Fracture Based Testing and Modelling, and Component Life Assessment of Welds

Kamran Nikbin

Mechanical Engineering Department, Imperial College, London, SW7 2AZ, UK
Corresponding author: k.nikbin@imperial.ac.uk

Abstract Fracture mechanics based methodologies are an important area of research that benefit life assessment techniques in components operating at elevated temperatures. There are many factors which determine a successful methodology for remaining life assessment of engineering components. Important elements are good testing techniques, the development of appropriate and accurate correlating parameters to treat the results in a the unified and verifiable manner in order to produce 'benchmark' material crack growth properties and developing accurate modelling procedures for life assessment methods. This presentation considers the first two aspects and identifies future trends and improvements in the developments of standardisations in creep and creep/fatigue crack growth testing of weldments containing residual stress. The paper highlights the important points in these pre-standardisation collaborative efforts by presenting the methods of analyses and example of their application to feature type components.
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Keywords Creep Damage; Damage Mechanics; Life Assessment; crack growth; fatigue

1. Introduction

The power generation industry is striving to meet criteria for clean and sustainable energy production by increasing efficiency while simultaneously decreasing levels of chemical emissions and pollutants. The efficiency of conventional steam and gas turbine power plant can be significantly improved by increasing the operating temperature, leading to reduced fuel consumption and lower levels of harmful emissions. With the trend towards higher operating temperatures and the competing need to extend the life of existing power plant, more accurate and reliable experimental data for use in improved predictions of component lifetimes at elevated temperatures are needed.

In recent years a number of European and International collaborative programmes [1-78] have developed the testing and analysis methodologies as well as a number of databases of laboratory crack growth data base on homogenous parent material. More recently work on crack growth of weldments has been initiated under the auspices of VAMAS TWA31 to address the problems relating to specimens containing welds.

The main objective is to establish accurate and reliable testing methods and a unified procedure for assessing creep crack growth at elevated temperatures in industrial specimens, which contain defects. Determination of procedures for analysing the test data using fracture mechanics concepts is important and therefore the validated correlating parameters are made available in the Code of Practice (CoP) [1]. Validation of results against measurements on standard Compact Tension C(T) laboratory specimens using ASTM E1457 has been also been carried out as it indicates the effects of constraint on specimen geometry and size. There are a number of parameters such as K, linear elastic fracture mechanics, Q^* based on the thermally activated process and K_{cmat} based on creep toughness properties that are included in the CoP [1]. However recommendations are only made on the basis that they are validated with experimental data. In this paper an outline of geometries that have been tested in a number of EU programmes are identified and the differences in method of analysis using the fracture mechanics parameter C^* in laboratory and components will be highlighted and compared for a pipe and plate component.

1.1 Background to life assessment codes

Components in the power generation and petrochemical industry operating at high temperatures are almost invariably submitted to static and/or combined cycle loading. The alloys used can vary between low carbon steels to high chrome superalloys with various alloying contents. In addition these components have welded parts which will have different alloying and microstructural properties. The failures can be due to large deformations, creep rupture and/or crack growth. The development of codes in different countries has moved in very similar direction and in many cases the methodology has been borrowed from a previously available code in another country. Early approaches to high temperature life assessment have used methodologies based on defect-free assessment codes. For example ASME Code Case N-47 [9] and the French RCC-MR [10], which have many similarities, are based on lifetime assessment of un-cracked structures. More recent methods make life assessments based on the presence of defects in the component. The more advanced codes dealing with defects over the range of creep and creep/fatigue interaction in initiation and growth of defects are the BS 7910 [11], British R5/R6 [12,13], the API RP 579 [14] and the French A16 [15] which have clear similarities in terms of methodology. It is also obvious from these assessment methods that the correct evaluation of the relevant fracture mechanics parameters, for which the lifetime prediction times are dependent upon, are extremely important.

It is also evident therefore that the detailed calculation steps, which are proposed in these documents alone, do not improve the accuracy of the life prediction results. In any event as these procedures have been validated for limited sets of geometries and ‘Benchmark’ material data, their use in other operating conditions will need careful judgment. These aspects have been considered in this paper in order to produce validated fracture mechanics parameters form different geometries for this purpose. The paper highlights recommendations for improved test methods so that verifiable material properties are collected. This allows the modelling methods using standard laboratory and feature component data to be used with increased confidence in life estimation codes. This pre-standardisation work is of relevance to ASTM, ISO, ASME, API (American Petroleum Institute) and PVRC (Pressure Vessels Research Council (USA)) as well as to allow further improvements to life assessment CoP such as R5, BS7910 and A16. Clearly the recommendations resulting from this CoP will be useful for increasing confidence in defect assessment codes.

2 Parameters for Analysing High Temperature Cracking

Typically, fracture mechanics concepts are used to characterise crack initiation and growth at high temperatures. Usually at short times the stress intensity factor K, or the elastic-plastic parameter J, is employed to describe the stress and strain distributions at a crack tip whereas at long times, when steady state conditions have been reached, the creep fracture mechanics term C^* is used [8,16-20]. During the intervening stage damage formation and stress redistribution is occurring at the crack tip. The parameters are validated by the right usage of parameters to describe creep brittle and creep ductile crack growth [8].

2.1. Steady state CCG analysis

Creep crack growth rate under steady state for a creep ductile material is usually analysed using the fracture mechanics parameter C^* [16-20]. The derivation for C^* which is analogous to J is well documented [16,17] and will not be detailed in this paper. Once a steady-state distribution of stress and creep damage has been developed ahead of a crack tip, it is usually found that creep crack growth rate $\dot{a}$ can be described by an expression of form [16-20]:

$$\dot{a} = D \cdot C^{*\phi} \tag{1}$$

where D and ϕ are material constants.

Where creep dominates most often the constants in Eqn. (1) are obtained from tests that are carried out on compact tension (C(T)) specimens based on the recommendations of ASTM E1457 [8] standard and hence, C^* is estimated experimentally from measurements of creep load-line displacement according to the experimentally determined value of C^* given by

$$C^* = \frac{P\dot{\Delta}^c}{B_n(W-a)}\frac{n}{n+1}\eta \tag{2}$$

where $\dot{\Delta}^c$ is the load line displacement rate due to creep alone, B_n, W and a are the specimen net thickness (accounting for side-grooves), width and crack length, respectively, n is the creep stress exponent. The geometry function η from [16,21-22] is given as

$$\eta = -\frac{1}{m}\frac{dm}{d(a/W)}\,. \tag{3}$$

Where m is a function of collapse load of the cracked body [22]. Solutions for the η functions, in different geometries, based on analytical solutions (limit load analyses) and finite element calculations are available [22]. From Eqn. (2) therefore providing that the displacement rates can be measured it is possible to simply derive C^* experimentally [23,24] for subsequent use in Eqn. (1).

2.2. Reference stress method of estimating *C**

The data obtained from C(T) specimens using Eqn. (1) is considered as ‘benchmark’ material data for creep crack growth properties of the materials in the same way as creep strain rate and rupture for uniaxial creep tests. These data can be employed directly in crack initiation and growth models described in the different codes [11-15] to estimate residual lives in components. For components such as pipes and plates, on the other hand, C^* must be determined from finite element analysis or reference stress methods. For this the reference stress procedure is adopted in line with that used in the defect assessment codes [11-15]. With this approach C^* is expressed approximately as [16]:

$$C^*_{ref} = \sigma_{ref} \cdot \dot{\varepsilon}_{ref} \cdot \left(\frac{K}{\sigma_{ref}} \right)^2 \tag{4}$$

where $\dot{\varepsilon}_{ref}$ is the creep strain rate at the appropriate σ_{ref} for the component and K is the stress intensity factor corresponding to the applied loading. When the creep strain rate $\dot{\varepsilon}$ at an applied stress σ can be described in terms of the Norton creep law [16]:

$$\dot{\varepsilon} = A \cdot \sigma^n \tag{5}$$

where A and n are material constants at constant temperature. Thus, Eqn. (4) can be rewritten as:

$$C^*_{ref} = A \cdot \sigma_{ref}^{n-1} \cdot K^2 \tag{6}$$

The typical value for n is between 5 and 12 for most metals. In addition, the concept of the average creep rate, $\dot{\varepsilon}_{Ave}$, obtained directly from rupture data, has been used to account for all three stages of creep as an approximate method for estimating the average creep rate $\dot{\varepsilon}_{Ave}$ as shown and defined by

$$\dot{\varepsilon}_{Ave} = \frac{\varepsilon_f}{t_R} = \dot{\varepsilon}_o \cdot \left(\frac{\sigma}{\sigma_0} \right)^{n_{Ave}} = A_{Ave} \cdot \sigma^{n_{Ave}} \tag{7}$$

where σ is the applied stress, ε_f is the uniaxial failure strain, t_R is the time-to-rupture and A_{Ave}, n_{Ave}, σ_o and $\dot{\varepsilon}_0$ are material constants.

2.3. Creep Crack Initiation (CCI) analysis

When a structure containing a defect is first loaded the stress distribution is given by the elastic K-field or the elastic-plastic J-field. Therefore, time is required for the stresses to redistribute to the steady-state creep stress distribution controlled by C^*. During this period, transient conditions exist which are not uniquely defined by C^*. In addition, a period of time is needed for creep damage to develop around the crack tip [16]. Furthermore due to the practical limitations of crack detection equipment, the initiation of crack growth is difficult to determine precisely. Typically, this ranges between an extension Δa of between about 0.1 and 0.5 mm depending on component and crack dimensions. For laboratory specimen such as CT, ASTM E1457 [8] identifies an extension of 0.2 mm to cover the entire transition time to steady state conditions and this distance also takes into account the resolution of crack monitoring equipment. However, in order to increase the confidence in the crack measurement of the different components, it has been determined, in this present work, that Δa = 0.5 mm was the best value to choose to compare both the CT data and the semi-elliptical defects in the pipes and plates.

From Eqn. (1) it may be expected that the time, t_i, to initiate a crack extension of Δa can be expressed by:

$$t_i = D_i \cdot C^{*\phi_i} \tag{8}$$

where D_i and ϕ_i are material constants. For steady-state cracking D_i is expected to be given approximately by $\Delta a / D$ with $\phi_i = -\phi$ and hence Eqn. (8) can be re-written as follows [23,24]:

$$t_i = \frac{\Delta a}{D} \cdot C^{*-\phi_i} \tag{9}$$

This equation assumes that the entire initiation period is governed by steady-state C^*. This cannot be expected to be true during at least part of the initiation period t_i. The applicability of the equation has been examined for the pipes and plates [1] in the same as has been done for crack growth.

2.4. Fatigue crack growth (FCG) rates

For fatigue crack growth it is assumed that the mechanism is time and temperature independent and K or J dominates at the crack tip. At room temperature under cyclic loading conditions, crack propagation usually occurs by a fatigue mechanism where the Paris Law can describe crack growth/cycle $(da/dN)_f$ in terms of stress intensity factor range ΔK by

$$\left(da/dN\right)_f = C' \Delta K^{m'} \tag{10}$$

Where da/dN is fatigue crack growth rate per cycle, C' and m' are material dependent parameters, which may be sensitive to the minimum to maximum load ratio R of the cycle. The procedure for fatigue crack growth testing is well known [25]. However for low frequency dwell periods where creep dominates the parameter of choice would be the same as for static creep testing such as C^*[16,26].

2.5. Analysis of creep/fatigue crack growth (CFCG) rates

At elevated temperatures combined creep and fatigue crack growth may take place. However in most cases fatigue dominates at higher frequencies (f>1Hz) and creep dominates at lower frequencies and dwell periods (f<0.1Hz) [26]. In most cases the total crack growth crack growth calculations under cyclic loading can be described as

$$(da/dN) = (da/dN)_C + (da/dN)_f \tag{11}$$

Where this linear summation combines creep and fatigue components. This can be refined using the method given in the British Energy's R5 Procedure [12].

Total crack growth per cycle, (*da/dN*), can be described by Eqns. (1,(10). It can be shown that a simple cumulative damage law can be applied to describe creep/fatigue interactions [26]. Fatigue analysis is usually conducted by using the linear elastic *K* parameter [1,8] and the creep portion can be described by *C** [26].

1. GEOMETRIES USED IN CRACK GROWTH TESTS

The VAMAS procedure covers a range of geometries for testing at high temperatures. These are placed in two categories. The first are the recommended standard fracture mechanics specimens and the second are the 'feature specimens' which cover all non-standard test specimens which could resemble components. These are described in brief in the following sections.

Table 1: Specimen names and abbreviations

C(T)	Compact Tension
CS(T)	C-Shaped Tension
SEN(T)	Single Edge Notched Tension geometry
SEN(B)	Single Edged Notched Bending geometry
DEN(T)	Double Edge Notched Tension geometry
M(T) or CC(T)	Middle Tension or Centre (through) Cracked Panel in Tension

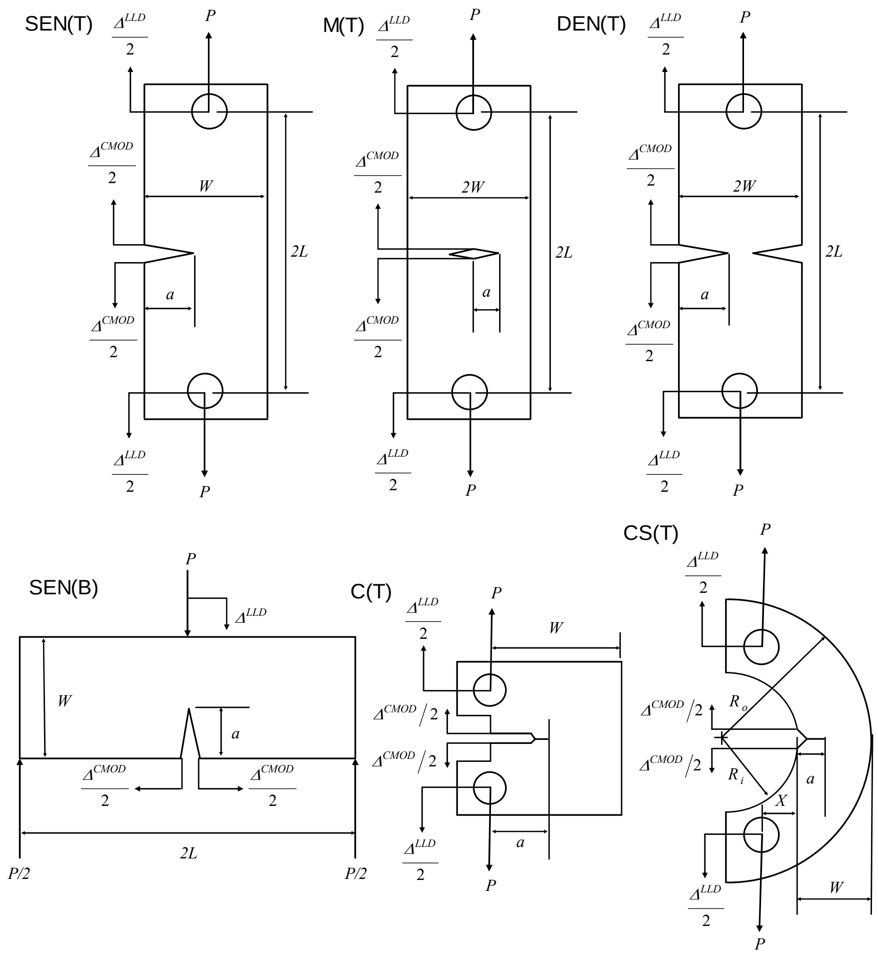

Figure 1: Schematic drawings for the fracture mechanics geometries showing the loading directions, and the load-line Δ^{LLD} and crack Mouth opening Δ^{CMOD} measuring positions.

2.6. Fracture mechanics specimens

As a result of EU collaborative programmes [2-7] especially in HIDA [3], LICON [4] and CRETE [5] tests were performed on a number of fracture mechanics geometries. The VAMAS procedure [1] uses the information provided by these programmes to identify and catalogue six specimen geometries, as given in Table 1, that have been verified for the purpose of creep and creep/fatigue crack growth and initiation testing and are comparable to C(T) test data [23]. Abbreviations denoting the specimen geometries are also given in Table 1. The choice of specific specimens does not mean that other geometries should not be used for testing but that they would need validation before their inclusion in the procedure. Detailed dimensions, machining instructions methods of setting up and limits of testing accuracies are described in the procedure. Figure 1 shows the schematic drawings of the six fracture mechanics geometries showing the loading directions, and the load-line Δ^{LLD} and crack Mouth opening Δ^{CMOD} measuring positions.

a) b)

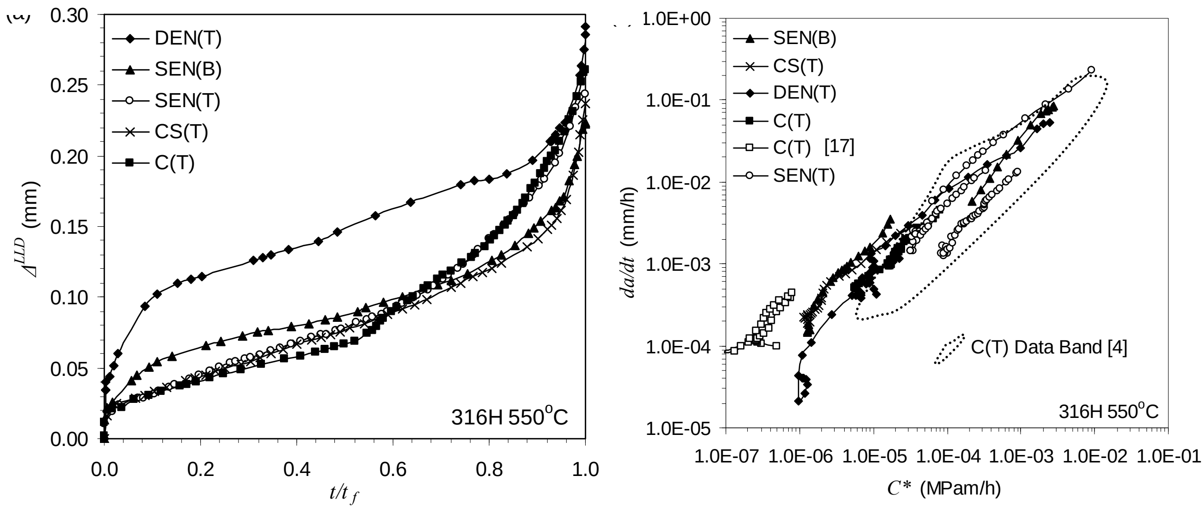

Figure 2: a)Example of normalised crack length versus time data and b) Comparison of the creep crack growth rates with C^* for different geometries with the C(T) databand, for $\Delta a \geq 0.2$ mm, in 316H stainless steel at 550 °C.

An example of data obtained and analysed from these specimens are shown in Fig. 2. Fig. 2a shows the normalised crack length versus time for the different geometries and Fig. 3b shows the correlation of the data when compared to a C(T) databand of the same 316 type stainless steel material. This suggests that for the range of sizes and geometries used the crack growth data obtained is comparable to within the inherent scatter of data.

2.7. Feature Specimens

Feature type specimens, which can represent component related geometries, were also tested for verification and validation in different collaborative programme [3]. These consist of pipes, plates and notched bar cracked specimens. The testing of such specimens is costly and difficult and is not recommended as a routine procedure for deriving data but they can be used to validate the laboratory data in comparison to components.

Analysis of component or feature component testing was an important part of VAMAS TWA25 procedure [1]. It has been shown previously that although different codes employ Eqns. (5-7), often different formulae are used to evaluate K and σ_{ref}. Greater sensitivity of C^* and cracking rate to reference stress than to K is expected from Eqn. (5) since ϕ in Eqn. (1) is close to one, and typically n>>1 and evidence of this has been demonstrated previously [28]. It has also been previously demonstrated that 'global' collapse solution represent best the cracking behaviour in pipe components [1]. Some examples of the comparisons of data for the plate and pipe with C(T) specimens are given in the next section to highlight the analysis and the difficulties that exist in producing and treating the data from feature test. Furthermore since it has been shown [28] that there is no absolute correct solution for reference stress in components and that in order to get an overall agreed definition compromises have to be made. It may be possible by using detailed FE analysis of the geometry in 3D and the right boundary conditions and material properties to improve the solutions in the future.

For plates there exist several reference stress solutions [11-15] which use Eqns. (4),(6) to derive C^*. However in the VAMAS procedure [1] one reference stress solution is chosen. It has been shown that for small partially penetrating defects in plates subjected to combined tension and bending loading, these reference stresses can significantly over-estimate creep crack growth rates. Therefore a recommended reference stress, which is based on a global collapse mechanism is expressed as follows:

$$\sigma_{ref\ Plate} = \frac{(\sigma_b + 3\cdot\gamma\cdot\sigma_m) + \left\{(\sigma_b + 3\cdot\gamma\cdot\sigma_m) + 9\cdot\sigma_m^2\cdot\left[(1-\gamma)^2 + 2\cdot\gamma\cdot(\alpha-\gamma)\right]\right\}^{1/2}}{3\cdot\left\{(1-\gamma)^2 + 2\cdot\gamma\cdot(\alpha-\gamma)\right\}} \qquad (12)$$

where $\gamma = (a\cdot c) / (W\cdot l)$ and $\alpha = a / W$. In these equations, a is crack depth, c is half crack length at the surface, W is the thickness of the plate and l is the half-width of the plate, respectively.

a) b)

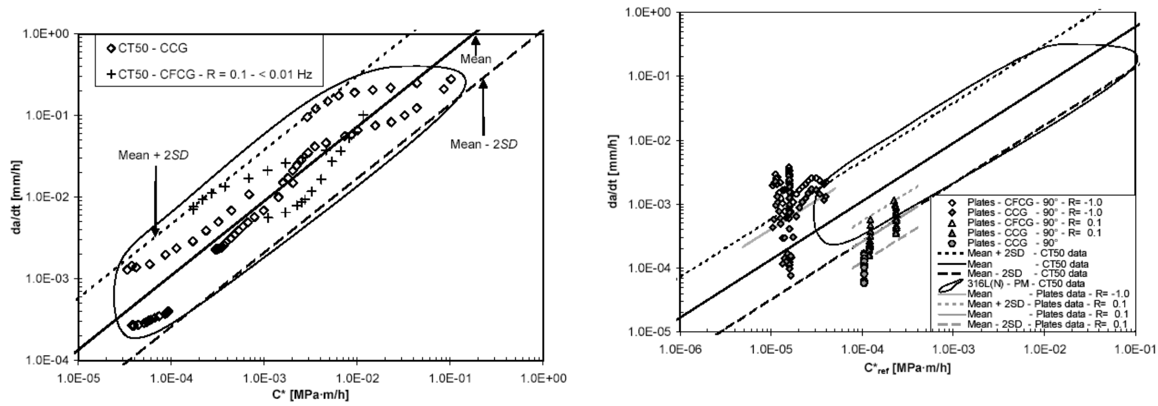

Figure 3: Effect of static and cyclic loading on crack growth rate, for 316LN at 650°C for a) C(T) specimens [3] showing the range of data scatter and b) comparison of plate crack growth data at different frequencies with the same C(T) databand as in Fig. 5(a)

Fig. 4 gives an example of comparing the effects of frequency and the plate geometry for a 316LN type stainless steel tested at 650 ^{o}C [3]. Fig. 5a highlights that for low frequencies the crack growth data for this steels lies within the scatter of the static load data, suggesting that the cracking is time dependent and due to creep at low frequencies. Fig. 5b compared the same databand with data from plate tests. In this case there is a clear difference between negative R ratios and the rest of the cyclic test data of the plate lying at the upper and lower bounds of the C(T) databand respectively. This suggests that caution would be needed in using standard laboratory tests to predict component behaviour where negative R-ratios are present.

2.8. Geometry definitions for pipe components

In the same way as the plates Eqns. (4),(6) are used to derive C^* for pipe geometries. Equations For a range of pipes also exist to derive K and reference stress. It has been shown that solutions for K

due to Raju and Newman [27] and the 'global' collapse solution for the reference stress are best to estimate C^* in the analysis for pipes. 'Global' solutions of reference stress are based on the collapse of the entire cross-section at the site of a defect. For a semi-elliptical axial defect in a pipe subjected to an internal pressure p, R6 [13] gives the reference stress as:

$$\sigma_{ref\ Pipe} = \frac{p}{\dfrac{1}{R_e - a} \cdot bate(a,c) + \ln\left(\dfrac{R_e - a}{R_i}\right)} \tag{13}$$

where *bate(a, c)* is given by : $$bate(a,c) = \frac{a}{\sqrt{1 + 1.61 \cdot \dfrac{c^2}{[(R_e - a) \cdot a]}}} \tag{14}$$

where $bate(a, c)$ function of dimensions, a is crack depth, c is half crack length at the surface and R_i and R_e are the internal and external radii of the pipe, respectively.

Figure 5 gives an example of comparison of crack growth analysis of the C(T) and pipes geometries in both parent and weld P22 steel tested at 565 ^{o}C. Fig. 6a shows little difference between parent and heat affected zone (HAZ) region tests for the C(T) P22 specimens. On the other hand Fig. 6b, for the pipe test whilst not showing a noticeable difference between parent and HAZ cracking it does show an effect due to geometry when compared with the databand of Fig. 6a. This could be due to constraint as well as the fact that derivation of data from pipe test are much more difficult than for standard C(T) specimen [8,28]. This highlights the fact that more tests would be needed to improve the validation of laboratory data with component data.

a) b)

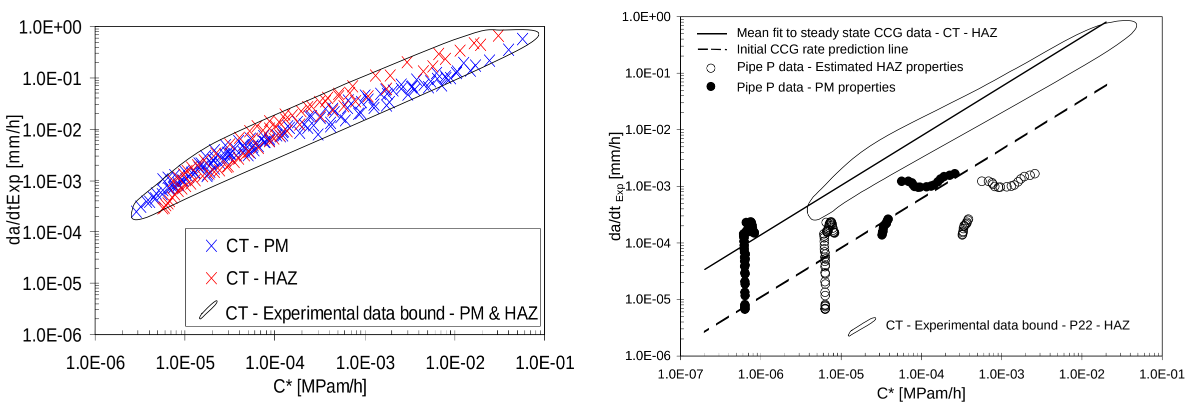

Figure 4: a) Comparison of welded and parent crack growth rate for P22 steel tested at 565 ^{o}C, and b) Comparison of crack growth versus C^* for P22 CT and pipe specimens with C(T) data band (Fig. 6a) showing the effects of geometry constraint on crack growth [3].

2. CONCLUSIONS

Creep and fatigue crack growth models as well as residual defect assessment codes need reliable and verifiable material properties data and validated fracture mechanics parameters for use in their predictive methodologies. The paper has incorporated the results from the research in a number of EU collaborative projects [2-6] to develop an overall methodology for deriving acceptable data and validated parameters for life assessment analysis. The results are also compatible with ASTM E1457 [8] standard for testing C(T) specimens. In addition the newly developed ASTM E2670 [29] on creep/fatigue crack growth testing identifies the problems associated with creep/fatigue interaction and presents an analysis method for a range of frequencies.

In addition the similarities of the approaches in the various codes do not necessarily imply that calculations by the different methods will give the same predictions. It may be possible that under certain controlled and validated circumstance the predictions can be optimised. It is clear that a critical comparison is only possible when the same method is used on another material and condition or the same test cases are examined by the different codes.

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4. REFERENCES

1. VAMAS TWA25, Code of Practice, ISO/TTA draft, ' Creep/fatigue Crack Growth in Components', VAMAS document, Ed. K. Nikbin, May 2005.
2. ‘CCG in C-Mn’, ‘CCG in Carbon-Manganese at 320-400’, Brite/Euram project, 1993-1997
3. ‘HIDA’, ‘High Temperature Defect Assessment’ Brite/Euram project, 1996-2000,
4. ‘LICON‘, ‘Accelerated Test Methods for Advanced Steels’ Brite/Euram project, 1997-2001
5. ‘CRETE’, ‘Creep Crack Growth Testing for an EU CoP’ , Brite/Euram project 2001-2004
6. FITNET, ‘Fitness for service analysis of structures using the FITNET procedure; An Overview’, 24th Int. Conf. on Offshore Mechanics and Artic Eng., Greece 12-17 June 2005.
7. 'SINTAP', ‘Structural integrity assessment procedures for European Industry’, Brite/Euram project no. BE 95-1426, contract no BRPR-CT95-0024, Final Report Nov. 1999.
8. ASTM E 1457-10, 2010, “Standard Test Method for Measurement of Creep Crack Growth Rates in Metals”, ASTM Standards 03.01.
9. ASME Boiler and Pressure Vessel Code (1991), Case N-47 (29), Class 1 components in elevated temperature service, Section III, Division I, ASME, New York.
10. RCC-MR (1985) Technical Appendix A3, Section 1, Subsection Z, Materials design and construction rules for mechanical components of FBR nuclear test islands, AFCEN, Paris.
11. BS7910,”Guide on methods for assessing the acceptability of flaws in fusion welded structures,” London, BSI, 2000.
12. R5-British Energy, “Defect assessment code of practice for High temperature metallic components,” British Energy Generation Ltd. 2000

13. R6, Assessment of the integrity of structures containing defects, Revision 3, British Energy Generation, 2000.
14. API RP 579, ‘Standardized fitness-for-service assessment techniques for pressurized equipment used in the petroleum industry’, API, 2004.
15. AFCEN, “Design and construction rules for mechanical components of FBR nuclear islands,” RCC-MR, Appendix A16, AFCEN, Paris.,1985
16. Webster, G.A. and Ainsworth R.A., ‘High temperature components life assessment’ Chapman and Hall, London, 1994.
17. Saxena, A. ‘Non-linear fracture mechanics for engineers’ CRC Press, Boca Raton, USA, 1998.
18. Nikbin, K.M., Smith, D.J. and Webster, G.A., 'Prediction of creep crack growth from uni-axial creep data', Proc. Roy. Soc. A.396, 1984, 183-197.
19. Nikbin, K.M., Smith, D.J. and Webster, G.A., 'An engineering approach to the prediction of creep crack growth', J. Eng. Mat. and Tech., Trans ASME, 108, 1986, 186-191.
20. Nikbin, K., ‘A unified European approach to high temperature defect assessment code and its incorporation in a knowledge base system’, Int. J. PVP, (2001) pp. 929-935.
21. Webster, G. A, Nikbin, K. M., Chorlton, M. R., Célard, N. J. C. and Ober, M. ‘Comparison of High Temperature Defect Assessments Methods’; Material at High Temperature; Vol. 15: pp. 337-346, 1998.
22. Davies, C. M., Kourmpetis, M., O'Dowd, N. P. and Nikbin, K. M., ‘Experimental Evaluation of the J or C* Parameter for a Range of Cracked Geometries’ published in ASTM STP 1480, 2006.
23. Davies, C. M., Mueller, F., Nikbin, K. M., O'Dowd, N. P. and Webster, G. A., ‘Analysis of Creep Crack Initiation and Growth in Different Geometries for 316H and Carbon Manganese Steels’, to be published in ASTM STP 1480, 2006.
24. Tan, M., Célard, N. J. C., Nikbin, K. M and Webster, G. A., ‘Comparison of Creep Crack Initiation and Growth in Four Steels Tested in HIDA’, International Journal of Pressure Vessels and Piping, 2001, 78(12), pp. 737-747.
25. ASTM E647-99, ‘Standard test method for measurement of fatigue crack growth rates’, ASTM 2000, 03-01, 591-630.
26. Winstone, M.R., Nikbin, K.M. and Webster, G.A., ‘Modes of failure under creep/fatigue loading of a nickel-based superalloy’, J. Mat. Sci., 20, 1985, 2471-2476.
27. Raju, I. S. and Newman, J. C. ‘Stress-Intensity Factors for Internal and External Surface Cracks in Cylindrical Vessels’; Journal of Pressure Vessel Technology; Vol. 104: pp. 293-298, 1982.
28. Wasmer, K., Nikbin, K. M., Webster, G. A., “Sensitivity of Creep Crack Initiation and Growth in Plates to Material Properties Variations”, Fatigue and Fracture Mechanics, ASTM STP 1461, Vol: 34, S. R. Daniewicz, J. C. Newman and K.-H. Schwalbe, Eds., ASTM International, West Conshohocken, PA, 2004.
29. ASTM E 2670-10, 20110 “Standard Test Method for Measurement of Creep/fatigue Crack Growth Rates in Metals”, ASTM Standards 03.01.