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Code of practice for creep/fatigue testing of cracked components

Code de bonne pratique pour les essais de fluage/fatigue des composants fissurés

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

To respond to the need for global collaboration on standardization questions at early stages of technological innovation, the ISO Council, following recommendations of the ISO/IEC Presidents' Advisory Board on Technological Trends, decided to establish a new series of ISO publications named ‘Technology Trends Assessments” (ISO/TTA). These publications are the results of either direct cooperation with prestandardization organizations or ad hoc Workshops of experts concerned with standardization needs and trends in emerging fields.

Technology Trends Assessments are thus the result of prestandardization work or research. As a condition of publication by ISO, ISO/TTAs shall not conflict with existing International Standards or draft International Standards (DIS), but shall contain information that would normally form the basis of standardization. ISO has decided to publish such documents to promote the harmonization of the objectives of ongoing prestandardization work with those of new initiatives in the Research and Development environment. It is intended that these publications will contribute towards rationalization of technological choice prior to market entry. Whilst ISO/TTAs are not Standards, it is intended that they will be able to be used as a basis for standards development in the future by the various existing standards agencies.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TTA 5 was prepared by VAMAS TWA25 and published under a memorandum of understanding concluded between ISO and VAMAS.

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Code of practice for creep/fatigue testing of cracked components

1. EXECUTIVE SUMMARY

Following a brief description of the mechanism for creep and creep/fatigue this document details testing methods and analysis procedures needed for creep and creep/fatigue crack growth testing of generic geometries containing cracks. Use of the terms 'generic geometries', ‘component’ or ‘feature component’, 'feature specimens' in testing assumes that the test geometry is non-standard as compared to standard laboratory fracture mechanics geometry such as the Compact Tension (C(T)). These tests maybe needed when the users need additional validation of results and in cases where excessive costs, unavailability of pedigree material, and other testing constraints would allow nominal numbers of tests can be carried out. So far as available, specific advice and additional reference material is given throughout the document in order to assist the user in carrying out a programme of testing and analysis of the data. Specific geometries are identified and appropriate fracture mechanics parameters are presented for each of them.

This document takes into account the experience gained in testing techniques from previous Standards and Codes of Practice [[a]-[jj]] and integrates early advances in the field of high temperature fracture mechanics [1-23] with the more recent findings [24-6772] to give advice on testing, measurement and analysis of CCI, CCG and CFCG data for a range of creep brittle to creep ductile materials using a very wide range of pre-cracked geometries. In quantitative terms the information from these tests can be used to consider the individual and combined effects of metallurgical, fabrication, operating temperature, and loading variables on creep crack growth life of a component.

This document, by the very nature of the subject’s diversity, cannot go into detail on every issue relating to the methods of testing and the type of geometry that could be tested. Rather it identifies common grounds in the procedures and highlights the sensitivity of the various parameters in completing a validated programme to derive material ‘basis’ data. Attempts have been made to simplify the procedures whilst at the same time not compromise the overall accuracy that is required in a test programme. Finally advice and recommendations are given to identify the limitations of test results and/or analysis for any specific condition.

2. SCOPE

The scope of this document is to recommend and establish standardized techniques for measuring and analysing Creep Crack Initiation (CCI), Creep Crack Growth (CCG), and Creep Fatigue Crack Growth (CFCG) characteristics using a wide range of pre-cracked standard and non-standard ‘feature’ geometries. Specimens considered in this document are shown in APPENDIX I. The list of geometries is not by any means complete and the user is advised to use appropriate information from other databases for other geometries to derive the relevant fracture mechanics parameters (see

Section 11) to use in the analysis. The validation of the parameters that are to be used however is important, especially 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 allows increased flexibility and a wider choice of geometries than previously were made available without comprising on the important issues such as accuracy of testing and data measurements and the appropriate derivation of the correlating parameter. Less emphasis and detail has been placed on cycle dependent fatigue test methods compared to time dependent creep test methods as fatigue testing has been comprehensively dealt with in other standards [g] and the parameters needed for its analysis are linear elastic in nature and therefore simpler than the non-linear time dependent creep regime.

3. SPECIFIC OBJECTIVES

Availability of Creep Crack Initiation (CCI) and Creep Crack Growth (CCG) and Creep/Fatigue Crack Growth (CFCG) properties are essential for defect assessments of components operating at elevated temperatures. Methods for deriving the uniaxial creep properties are well established. The following identifies the specific objectives for this CoP

1 The user is given advice and information on specific test geometries, techniques, testing methods to allow obtain the maximum amount of verifiable test information for creep and creep/fatigue tests.

2 The information presented has been derived from collaborative experiments on a range of geometries forming the basis for the validation of results in this CoP.

3 Maximum flexibility has been introduced in test techniques without compromising accuracy. Hence the advice will also be relevant to geometries that are not identified specifically in the appendices.

4 Advice is given on specimen selection and the appropriateness of fracture mechanics parameters for use in the analysis taking into account the creep properties of the material.

5 Without compromising overall accuracy simplifications of parameters have been introduced and the appropriate variability due to the method of analysis is estimated.

6 The results for the geometries listed in Appendix I have been compared and validated and the analysis methods standardized so that testing variability between different laboratories can be reduced to a minimum.

7 The CoP sets out to identify the commonality in the wide variety tests and provides the user with sufficient advice to devise, carry out and analyse a test.

In effect the overall objective of this CoP is to unify, as far as possible, testing and analysis methods between different laboratories. This is in order that subsequent or future analysis of the data or its use in life assessment analysis could be performed with confidence and increased overall accuracy.

4. INTRODUCTION

The Versailles Project on Advanced Materials and Standards (VAMAS) supports trade in high technology products through International collaborative projects aimed at providing the technical basis for drafting codes of practice and specifications for advanced materials. The scope of the collaboration embraces all agreed aspects of enabling science and technology which are required as a precursor to the drafting of standards for advanced materials. The VAMAS activity emphasizes collaboration on pre-standards measurement research, inter-comparison of test results, and consolidation of existing views on priorities for standardization action.

4.1 Background to VAMAS Creep Crack Growth Initiatives

At this point it is useful to outline the background to the development of this document as it will place it in context with the already available codes and standards related to this subject.

VAMAS has been active in the field of standardisation of testing and analysis of elevated temperatures fracture mechanics specimens since 1987. A working group, TWA 11, was setup in 1987-1992 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 cracking conditions. The findings were incorporated into ASTM test procedure E1457-92 [i] 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 testing procedure, to incorporate the methodology for a more creep brittle circumstances. The findings of TWA19 were published in a special issue of Engineering Fracture Mechanics [11]. Subsequently a revised version of the ASTM testing standards E1457-01 [i] was published. This edition covers the wider range of creep ductile to creep brittle testing conditions observed in engineering alloys.

Following these earlier developments it has become evident recently that industry needs additional justifications and verifications in order to apply the standard test data with confidence in present component defect assessment codes such as R5 [29-31], A16 [32-33], BS-7910 [34] and API 579 [35]. As a result of experience gained from TWA 11 and TWA 19 the present TWA 25 was established in June.

4.2 Background to Industrial needs for validated Test Data

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 modeled, 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.

Figure 1 shows a schematic of the overall relationship between testing and component assessment showing the circular link between developing test methods and applying it to life assessment which in turn feeds information back into improving testing methods. The main objective of developing testing procedures is to improve the reliability of design and life assessment codes, which use material basis data for their calculations. In developing a testing standard methodology for laboratory specimens 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 seemed appropriate to develop a testing method for components and integrate it with life assessment codes for creep and creep/fatigue of components.

4.3 Relevance of Testing Methods to Life Assessment Codes

4.3.1 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 used methodologies that were based on defect-free assessment codes. For example ASME Code Case N-47 [36] and the French RCC-MR [37], which have many similarities, are based on lifetime assessment of un-cracked structures. The materials properties data that are used for these codes is usually uniaxial properties and S-N curves for fatigue.

More recent methods make life assessments based on the presence of defects in the component. The codes dealing with defects [31,32,34,35] vary in the extent of the range of failure behaviour they cover. Essentially fracture mechanics solutions dealing creep and creep/fatigue interaction in initiation and growth of defects are covered. In terms of creep crack growth all propose similar approaches but use different formulae which is likely to affect the predictive solutions. In such codes material properties, dealing with crack growth data that are needed are more complex compared to uniaxial data both in terms of testing methods and derivation.

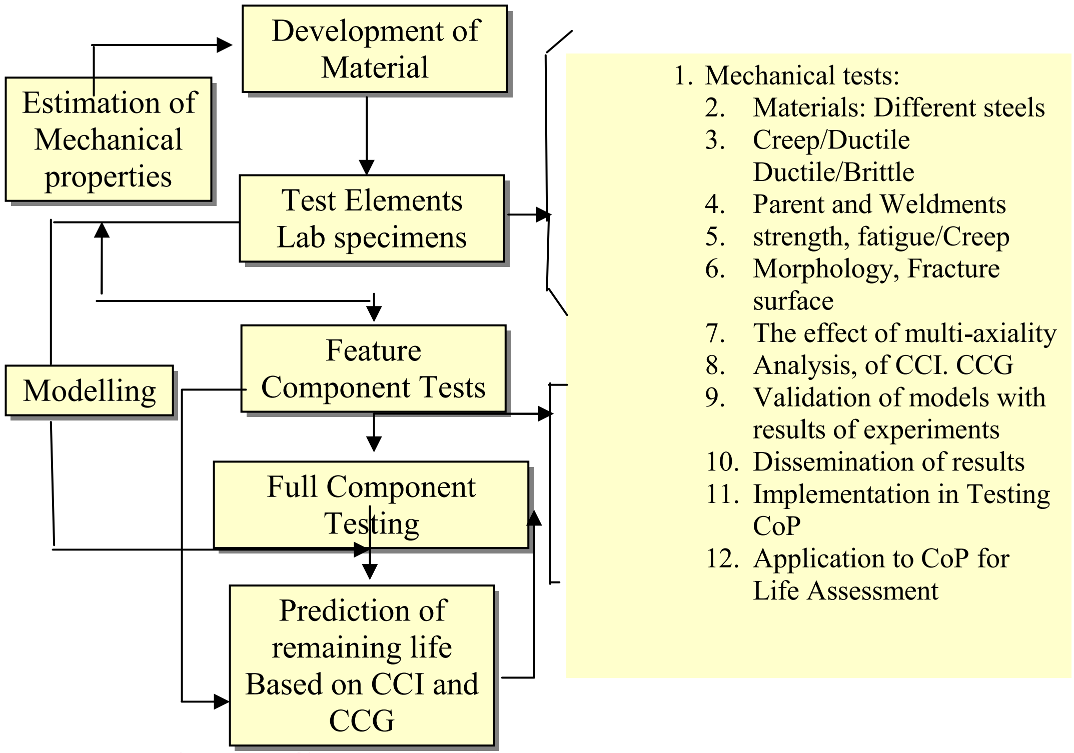

Figure 1: Schematic of the objectives in high temperature testing procedures.

4.3.2 Relation between laboratory tests and Component Assessment Codes

Generally defect assessment problems 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 tests or behaviour. This is an important point since size and geometry differences impose various degrees of constraint [25], which affects crack growth and initiation. Furthermore the development of residual stresses 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 checking.

The codes [31,32,34,35] attempt to deal comprehensively with assessment and remaining life estimation procedures that can be used at the design stage and for in service situations. The Codes' approach allows the expert to make decisions based on predictions made using the methodology in relation to the operating circumstances of the component. 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 have been 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.

4.3.3 Factors involved in the development of assessment codes

Figure 1 highlights the importance of research in the improvement and extension of industrial codes. The trend in the development of the codes suggests that, in addition to verification of data between laboratory tests and component tests the following factors need to be considered

1. 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.
2. 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.
3. Improvements in the evaluation of the relevant parameters such as K, limit load concepts, reference stress σ_{ref} and C^* since they can be very different according to the method of derivation. Use of 3D non-linear FE methods would help in this task.
4. The uses of short-term small laboratory data for use in long-term component life predictions further increases the possibilities of a wrong prediction. The relationship between short and long term behaviour needs to be quantified.
5. Difficulty in ascertaining the level of crack tip constraint and multiaxiality effects in the component could reduce the accuracy of crack growth predictions, in the extreme, by about a factor of 30. Use of 3D FE modeling would assist in this task.
6. Unknowns in modeling 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.
7. Non-destructive examination methods (NDE) of measuring defects in components, during operation and/or shutdown and insufficient crack measurement data during operation, are likely to add to errors involved in life-time assessment.
8. Probabilistic assessment of data and the predictions are required to deal with the material properties sensitivity to the models, test data scatter and unknowns in the parameters and predictive models.

Furthermore 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 optimized. 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.

4.4 Requirements for the VAMAS TWA 25 CoP

The international project, under the auspices of VAMAS (Versailles Agreement on Advanced Materials and Standards), Technical Working Area 25 (TWA 25) was initiated in June 1999. The broad was for the committee to recommend testing, analysis and life prediction methods for assessing elevated temperature creep and creep/fatigue crack growth in metallic components containing defects and to carry out and gather together the under-pinning and pre-standard research necessary to develop a standard. The investigation involved the collaboration of a number of industrial and research establishments (see Section [5]). The work followed the already established high temperature testing methodology of standard specimens developed previously by the VAMAS TWA11 (1988-92) and TWA19 (1993-1998) committees. The information from these studies, the work performed by ASTM E08 Creep Crack Growth Committee and a number of collaborative EU (BRITE/EURAM) projects based on high temperature crack growth (see Section 5, acknowledgements) was used in TWA25 to develop this document. Some of the results have been published previously in a special issue of the International Journal of Pressure Vessel and piping [24]. In addition to the input from partners' information from historical work plus results form the more recent work found in the literature has also been used in the development of this Code of Practice (CoP). The comprehensive review was performed in order to validate the testing and analysis procedures and give practical advice to the user of this document.

This document therefore reports the findings of a comprehensive study which was carried out by the VAMAS Technical Working Area TWA 25 to investigate methods for testing non-standard pre-cracked components under static and cyclic loading at elevated temperatures. This document is aimed at demonstrating the methodology in testing procedures and the subsequent analysis of the reported data. The document has been set out in such a way that it would be possible to expand it in future updates to take account of new information and data.

4.5 ISO requirements

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