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STANDARDISATION OF CREEP/FATIGUE CRACK GROWTH TESTING IN COMPONENTS

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ABSTRACT

In both power generation plants and the chemical industries there is a need to assess the significance of defects which may exist in high temperature equipment operating in the creep and creep/fatigue range. The defect assessment codes [1-4] need verifiable materials data for use in their analysis. The fracture committee in Versailles Agreement for Materials and Standards (VAMAS) has been active in developing and disseminating testing and analysis methodology in this field since 1987. This paper reviews the methods of analysis used in short term small laboratory creep crack growth data and their relevance to long term crack initiation and growth in components. It is clear [4] that industry needs additional justifications in order to accept further the present defect assessment codes. The review of industrial needs indicates that feature component testing which best simulates the stress state of the actual component should be used to validate the failure predictions and increase confidence in defect assessment codes. It is therefore concluded that a standardisation programme for testing and analysis would be relevant. The programme objectives for VAMAS TWA25 committee on 'Creep/fatigue crack growth of components' are reviewed and conclusions are presented as to the future developments.

KEYWORDS

Fracture, creep, fatigue, crack growth, VAMAS, test standards

INTRODUCTION

VAMAS has been active in the field of standardisation of testing and analysis of elevated temperatures fracture mechanics specimens since 1987. Between 1987-1992 a new working group, TWA 11, was setup to develop and formulate a standard for a high temperature test method. This involved making recommendations for measuring the creep crack growth properties of materials and using the creep fracture mechanics parameter C^* in the analysis of the data. The method was restricted to creep ductile situations. The findings were incorporated into ASTM test procedure E1457-92 [5] that was the first standard to deal with crack growth testing at elevated temperatures.

This methodology was extended under TWA 19 (1993-1998) to conditions where only limited creep deformation or otherwise creep brittle conditions were observed. As a consequence of a Round Robin testing and analysis programme on four relatively creep brittle alloys, namely two aluminium a titanium and a carbon-manganese alloy, recommendations were made to change the original procedure, to incorporate the methodology for a more creep brittle circumstances. Subsequently a revised version of the ASTM testing standards E1457-98 [6] was produced. Furthermore E1457-98 is about to be replaced with a new version in the year 2001 which will take into account most of VAMAS TWA 19 recommendations [7]. It will cover the wider range of creep ductile to creep brittle testing conditions observed in engineering alloys.

It is clear [4] that industry needs additional justifications in order to accept further the present defect assessment codes. As a result of experience gained from TWA 11 and TWA 19 the present TWA 25 was established in June 1999 with the broad aim of recommending testing, analysis and life prediction methods for assessing elevated temperature creep and creep/fatigue crack growth in metallic components containing defects. The overall objectives of TWA 25 are defined as follows

- Recommend accurate and reliable procedures for test methods in creep and creep/fatigue crack growth of non-standard geometries at elevated temperatures.
- Determine best procedures for analysing the test data using fracture mechanics concepts.
- Provide validation of results against measurements on standard laboratory specimens using the ASTM E1457-98.
- Propose relevant models for life assessment methods for cracked components.

BACKGROUND TO CRACK GROWTH RATE ANALYSIS

Crack growth in creep and fatigue can be described in various way using different correlating parameters [7-8]. However three parameters such as stress intensity factor, K [9], reference stress, σ_{ref} [10] and C^* [11] have been widely used, both in test data and the codes [1-6] to correlate creep crack growth rate data at elevated temperatures. The correlations of steady state crack growth rate with K, reference stress and C^* can be represented by straight lines of different slopes on log/log plots and expressed by power laws of the form

$$\dot{a} = AK^{m} \tag{1}$$

$$\dot{a} = H(\sigma_{ref})^{p} \tag{2}$$

$$\dot{a} = D_{o}C^{*\varphi} \tag{3}$$

where A, H, D_{o}, m, p and φ and are material constants. A steady state relationship between crack growth rate and the parameters in eqns. 2 and 3, 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.

For fatigue it is assumed that the mechanism is time and temperature independent. At room temperature under cyclic loading conditions, crack propagation usually occurs by a fatigue mechanism where the Paris Law can describe crack growth/cycle $(da/dN)_{\mathrm{F}}$ in terms of stress intensity factor range ΔK by

$$(da/dN)_{\mathrm{F}} = C\Delta K^{m} \tag{4}$$

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. At elevated temperatures combined creep and fatigue crack growth may take place.

In most cases the crack growth rate at elevated temperature is described in terms of eqn. (3). The cracking per cycle due to fatigue is calculated from the equation (4). The predictions made using these equations may be over conservative where the stresses at one end of the cycle are compressive. If the margins against failure are insufficient, the fatigue crack growth calculations can be refined using the method given in the British Energy's R5 Procedure. The corrections for compressive stress given in BS7910 should not be used, as these are inapplicable when creep occurs. Total crack growth per cycle, *(da/dN),* is given by

$$(da/dN) = (da/dN)_c + (da/dN)_f \tag{5}$$

Where this linear summation combines creep and creep/fatigue components. Previous studies [1-3] have shown that a simple cumulative damage law can be applied to describe creep/fatigue interactions.

The choice of the most appropriate crack growth rate relating parameter depends on whether the material exhibits creep-ductile or creep-brittle behaviour. Validity Criteria are employed [4-5] for choosing the appropriate crack growth rate relating parameter. For steady-state creep crack growth Ct or $C^*(t)$ [5-6] correlate rates in creep-ductile materials. C_t is used for data in the small-scale creep region to the extensive creep region and $C^*(t)$ for data in the extensive creep region. Using Eqn. 7 the steady-state creep crack growth rate in creep-brittle materials [6] is correlated by K.

Estimates of C^* can be obtained by experimental, numerical and limit analysis methods [1,11-13]. The experimental procedure is applicable to laboratory specimens as specified in ASTM E1457 [5-6] and the other two methods are needed when C^* is calculated for components. Experimentally C^* is calculated from the general relationship,

$$C^* = (P\dot{\Delta}_c / WB_n)F \tag{6}$$

where $\dot{\Delta}_c$ is the load-line creep displacement rate, F is a non-dimensional factor which can be obtained from limit analysis techniques [13-14], B_n is the net thickness of the specimen with side-grooves and W is the width. In general, eqn. (6) is used to estimate the values of C^* for tests in the laboratory.

The method, which has been widely adopted in life assessment codes [1-3], is one based on reference stress concepts [1-3]. Reference stress procedures are employed to evaluate C^* for feature and actual component tests where the load-line deformation rate is not available. By determining;

$$C^* = \sigma_{ref} . \dot{\varepsilon}_{ref} \left(\frac{K}{\sigma_{ref}} \right)^2 \tag{7}$$

Where $\dot{\varepsilon}_{ref}$ is the creep strain rate at the reference stress, σ_{ref} and K is the stress intensity factor. Usually it is most convenient to employ limit analysis to obtain $\sigma_{ref}=\sigma_y(P/P_{lc})$, where P_{lc} is the collapse load of a cracked body and σ_y is the yield stress. The value of P_{lc} will depend on the collapse mechanism assumed and whether plane stress or plane strain conditions apply. σ_{ref} can be derived from either limit load solutions [14] or directly from numerical calculations using elastic/plastic finite element analysis.

INDUSTRIAL BACKGROUND

Manufacturer's recommendations and their past experience have usually been the basis for the design of vital engine components such as turbine blades, vanes and discs and in critical engineering components such as gas steam pipes, pressure vessels and in weldments which might contain pre-existing defects. In recent times however crack growth initiation and failure analyses have become more acceptable as an independent design and remaining life assessment methodology. The development of high temperature fracture mechanics concepts, through which the time dependent effects of creep could be modelled, uses experimental uniaxial and crack growth data from simple laboratory tests specimens in order to predict failure times under operating conditions. Furthermore the improvement in non-destructive inspections and testing methods (NDT) has allowed smaller and smaller defects to be detected and the need for more reliable methods for predicting crack initiation/incubation periods and steady crack growth rates.

The final objective of developing testing procedures is to improve the reliability of life assessment codes, which use test information. In developing a testing standard methodology for laboratory specimens [5,6] a first step was taken to improve life prediction procedures of components. However life extension calculations of components requires a validated fracture mechanics model for crack initiation and growth as well as detailed knowledge of component non-linear time dependent stress analysis, past service records and postulated future operations together with 'appropriate' mechanical properties. It therefore seems appropriate to develop a testing method for components and integrate it with life assessment codes for creep and creep/fatigue of components.

BACKGROUND TO LIFE ASSESSMENT CODES

Components in the power generation and petro-chemical industry operating at high temperatures are almost invariably submitted to static and/or combined cycle loading. They may fail by net section rupture, crack growth or a combination of both. The development of codes in different countries has moved in similar direction and in many cases the methodology has been borrowed from a previously available code in another country. The early approaches to high temperature life assessment show methodologies that were based on defect-free assessment codes. For example ASME Code Case N-47 [15] and the French RCC-MR [16], 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 British R5, BS 7910 and French A16 [1-3] which have clear similarities in terms of methodology.

Generally defect assessment can be divided into two regions. Firstly the initiation region whose limit can be determined either from micro-mechanical models or from NDT limits and secondly the steady crack growth region which can be described using the fracture mechanics parameters such as K, reference stress σ_{ref} and C^*. The more recent defect assessment procedures mentioned above are based on experimental and analytical models to assess crack initiation and growth and to determine the remaining useful life of such components. These codes base their analysis on tests taken from laboratory specimens, which are invariably derived from small specimens at short test times. Therefore there is no direct verification of the predicted results with component testing [17]. This is an important point since size and geometry differences impose various degrees of constraint, which affects crack growth and initiation. Furthermore the development of residual stresses [18] during fabrication and loading history which may be non-existent in small laboratory testing will need to be considered for components.

In addition it is clear 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 that the detailed calculation steps, which are proposed in these documents, do not in themselves improve the accuracy of the life prediction results. In any event as these procedures have been validated for limited sets of geometries and material data their use in other operating conditions will need careful judgment.

The codes [1-3] attempt to deal comprehensively with assessment and remaining life estimation procedures that can be used at the design stage and for in service situations. They stress upon a life assessment approach allowing the expert to decide upon the applicability of the predictions in relation to the operating circumstances. The concept implies that the codes need to show they are both reliable and understandable over a range of material and loading conditions that may not been have previously examined or validated by the code developer. This is particularly important as new higher strength steels, which have little or no long-term material properties database, are developed or used by the power industry.

Therefore the trend in the development of the codes is suggesting that, in addition to verification of data between laboratory tests and component tests, increased flexibility in dealing with the information and the analysis is an important factor. This acknowledges the fact that calculations however detailed and sophisticated will not necessarily come up with the correct predictions due to various unknowns in assessment procedure. These can be attributed to a number of factors many of which are beyond the control of the engineer using the code. They are as follows

- The available material property data for the analysis is invariably insufficient or crude and since they are usually taken from either historical data, results from different batches of material or tested in different laboratories with insufficient number of tests specimens they are likely to contain a large scatter.
- The scatter and sensitivity in creep properties inherently produce a large variation in the calculations. Upper and lower bounds are therefore introduced which give widely different life prediction results.
- The evaluation of the relevant parameters such as *K*, limit load concepts, reference stress σ_{ref} and C^* are different according to the method of derivation.
- The uses of short-term small laboratory data for use in long-term component life predictions further increases the possibilities of a wrong prediction.
- Difficulty in ascertaining the level of crack tip constraint and multi-axiality effects in the component will reduce the accuracy of crack growth predictions by about a factor of 30.
- Unknowns in modelling the actual loading history, component system stresses and additional unknowns such as little or no knowledge of past service history, residual stresses also act as sources of error in predictions.
- Non-destructive (NDT) methods of measuring defects in components, during operation and/or shutdown and insufficient crack measurement data during operation, is likely to add to errors involved in life-time assessment.

All these factors suggest that however detailed sophisticated and accurate a particular calculation is, the result will still need to be treated with caution. In addition the similarity 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.

TWA 25 will attempt to fill this gap in order that modelling methods and test data from standard laboratory and feature component tests can be used with increased confidence in life estimation codes. Early indications are that relevant ASTM and ASME, API (American Petroleum Institute) and PVRC (Pressure Vessels Research Council (USA)) bodies have shown interest in the progress of this project. Clearly the recommendations resulting from this project will be useful for increasing confidence in defect assessment codes.

OBJECTIVES FOR TWA 25

On the basis of the established background of creep and creep/fatigue crack growth test methods and also life assessment methodology that has been discussed a programme of work has been setup in TWA 25. This is presented in this section.

The main objective is to establish accurate and reliable procedures for assessing creep crack growth at elevated temperatures in components, which contain defects, determine procedures for analysing the test data using fracture mechanics concepts and validation of results against measurements on standard laboratory specimens using ASTM E1457-98. Finally, in the light of established results, to propose recommendations to both testing methods for components and changes to life assessment codes.

It has been clear that there is substantial interest shown by the power generation industry in developing this field. A number of participants from Europe, Japan and USA are involved. The core group contains over 25 institutions that have registered interest and participate at the meetings. The overall programme for **TWA 25** is spread over 4 years. The plan for implementing the objectives are described below;

a) Gather together experts from industry and research institutes in order to identify their specific needs with respect to feature component testing.
b) Produce a data-base of available feature component test data

c) A survey of experts in relation to their preferred testing and analysis methods at high temperatures
d) A round robin analysis exercise using data from actual feature tests
e) Identify acceptable feature components and best practice for test methods.
f) Establish reliable methods for the analysis and interpretation of the data.
g) Develop methods of calibrating the results in terms of material crack growth properties data of standard fracture mechanics specimens.
h) Dissemination and recommendation of results via a special publication produced by experts in the field.

CONCLUSIONS

The background to the present TWA 25 has been presented and it has been established that there is a need in industry to improve life assessment methods in terms of creep and creep/fatigue crack initiation and growth in components, which operate at elevated temperatures. Therefore a programme of works has been set up where the emphasis has been initially placed on collecting information and experience from participating partners. The collection and the development of this knowledge database will dictate, to a great extent, the decisions regarding next round of this collaborative project. Indications are that there is firm industrial support for TWA 25 and it is hoped that over the next three years positive collaboration from members will make this a successful TWA.

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