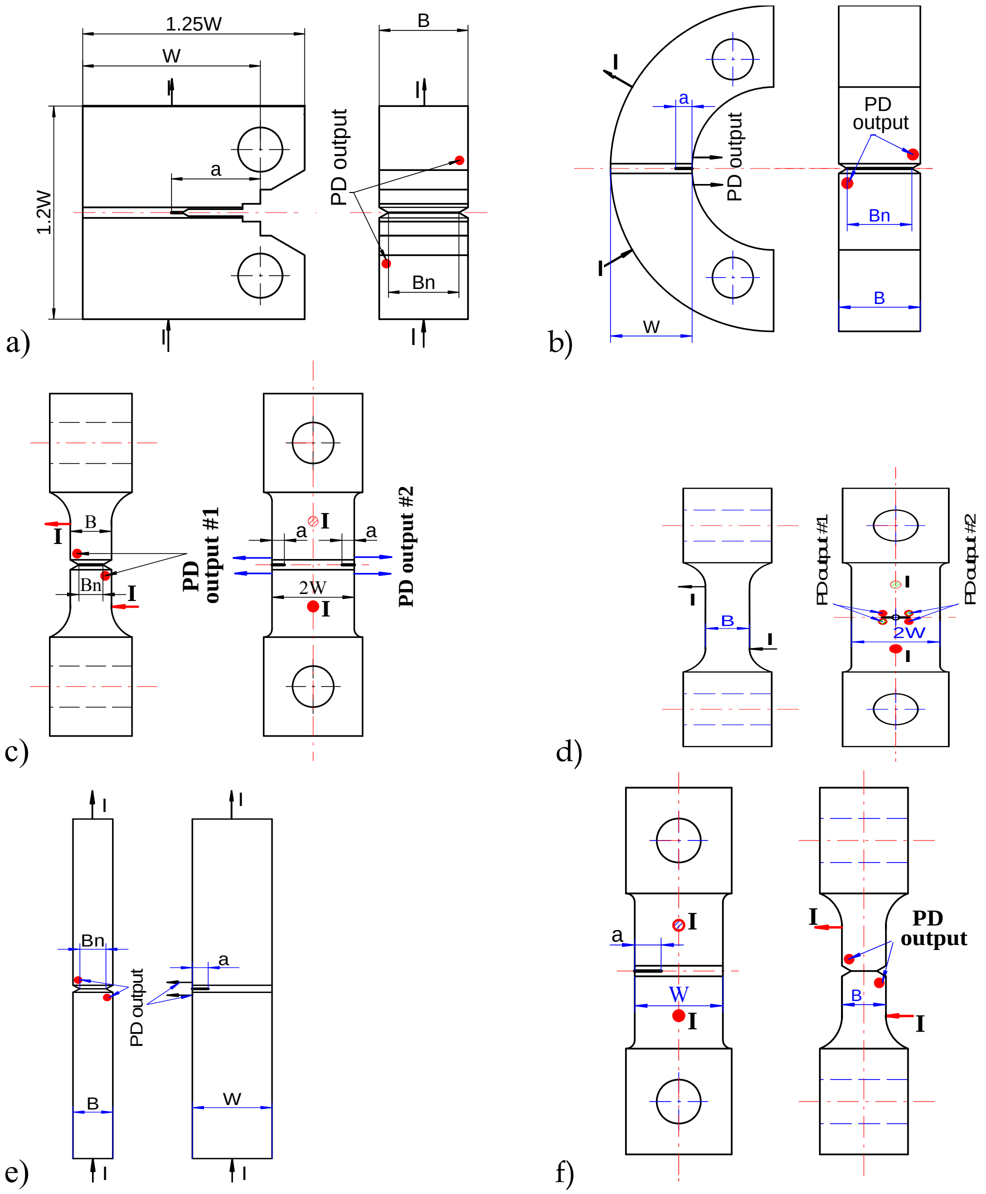

Fig.1. Specimen geometries a) Compact Tension, C(T); b) C-Shaped Tension, CS(T) c) Double Edge Notched Tension, DEN(T); d) Middle cracked Tension, M(T); e) Single Edge Notched Bend, SEN(B); f) Single Edge Notched Tension SEN(T).

2.2.1 Geometry, Size, Dimensions and Machining of the Specimens

The recommended specimen geometries have the size chosen suitable for the test capacity of the loading system, and heating furnace with sufficient room for attaching the necessary extensometers. It should provide sufficient ligament size for stable crack growth. The dimensions of specimens shown in Fig. 1 for experimental and numerical validation are given in [11]. It is possible to use half or double size thickness specimens, or any intermediate ratios depending on machine capacity and the need to consider size and constraint effects. The initial crack lengths shall be within a range of (0.2-0.4) a_o/W for tension specimens, (0.3-0.5) a_o/W for the other specimens.

Specimen abbreviations and loading arrangements are: Compact Tension C(T) in Pin loading, C-Shape Tension CS(T) in Pin loading, Double Edge Notched Tension DEN(T) in Pin loading/thread, Middle Crack Tension M(T) in Pin loading/thread, Single Edge Notched Bend SEN(B), Single Edge Notched Tension SEN(T) in Pin loading/thread.

Fatigue pre-cracked starter cracks have been used in cases where there is high creep ductility and where CCI information may be affected by the initial crack-tip conditions. The preferred method for deriving steady state CCG is to use electric discharge machining (EDM), especially for creep brittle conditions. Side grooving (SG) is needed to get a straight crack front, i.e. 20% in total.

2.3 Tests

Test techniques together with accuracy limits for measuring test variables will provide correct and repeatable test data that help to reduce data scatter. Constant load or constant displacement rate tests may be used in CCI and CCG testing. In some cases where the material is very brittle (with uniaxial creep failure strain <10 per cent) or very stress sensitive with the creep index $n >> 10$, it is advisable to perform constant displacement tests rather than constant load tests.

Test methods cover isotropic polycrystalline metallic materials. Where material inhomogenity exists such as in testing single crystals, directionally solidified materials, welds (Cross-welds and Heat Affected Zone (HAZ)) the testing techniques are subject to verification [12]. However, caution should be exercised with the treatment of the data and its analysis since the correlation parameters have been validated only for homogenous materials.

2.3.1 Preparing the Specimens

Prior to testing, specimen preparation consists of spot welding of thermocouples and potential drop (PD) wires. For advice on positioning of the wires advice should be sought from the PD equipment manufacturer. Current input wires should be placed remote from the crack tip and the potential output wires should be placed on the opposite face of the specimen, aligned near the crack tip, as shown in the specimen Fig. 1.

2.4 Environment

Aggressive environments at high temperatures can significantly affect the CFCI and CFCG behaviour. Attention must, therefore, be given to the proper selection and control of temperature and environment in data generation. All relevant information should be fully logged for each test in order to identify diversions from the norm as specified in the CoP [9].

Tests are mostly carried out in laboratory air at test temperatures. Tests should be done in vacuum or aggressive atmosphere in order to simulate service conditions of the structural component to be assessed. Note that aggressive environment enhances damage and hence affects the crack initiation and growth processes.

2.5 Measurements During Tests

The load, potential drop and displacement data should be logged all the way to full load starting from pre-load. This information is important both for the subsequent analysis of the data using C* and K. Any instantaneous deviation from the elastic loading condition prior to creep at or near zero time should be noted. In addition the load/displacement measured will give the specimen's elastic compliance for the initial crack length. The values of initial elastic displacement Δ_{ei} at full load and the final elastic displacement Δ_{ef} during the final unloading should be measured and logged in addition to the time increment Δ_t between the two readings. It is also possible to perform a partial unloading during the test if there was concern regarding a premature failure of the test piece. Partial unloading compliance may also be used for crack length estimation during the testing.

2.6 Test Interruption and Termination

Data logging and taking additional readings at the beginning of the test when rapid changes occur is important. Also when the test nears its final stage and CCG begins to accelerate additional readings should be taken. A decision must be made at some point to stop the test when CCG begins to accelerate towards rupture. It is ideal to stop the test just before failure or approximately when the specimen has reached 90-95% of life. Alternatively, the test should be stopped as soon as both the potential drop and the displacement measurements indicate that final failure of the specimen is imminent noted in crack growth rate acceleration. On-line crack length calculations using Johnson's formula as well as unloading compliance measurements may give guidance in making the test stopping decision.

2.7 Post Test Measurements and Metallographic Examination

An accurate measure of the initial (a_o) and final (a_f) crack front and crack size should be made when the specimen is broken open outside the furnace after testing. The total crack extension, Δa_f, is derived by subtracting the initial crack size, a_o from the value of the final crack size, a_f. The final crack size shall be determined from fracture surface measurements where possible. The initial and final measured crack lengths are used to compute the incremental crack length from PD measurements obtained during the tests. Post-test measurements should be carried out on the specimen. Any dimensional changes, necking, crack front shape and observing the fractured surface should be recorded. Detailed metallography to observe damage ahead of the crack tip, especially when crack initiation is of interest should be performed. Crack tip damage development is examined on completion of the test, on the sectioned half of the specimen, normal to the crack plane, using EDM and the other half is broken open for the fractography.

2.8 Choice of Appropriate Correlating Parameter: C*, Ct, J, K

The choice of the appropriate crack growth rate correlation parameter depends mainly on the material behaviour under service conditions, whether the material exhibits creep-ductile or creep-brittle behaviour [1, 13]. Steady-state creep crack growth rates in creep-ductile materials, exhibiting extensive creep, are correlated with C*. In the small-scale creep region the parameter C_t could also be used. However for most practical examples in laboratory test pieces, it can be assumed that $C_t \cong C^*$ [1, 13]. Therefore this procedure will adopt C* for use in the correlation of the data for extensive creep conditions.

Creep crack initiation (CCI) could constitute a major portion of the time to failure. The collected data for initiation times to a crack extension of 0.2 mm can be correlated with K, C* or K^c_{mat}. In most cases initiation times are inversely proportional to the parameters. The same condition regarding the validity of K or C* will apply as specified for CCG. The users are advised, in any event, to correlate CCI and CCG data with K and C* using the formulae given in [9], and report their findings.

The correlations of steady state crack growth rate with K and C* can be represented by straight lines of different slopes on log/log plots and expressed by power laws of the form

$$\dot{a} = A' K^{m'} \tag{1}$$

$$\dot{a} = D_o C^{*\phi} \tag{2}$$

where A', Do, m', and ϕ and are material constants. A steady state relationship between crack growth rate and the parameters in equations (1) and (2) physically imply a progressively accelerating creep crack growth rate.

In experimental data the two main components of the total displacement rate, $\dot{\Delta}$, are usually creep and elastic components, $\dot{\Delta}_c$ and $\dot{\Delta}_e$. The necessary condition for C* correlation is that $\dot{\Delta}_c / \dot{\Delta} \geq 0.5$. This can be tested by incrementally checking $\dot{\Delta}$ and calculating the $\dot{\Delta}_e$ component from either the compliance of the specimen or numerical calculation of $\dot{\Delta}_e$ and plotting $\dot{\Delta}_c / \dot{\Delta}$ versus test time. If this condition is established then C* can be determined using the total measured displacement rate, $\dot{\Delta}$, for the cases $\dot{\Delta}_c \cong \dot{\Delta}$.

In creep-brittle materials ($\varepsilon_f < 10\%$) which constitute a minor portion of the observed component creep behaviour, C* will not be valid. Therefore, if $\dot{\Delta}_c / \dot{\Delta} \leq 0.25$ for which the data are classified as being creep-brittle K may be used for correlating the crack growth data. However, these are not verified for this CoP.

Steady-state creep conditions are said to have been achieved when a fully developed creep stress distribution has been produced at the crack tip.

Under small-scale creep conditions, C* is not path-independent and is related to the crack tip stress and strain fields only for paths local to the crack tip and well within the creep zone boundary. Under these circumstances, C_t is related uniquely to the rate of expansion of the creep zone size [13]. There is considerable experimental evidence that the C_t parameter correlates uniquely with creep crack growth rate in the entire regime ranging from small-scale to extensive creep regime and is equal to C* in the extensive creep regime. For CCI correlation the time to 0.2 mm crack growth, defined as crack initiation period, t_i, should be plotted as a function of C* or K.

2.8.1 Creep Crack Growth Rate, da/dt.

CCG rate is correlated with the crack tip parameter K or C*. Background information on the rationale for employing the fracture mechanics approach in the analyses of creep crack growth data is presented in [9,11]. In order to correlate da/dt versus K or C*, the required material properties may be obtained from uniaxial and CCG tests. The test conditions in which the tests are performed, and the data reduction method and fitting may have considerable effect on the test results. The da/dt values are determined from crack size data using a secant or seven-point polynomial fit of crack length data. The da/dt vs. time and da/dt vs. C* correlations may contain kinks due to high degree polynomial fit of crack length or load line deflection that may be misinterpreted as material phenomena such as pop-in in crack growth. Therefore, a low degree of polynomial fit of test data is recommended for data reduction.

The appropriate solutions for K and C* are presented for crack growth rate correlations in an annex of [9]. These are valid for the size and specification of the test geometries given in Fig.1. For a side-grooved specimen the applied load will be acting over a shorter crack front, equal to the net section thickness B_n, and, therefore, the stress intensity will be higher by the following amount [9]:

$$K_{\mathrm{n}} = K\left(\frac{B}{B_{\mathrm{n}}}\right)^{0.5} \tag{3}$$

where B is the gross section thickness and

$$K = \sigma\sqrt{\pi a}\cdot Y(a/W) \tag{4}$$

where Y(a/W) is a function of geometry, crack length a and width W, as shown in Fig. 1. For specimens loaded under a tensile load P the membrane stress, σ_{m}, is given by

$$\sigma_{\mathrm{m}} = P/(BW) \tag{5}$$

(replace W with 2W for M(T) and DEN(T) specimens), and for specimens subjected to a constant bending moment M the nominal bending stress at the outer fibre (surface) is given by

$$\sigma_{\mathrm{b}} = 6M/\left(BW^{2}\right) \tag{6}$$

Where analytical expressions do not exist or where an alternative solution is sought, K can be calculated from the EPRI J integral:

$$K = \sqrt{EJ_{\mathrm{el}}} \tag{7}$$

where $J_{el}=J_{N=1}$ given by the following formula:

$$J = \sigma_{\mathrm{o}}\varepsilon_{\mathrm{o}}(W-a)h_1\left(\frac{P}{P_{\mathrm{o}}}\right)^{N+1} \tag{8}$$

with P_o is the limit load, N is the strain hardening exponent defined as $P/P_y=(\varepsilon/\varepsilon_y)^N$, and the $h_1$functions are tabulated in Reference [9].

The crack growth initiation toughness under creep conditions may be denoted by K^{c}_{mat}, which is named in the literature as creep toughness [14,15]. The values of K^{c}_{mat} may be derived from creep crack growth tests as a function of crack growth increment, Δa, using

$$K^{c}_{mat} = \sqrt{E'J_{T}} \tag{9}$$

or inserting J into eq. (9), alternative expression is

$$K_{mat}^{c} = \left[\frac{E'\eta U_T}{B_n(W - a_0)} \right]^{1/2} \tag{10}$$

based on the ESIS fracture toughness testing procedure [16] method for evaluating J_T where U_T is the total area under the load-displacement curve partitioned into elastic, plastic and creep components, denoted U_e, U_p, U_c, respectively.

Considering the elastic contribution to J based on K^2/E' are more robust than the ESIS approach based on U_e, the following expression for direct evaluation of creep toughness from experimental load-displacement information has been proposed [15] as

$$K_{mat}^{c} = \left[K^2 + \frac{E'\eta}{B_n(w - a_0)} \left(U_p + \frac{n}{n+1} U_c \right) \right]^{1/2} \tag{11}$$

where the factor n/(n+1) is required for consistency with standard creep crack growth testing procedures [1].

2.9 Number of Tests

The da/dt values at a given value of C* can vary by a factor of two for creep-ductile materials if all other variables such as geometry, specimen size, crack size, loading method and temperature are kept constant. For creep-brittle materials, the scatter in da/dt versus K relationship can be up to a factor of 4. This scatter may be increased further by variables such as microstructural differences, loading precision, environmental control, and data processing techniques. Therefore, it is good practice to conduct repeat tests at the same conditions. When this is impractical, multiple specimens should be planned such that regions of overlapping da/dt versus C*, or K data are obtained. Confidence in the data will increase with the number of tests performed on any one batch of material.

The minimum number of specimens to be tested is dependent on a number of factors. It is suggested that a minimum of five tests at different loads should be performed. If the material exhibits such factors as irregular voids, large grains, weld (X-weld, HAZ) and other inhomogeneities the minimum number of tests should be increased [12]. Also, more tests should be performed if the material CCG behaviour exhibits increased scatter regardless of the reason for the variability. If there is insufficient material available or if there are other reasons which would restrict multiple testing then the results should be considered with increased caution.

The holding time at temperature prior to the start of test should be governed by the time necessary to ensure that the temperature can be maintained within ±2°C [12]. This time will not be less than one hour per 25 mm of specimen thickness.

Report the time to attain test temperature and the time at temperature before loading.
If failure of the specimen occurs prior to the stoppage of the test then measurements of the final crack size on the fractured surface may not be possible. In this case or when $\Delta a_f/a_i > 0.2$ an upper bound estimate of the final crack size should be made (i.e. < 0.75a/W). However, a repeat test may also be needed.

3. Application to experimental CCG data

The CCG data is obtained from tests [11] on different geometries as shown in the legend of the Figure 2. Two SEN(T) specimens tested at two partners labs. demonstrate the lab. to lab. variation of data, hence the need for harmonisation of CCG testing and assessment.

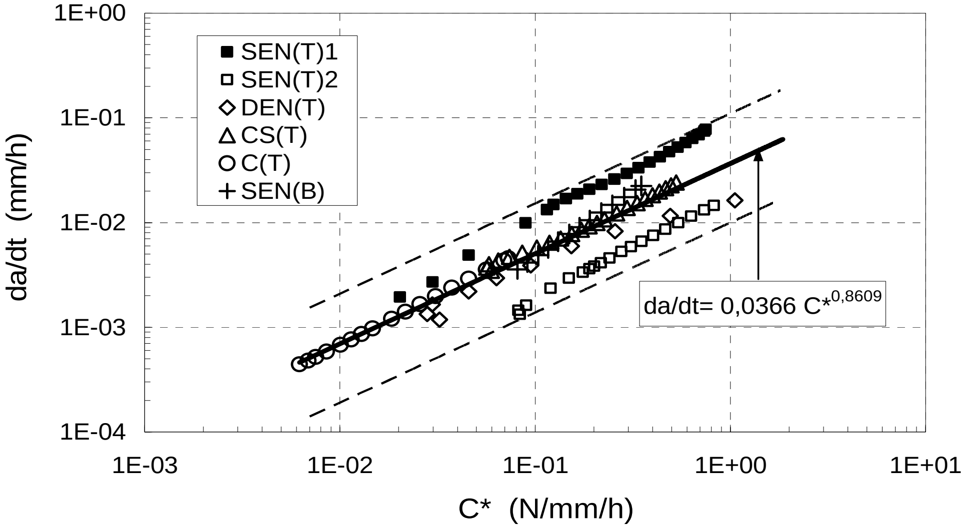

Fig.2. CCG rate data as a function of C for 316H stainless steel at 550°C. Upper and lower bands are given in dashed lines.*

Note that the data received from the partners is presented without any further processing and reduction. The figure points out the encouraging low scatter of CCG data from different specimen geometries that may be represented by a linear fit to data. A major deviation is seen in DEN(T) and SEN(T) specimens. Lab. to lab. variation in SEN(T) data defined the upper and lower limits of the scatter band. C* may be calculated using Crack Mouth Opening Displacement (CMOD) or Load Line Displacement (LLD) as shown in Fig. 3. C* calculated by using CMOD gives lower values for both loading geometries of SEN(B) and SEN(T) than C* calculated by using the LLD, however , the difference is small.

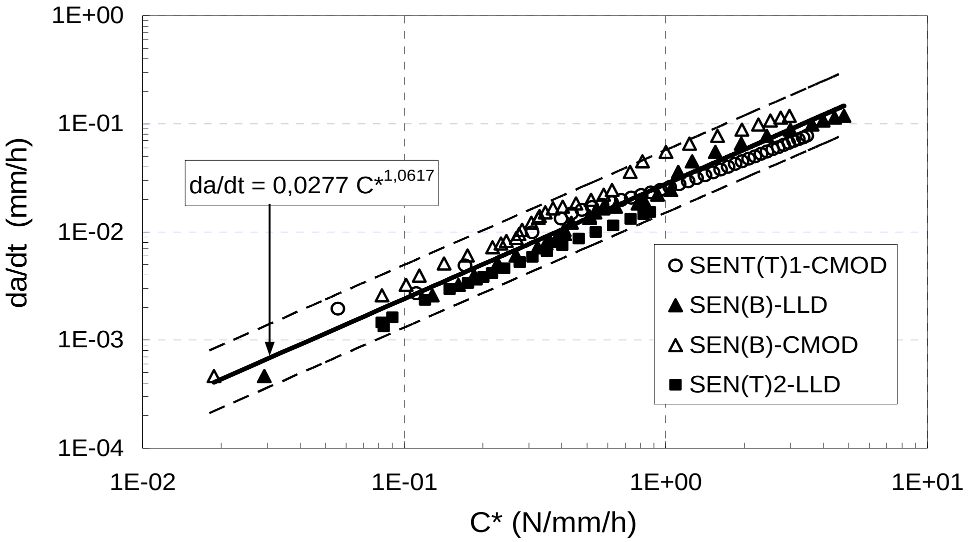

Fig.3. CCG rate as a function of C calculated using Crack Mouth Opening Displacement (CMOD) and Load Line Displacement (LLD) SEN(T) and SEN(B).*

4. Summary

Procedures for assessing the significance of flaws in components that operate in the low to high temperature range describe failure by net section rupture, crack growth or some combination of both processes. The comparison between the applied and the material side is made with relevant crack tip parameters such as the linear elastic stress intensity factor, K, the J integral, the reference stress, σ_{ref}, and C* that may be determined experimentally. The presented CoP gives guidelines for experimental determination of CCG rate data and correlation with crack tip parameters for a range of specimen geometries of industrial relevance.

For the final issue of the reported CoP a number of aspects will be addressed within the project [2] that include; constraint, material properties, eta factor, FE analysis, stress relaxation and stress-strain fields, residual stresses, partitioning displacement, analysis of elastic-creep, elastic compliance measurements.

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