CODE OF PRACTICE FOR CREEP CRACK GROWTH TESTING OF INDUSTRIAL SPECIMENS

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ABSTRACT

A Code of Practice (CoP) drafted based on the activities within internal, national and international, partially EC funded projects, e.g. CRETE, is presented. The guidelines are followed in specimen selection for the experimental work. The CoP is prepared based on the authors' and project partners long years of experience in the subject field of high temperature testing, deformation studies and creep crack growth on ferritic and austenitic materials including C-Mn, P22, P91 and 316 steels. FE calculations and validation tests were carried out on industrially relevant specimen geometries. The CoP gives advice on testing, measurements and analysis of test data for a range of creep brittle to creep ductile materials. The code may be used for material selection criteria and inspection requirements for damage tolerant applications and life assessment.

1 INTRODUCTION

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 [ASTM, 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 European project [CRETE, 2] that will serve for harmonization of testing and defect tolerance assessment of components. Recent reviews of high temperature defect assessment procedures [Dogan, 3] and significance of creep in defect assessment procedures for low to high temperature [Dogan,Ainsworth, 4] emphasize the need for reliable crack growth data. The British Standard document [BS7910, 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.

The minimum detectable crack size will affect the subsequent calculations and therefore improvements in detection techniques will assist in improved life estimation procedures. The BS 7910 [5], R5 [6] and A16 [7] procedures describe methodologies for crack shape characterization.

2 CODE OF PRACTICE

2.1 Scope and Use

The specific aim of the CoP document is to provide recommendations and guidance for a harmonized procedure for measuring and analyzing Creep Crack Initiation (CCI) and CCG 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 [Dogan et al., 8].

2.2 Specimens

The novel aspect of the presented CoP is the inclusion of component relevant industrial specimen geometries [Dogan et al., 8]. It covers testing and analysis of CCG in metallic materials using six different cracked geometries [Fig. 1].

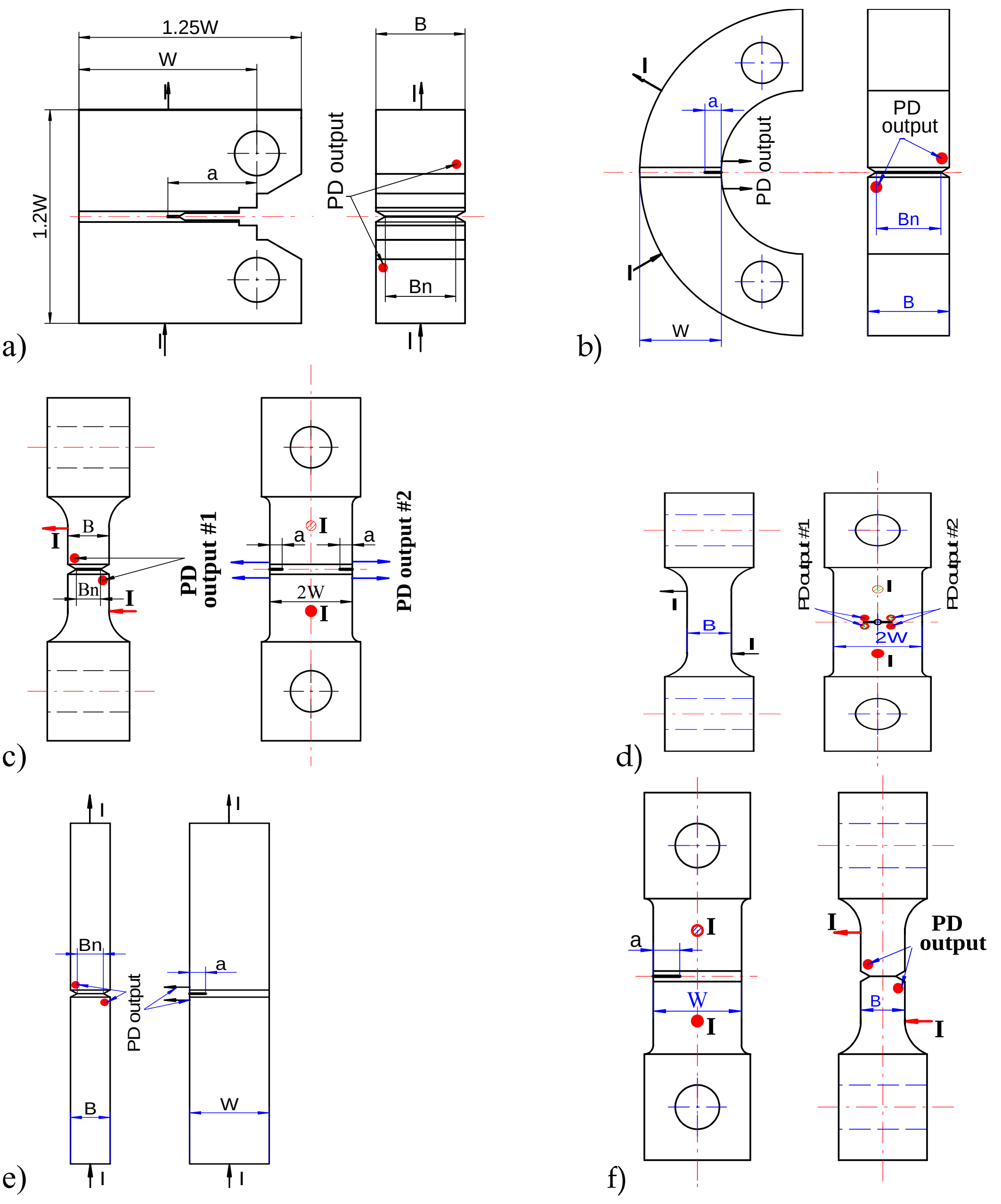

Fig.1. Specimen geometries a) Compact Tension, C(T); b) C-Shaped Tension, CS(T) c) Double Edge Notched Tension, DEN(T); d) Middle cracked Tension, M(T); e) Single Edge Notched Bend, SEN(B); f) Single Edge Notched Tension SEN(T).

The choice of specimen should reflect a number of factors [Dean, 9] such as: 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.
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 [Bicego et al., 10]. 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.

2.3 Tests

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 $n \gg 10$, 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 [Dogan, 11].
Aggressive environments at high temperatures can significantly affect the CCI and CCG 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 [Dogan et al., 8]. 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.
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.
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 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.

2.4 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 [ASTM,1, EFM,12]. 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 $C_t \cong C^*$ [ASTM,1, EFM,12]. 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 or C*. 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 [Dogan et al., 8], 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

$$\dot{a} = A' K^{m'} \quad (1)$$

$$\dot{a} = D_o C^{*\phi} \quad (2)$$

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.

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 [EFM, 12].

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.

2.5 Application to experimental CCG data

The CCG data is obtained from tests [Bicego et al., 10] 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.

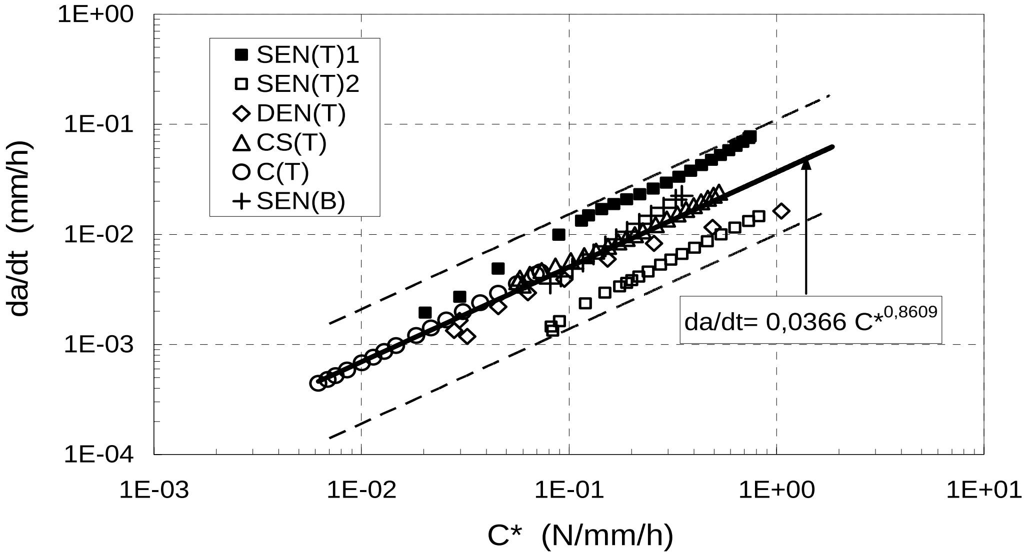

Fig.2. CCG rate data as a function of C* for 316H stainless steel at 550°C. Upper and lower bands are given in dashed lines.

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

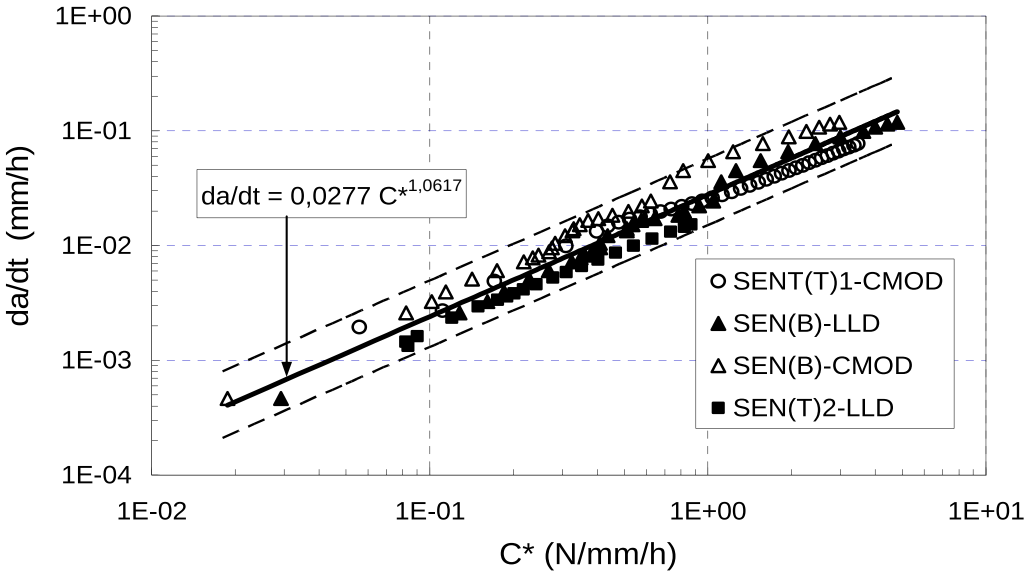

Fig.3. CCG rate as a function of C* calculated using Crack Mouth Opening Displacement (CMOD) and Load Line Displacement (LLD) SEN(T) and SEN(B).

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.

3 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.

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