GKSS FORSCHUNGSZENTRUM in der HELMHOLTZ GEMEINSCHAFT

Development of European Creep Crack Growth Testing Code of Practice for Industrial Specimens

Authors:

B. Dogan
K. Nikbin
B. Petrovski

GKSS 2004/6

ISSN 0344-9629

Paper presented at EPRI Int. Conf. "Materials and Corrosion Experience for Fossil Power Plants",
Nov. 18–21, 2003, Wild Dunes Resort, Isle of Palms, South Carolina, USA

DEVELOPMENT OF EUROPEAN CREEP CRACK GROWTH TESTING CODE OF PRACTICE FOR INDUSTRIAL SPECIMENS

B. Dogan*, K. Nikbin[+] and B. Petrovski[◊]

*GKSS Research Centre, D-21502 Geesthacht, Germany,
[+]IC, Exhibition Road, London, SW7 2BX, UK.
[◊]IfW-TUD, D-64283 Darmstadt, Germany.

Abstract

The integrity and residual life assessment of high temperature components require defects, detected or assumed to exist, through minimum allowable limits of detectable flaws using non-destructive testing methods. It relies on information obtained from the material's mechanical, uniaxial creep, creep crack initiation and growth properties. The information derived from experiments needs to be validated and harmonised following a Code of Practice that data variability between different institutions can be reduced to a minimum.

The present paper reports on a Code of Practice (CoP) being prepared within the framework of the partially European Commission funded project CRETE [1]. The novel aspect of the presented CoP is the inclusion of component relevant industrial specimen geometries. It covers testing and analysis of Creep Crack growth (CCG) in metallic materials at elevated temperature using six different cracked geometries that have been validated in [1].
It aims to give advice on testing, measurements and analysis of creep crack growth data for a range of creep brittle to creep ductile materials using component service relevant specimen geometries and sizes. The CoP may be used for material selection criteria and inspection requirements for damage tolerant applications. In quantitative terms, these types of tests can be used to assess the individual and combined effects of metallurgical, fabrication, operating temperature, and loading conditions on creep crack growth life. Further issues will be addressed including material properties, damage and crack growth related constraint effect, stress relaxation and stress-strain fields, residual stresses, partitioning displacement, analysis of elastic-creep, elastic compliance measurements.

1 Introduction

The industrial need for harmonized procedures for material testing and data analysis cover 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 limted in scope and international acceptance. The most widely used standard for creep crack growth testing of metallic materials [2] is mainly addressing compact type, C(T), specimens testing. Therefore, the outstanding need for characterization of industrial specimens is being worked on in a European collaborative work [1] that will lead to 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 procedure 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. In contrast, the R5 [6] procedure does not supply elevated temperature data, except where specifically used to validate the procedures. Instead, the user is referred to other data compendia such as an internal British Energy compendium, or is encouraged to determine properties on material relevant to the investigation in hand.

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 presented CoP gives guidelines for experimental determination of CCG rate data.

2 European Code of Practice for CCG Testing of Industrial Specimens

The present Code of Practice (CoP) [9] will be published and distributed in its final form at the conclusion of the CRETE project. However, even in its early draft form prepared based on the authors and project partners long years of experience in the subject field of high temperature testing and creep crack growth, it will give guidance to experimental work being carried out within the framework of the project. 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 this document is to provide recommendations and guidance for a harmonized procedure for measuring and analyzing 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. Furthermore, where concern exists regarding the compatibility of test geometry with the actual component in terms of size, the type of loading and stress state this document gives additional flexibility and a wider choice to carry out and analyze creep crack growth tests.

2.2 Material

Material procurement is either from new virgin material or from service exposed or ex-service variations. Therefore detailed information of the material composition, pedigree, service-history (if any), heat-treatment and hardness will be logged.

2.3 Specimens

The novel aspect of the presented CoP is the inclusion of component relevant industrial specimen geometries. It covers testing and analysis of CCG in metallic materials at elevated temperature using six different cracked geometries [Figures 1–6], that have been validated in [1].

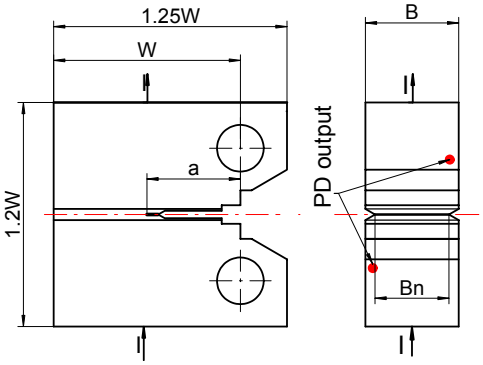

Figure 1. C(T) Specimen.

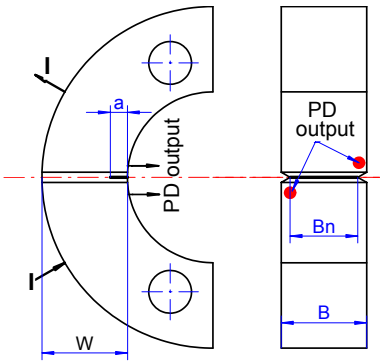

Figure 2. CS(T) Specimen.

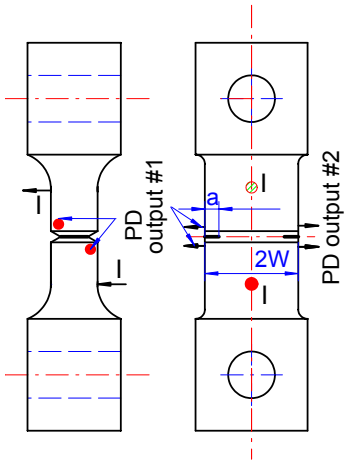

Figure 3. DEN(T) Specimen.

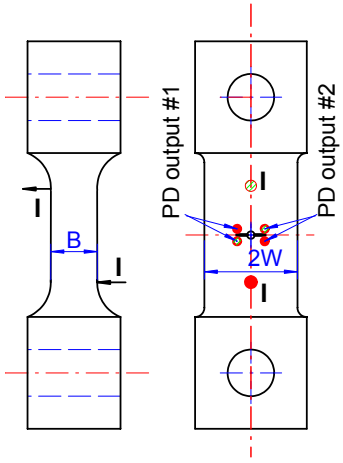

Figure 4. M(T) Specimen.

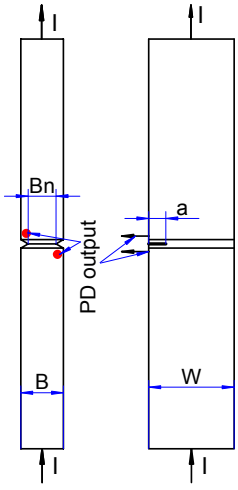

Figure 5. SEN(B) Specimen.

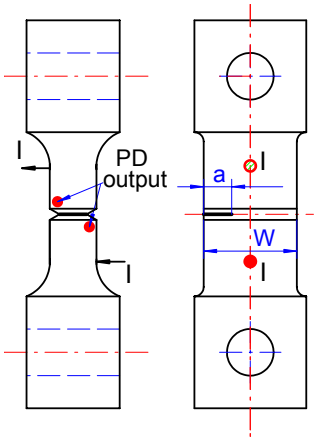

Figure 6. SEN(T) Specimen.

The choice of specimen should reflect a number of factors 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.

2.3.1 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 a stably growing crack. The specimen dimensions shall be as given in Figures 1–6, typical values chosen for validation [1] are given in Table 1.

Table 1. Specimen dimensions chosen for validation in [1].

Specimen	B (mm)	B_n (mm)	W (mm)	a_o (mm)	Length, L (mm)	Load Line offset, x (mm)
C(T)	25	20	50	40		
CS(T)	25	20	25	5	-	12.5
DEN(T)	12.5	10	12.5[#]	3.75[#]	100	-
M(T)	12.5	10	12.5[#]	3.75[#]	100	-
SEN(B)	12.5	10	25	-5	100[@]	-
SEN(T)	12.5	10	25	7.5	100	-

[#] Semi-dimensions for DEN(T) / M(T), [@] Span for SEN(B), B_n is net section thickness.

Its 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 – Specimen geometries and loading arrangements are as follows: 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.

2.3.2 Starter Sharp Crack – is introduced following two methods. 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 an Electro Discharge Machining (EDM), especially for creep brittle conditions, as it gives consistency and a sharp flat crack starter. The cutting diameter should ideally be 0.1 mm.

2.3.3 Side Grooving – is needed to get straight crack front. The depth of required side grooves for a particular material might only be found by trial and error but a total reduction of 20 % (10 % on each side of the specimen) has been found to work well for many materials. However, for extremely creep-ductile materials, a total side-groove reduction of up to 40 % may be needed to produce straight crack fronts. Any included angle of side groove less than 90° is allowed. Root radius shall be < 0.4 ±0.1 mm.

2.4 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 inhomogeneity exists such as in testing single crystals, directionally solidified materials, welds (X-welds and Heat Affected Zone (HAZ)) the testing techniques are subject to verification [11]. 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.

2.4.1 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 Figures 1–6.

2.5 Environment

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 [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.

2.6 Measurements; Displacement (LLD, CMOD), Load, Potential, Temperature

The displacement gauge should ideally have a working range of no more than twice the displacement expected during the test. Accuracy of the gauge should be within ±1 % of the full working range of the gauge. In calibration, the maximum deviation of the individual data points from the fit to the data shall not exceed ±1 % of the working range. Knife edges are recommended for friction-free seating of the gauge. Parallel alignment of the knife edges must be maintained to within ±1°.

For crack length measurements primarily a crack size monitoring equipment capable of reliably resolving crack extensions of at least ±0.1 mm at the test temperature is recommended. The selected crack size measurement technique must be capable of measuring the average crack size across the thickness. Since crack extension across the thickness of the specimen is not always uniform, surface crack length measurements by optical means are not considered reliable as a primary method. Optical observation may be used as an auxiliary measurement method. Where there is oxidation on the surface of the specimen the surface can be coated with a brittle high temperature paint which will adhere to the surface. This method is usually good where crack growth of greater than 5 mm is measured.

2.7 Measurements During Tests

The 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. Note should be taken of possible instantaneous deviation from the elastic loading condition prior to creep at or near zero time. In addition the load/displacement measured will give the specimen's elastic compliance for the initial crack length. The values of initial elastic displacement Δe_i at full load and the final elastic displacement Δe_f during the final unloading should be measured and logged in addition to the time increment Δt 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 testing.

2.8 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.

2.9 Post Test Measurements and Metallographic Examination

An accurate measure of the initial (a_0) 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_0 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 fractography.

2.10 Choice of Appropriate CCI or CCG Correlating Parameter: C(t), C_t, 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 [2,12]. Steady-state creep crack growth rates in creep-ductile materials, exhibiting extensive creep, are correlated with C*(t). 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*(t) [2,12]. Therefore this procedure will adopt C*(t) 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*(t)* or K^c_{mat}. In most cases initiation times are inversely proportional to the parameters. Same condition regarding the validity of *K* or *C*(t)* 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 [1], and report their findings.

Crack growth at high temperatures can be described in various ways using different correlating parameters [9]. However, two parameters, the stress intensity factor, *K* and *C*,* are widely used both in experimental data correlation and in life assessment codes for CCI and CCG at elevated temperatures. 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', D_o, 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. The elastic stress intensity factor *K* and the *C** parameter have generally been proposed for creep-brittle and creep-ductile materials, respectively. However it is necessary to verify the suitability of any of these parameters with respect to crack growth prediction in different materials.

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 (ε_f<10%) which constitutes 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 for which parameter *K* could be used for correlating the crack growth data. However these are not verified for this CoP.

The value of *C*(t)* corresponding to the steady-state conditions is called C*. Steady-state is 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*(t) 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, Ct is related uniquely to the rate of expansion of the creep zone size [12]. There is considerable experimental evidence that the Ct 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*(t) in the extensive creep regime. For CCI correlation the time to 0.2 mm, defined as crack initiation period, t_i, crack growth versus C* or K should be plotted.

2.10.1 Creep Crack Growth Rate, da/dt – expressed as a function of *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]. In order to correlate *da/dt* versus *K* or *C*,* the material properties needed may be obtained from uniaxial and CCG tests. The test conditions in which the tests are performed may have a considerable effect on the test results. In an annex of [1] the appropriate solutions for *K* and *C** are presented. These are valid for the size and specification of the test geometries identified in Figs.1–6. As a background, 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]:

$$K_n = K\left(\frac{B}{B_n}\right)^{0.5} \tag{3}$$

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 geometry width *W*, as defined in Figures 1–6. For specimens loaded under a tensile load *P* the membrane stress is given by

$$\sigma_m = P/(BW) \tag{5}$$

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

$$\sigma_b = 6M/(BW^2) \tag{6}$$

For DEN(T) and M(T) specimens the width *W* is replaced by $2W$.

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 $J_{\mathrm{el}} = J_{N=1}$ 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].

2.11 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 micro-structural 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 inferences drawn from 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 [11]. 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 availability of the material or if there are other reasons which would restrict multiple testing then the results should be considered with increased caution. The time for holding at temperature prior to start of test should be governed by the time necessary to ensure that the temperature can be maintained within ±2 °C [11]. 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 fractography measurements of the final crack size 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. However a repeat test may be also needed. From numerous tests observed in the literature this upper bound crack length will more than likely never exceed 0.75 a/W.

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 Crack Tip Opening Displacement, CTOD, 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 [1] 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.

4 Acknowledgements

The CoP has been prepared with EC financial support within the FP5 ‘CRETE’ Project Contract N°: G6RD-CT-2001-00527, Project N°: GRD2-2000-30021 (2001–2004). Contributions in drafting the document from the ‘CRETE’ Partners CESI – Centro Elettrotecnico Sperimentale Italiano – IT, GKSS-Forschungszentrum Geesthacht GmbH – DE, Imperial College London – UK, British Energy Generation Ltd – UK, Technische Universitaet Darmstadt – DE, Centre Technique des Industries Mecaniques – FR, VTT Industrial Systems – FI that is greatfully acknowledged. Thanks are due to U. Ceyhan of GKSS – DE for his technical assistance in drafting of the CoP.

References

1. EC Project CRETE: Development and Harmonisation of Creep Crack Growth Testing for Industrial Specimens – A Root to a European Code of Practice. EC Project No: GRD2-2000-30021.
2. ASTM E1457-00, “Standard test method for measurement of creep crack growth rates in metals”, ASTM 03.01, Philadelphia: ASTM 2000, PA 19103, USA.
3. B. Dogan, “High temperature defect assessment procedures”, Int. J.of Pressure Vessels and Piping, 80, 2003, p.149.
4. B. Dogan and R. Ainsworth, “Defect assessment procedure for low to high temperature”, ASME Conf. PVP2003-2032, Vol. 463, 2003, p.105.
5. British Standard BS7910, “Guidance on methods for assessing the acceptability of flaws in metallic structures”, British Standards Institution, 2000.
6. Goodall I.W. (Ed.), “Assessment procedure for the high temperature response of structures”, R5, British Energy, Issue 2, 1998.
7. RCC-MR Appendix A16, AFCEN (1995), Paris. France.
8. A.M. Clayton, B. Tomkins, J. Wintle and E. Morland, “A review of structural integrity in UK industry”, HMSO, London, 1991, p.1.
9. B. Dogan, K. Nikbin and B. Petrovski, Code of Practice for European Creep Crack Growth Testing of Industrial Specimens. 1st Draft, EC Project CRETE, Deliverable 6, 2003.
10. D. Dean, Selection of Specimens. EC Project CRETE, Deliverable 7, 2003.
11. B. Dogan, “CoP for High Temperature Testing of Weldments”. ESIS TC11, WG: HTTW, 1st Draft 2003.
12. Engineering Fracture Mechanics, Special Issue on Crack Growth in Creep-brittle Materials, Vol. 62, No.1, January1999.