THE BEHAVIOUR OF NOTCHED PETRO-REFINERY STEEL COMPONENTS AT HIGH TEMPERATURE

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Laboratory techniques to assess the behaviour of notched components under multiaxial stress, have been developed for application to the specific case of 2¼Cr-1Mo tubes with internal, axial notches subjected to internal pressure using either argon or hydrogen at 600°C. Post test metallographic evidence points to a change in failure mechanism brought about by the action of hydrogen. This influences the stress rupture behaviour which is shown to correlate well with ISO data when using a limit load solution of reference stress, incorporating the appropriate multiaxial stress rupture criterion. While the measured damage evolution rates for the argon tests are difficult to interpret due to highly ductile behaviour, under hydrogen conditions the C* integral for creep crack growth provides encouraging results.

INTRODUCTION

For plant operating at high temperatures, confident structural integrity assessment depends on the accurate prediction of defect behaviour under creep conditions. Unfortunately, many assumptions are necessary when predictions are based on conventional, uniaxial crack growth data as, in practice, plant components are of a complex geometry and operate under multiaxial stress conditions. Uncertainty about the validity of these assumptions necessitates that life predictions are generally conservative. For a number of years the Joint Research Centre (JRC) has been developing methods for high temperature crack growth testing of model component specimens. These aim to validate industrial practice, without recourse to damaging real components, and have been applied to components of austenitic (1) and ferritic (2) steels containing external defects under multiaxial stress.

In several industrial applications, the challenge of incorporating multiaxial stress and complex geometry in analysis may be additionally compounded by the

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presence of environmentally assisted degradation. By placing defects in the model components so that they are exposed to the relevant corroding environment, the test method can be adapted to also include this aspect of service conditions.

A particular problem for the petro-refinery industry is "hydrogen attack" which occurs in the presence of high pressure hydrogen at temperatures where creep is also activated. The phenomenon, distinctly different from hydrogen embrittlement, involves the reaction of atomic hydrogen with carbon from dissociated carbides in steels. Methane is formed which is unable to escape from the material and accumulates at high pressures in bubbles. Normally located along grain boundaries, these bubbles can cause degradation of many mechanical properties including toughness, strength, and ductility. Unexpected failure of hydrogen containing pressure vessels and piping is likely to be dangerous as well as extremely costly. However, due to the experimental difficulties associated with testing with explosive high pressure hydrogen at high temperatures, there is a virtual absence of laboratory data on the effects of hydrogen attack. As a result, design and operating decisions have to be very conservative, and traditionally rely on the Nelson curves (3). These are derived from plant experience, and have many widely recognised limitations. In this laboratory, crack growth tests have been carried out on model component specimens pressurised with both hydrogen and argon, thus generating conditions under which hydrogen attack could be expected to occur, and allowing for a comparison of behaviour with the results generated in an inert environment.

EXPERIMENTAL METHODOLOGY

The material selected for this study was 2¼Cr-1Mo in annealed form, widely used in both power generation and petrochemical industries and subject of the COST 501 WP5 project (4). The material was supplied in the form of a 70mm wall steam pipe, which had been manufactured for service, and from which creep, compact tension (CT) and component specimens were fabricated. Creep tests were carried out by partners in the COST project, while 25mm CT specimens were tested at the JRC, following the guidelines set down in the ASTM standard for creep crack growth (CCG) testing (5). Component test pieces were in the form of tubular specimens of length 130mm, with internal diameters of 29 or 32mm, and wall thicknesses of 3 or 5mm respectively. An axially orientated notch, was spark eroded internally at the mid length of each specimen using a 0.3mm wide, 15mm long, copper electrode. After measuring the exact depth of the notch using a rubber replica technique, pressure retaining end features were electron beam welded to the tubes to facilitate loading.

The crack growth emanating from the notch was measured by a direct current potential drop (PD) technique specifically developed at JRC for tubular components. This method had previously been applied to externally located axial defects (1,2), but was found to work equally well for internal notches. A DC current of 60 amps, supplied through plates welded at an angular position 60° from the defect, produced a uniform current field oriented perpendicularly to the notch. The change in voltage caused by crack propagation was measured by 7 pairs of stainless steel wires, spot welded 6mm apart either side of the machined notch. These were located at intervals along the length and also beyond in order to monitor any crack extension in the longitudinal direction (figure 1). A final pair of probes was placed away from the defect, but within the uniform current field to provide a reference output. The crack length was evaluated from the PD data via a calibration function generated using a two dimensional aluminium foil representation of the tube. This calibration method was supported by actual crack length and voltage change data from failed specimens.

The instrumented tubes were installed in the concrete safety cells of the testing facility, where they were loaded at 600°C using internal pressure of either argon or hydrogen gas. The guidelines on procedure and conditions given in the Internal Pressure Testing Code of Practice (6) were followed with extra precautions being taken for the hydrogen tests. As failure of the specimens led to leakage of very high pressure hydrogen at elevated temperatures, it was necessary to contain the tests in a blanket of safety gas (argon), in order to preclude the possibility of a chemical explosion. This was achieved by means of a bell housing which encased the furnace and specimen. The level of oxygen in this safety gas was monitored during testing, as was the level of hydrogen in the bell housing, the test cell, and in the control area of the facility. All alarms were connected to the infrastructural control system so that appropriate action was triggered on detection of potentially unsafe gas levels. Prior to loading, the tubes were flushed with helium, and then hydrogen to ensure the absence of any oxygen. Details of all tests carried out including loading conditions, environment, and rupture lives are given in Table 1.

TABLE 1- Results for axially notched components at 600°C

Environment	Load (Bar)	Geometry (mm)		σ_{ref} Kiefner, von Mises (MPa)	Failure Time (hrs)
		wall (t)	notch (a)		
Argon	165	3	1.77	112.5	215
Argon	165	3	1.4	98.1	558
Argon	267	5	2	98.0	504
Hydrogen	258	5	1.82	93	374
Hydrogen	250	5	1.77	89.7	550
Hydrogen	277	3	1.615	101.4	223

RESULTS AND DISCUSSION

Stress Dependence of Rupture

It is necessary to identify an appropriate database for the purpose of stress rupture correlation. Strictly speaking, a database for comparison would match both component geometry and evolution of stress, but in the absence of such tests a reasonable alternative must be used. As in a related publication (7), it has been decided to employ the ISO data line for annealed 2¼Cr-1Mo, which fits well with all uniaxial COST data at this temperature. Multiaxial creep tests on un-notched tubular components also provide data which, when adapted to take into account the operative multiaxial stress rupture criteria (MSRC), also lie adjacent to the line. Before discussing notched components it is useful to note that results from crack growth tests on CT specimens also correlated well with this data when plotted in terms of a plane strain limit load solution, combined with a von Mises MSRC.

An indication of the suitable limit load solution to describe the behaviour of the axially notched tubes can be found from post test examination of the specimens. Three factors are of importance: the type of failure (global or local), the MSRC, and whether plane strain or plane stress conditions apply. As was expected from the sizes of initial notches (8), in all tubes failure occurred locally by a small leak at the centre of the notch. This indicates that the expression developed by Kiefner et al (9) to characterise local collapse is more appropriate than others (10) produced for the case of global collapse. As used by Ainsworth et al (11) for high temperature life assessment, this limit load solution has been applied to calculate a representative reference stress, yielding the expression

$$\frac{\sigma_{ref}\, t}{P\, R} = \frac{\eta}{\left[1 - \dfrac{1-\eta}{\sqrt{1+\dfrac{1.05c^2}{Rt}}}\right]}$$

where P is the internal pressure, t is the specimen wall thickness, η = 1-a/t, c is half the notch length, and R is the mean tube radius.

The Kiefner limit load formulation is defined for Tresca plane strain conditions. In order to compare alternatives, a von Mises plane strain version can be derived using the relation $(\sigma_{ref})_{von\ Mises} = \sqrt{3}/2.(\sigma_{ref})_{Tresca}$. There is no plane stress solution available in the literature. Church (2) suggests use of the mean wall hoop stress at the ligament as an upper bound to the operating stress which does not take into account the effect of notch length. This yields very high values of stress as it does not reflect the influence of the constraining material around the notch. It can however, be taken that the plane stress solution is usually significantly higher than that for plane strain for any given specimen geometry.

Considering the tubes tested in argon first, the large amount of deformation visible in the ligament and some voids along the direction of the principal stress (figure 2), indicate that the controlling MSRC is von Mises. Whether failure has occurred under plane strain or plane stress conditions is less easy to identify. The two factors of notch length and bulging at the crack ligament are pertinent. Previous work (12,1) suggests that while a longer notch will experience plane strain conditions, a 15mm notch, such as in these tests, will experience conditions nearer plane stress. Some bulging is also evident in post test specimens indicating that the local bending stresses, which were its cause, breached plane strain conditions (9).

On examination of the stress rupture results for argon tests it emerges that the Kiefner formulation, calculated for von Mises MSRC under plane strain conditions, produces the closest correlation with other results (figure 3). It is not yet evident why the plane strain solution is appropriate although it is possible that plane strain conditions are operating for the majority of the test time, until the ligament thins to such an extent that bulging takes over prior to failure.

For the tubes tested in a hydrogen environment, (while considerations of local collapse and stress state are the same), metallographic examination points to a significant difference between the mechanism by which failure has occurred. A large number of voids are evident, mostly sited on grain boundaries, the largest oriented perpendicular to the Maximum Principal Stress (MPS). The accompanying deformation is significantly less than that seen for the argon tests (figure 4). This type of damage is characteristic of MPS or Tresca control, and when stress is calculated supposing this criteria, results do correlate well with baseline data (figure 3). In material which has not been exposed to hydrogen, MPS control is usually only observed at lower stresses (2). Voids were not visible away from the notch root, i.e. at the tube inner surface, which is suggested to be indicative of stress assisted hydrogen attack at the notch.

<u>Damage Evolution Assessment</u>

The measured PD change across the notch during a test reflects both deformation in terms of thinning of the remaining ligament, as well as crack growth. This material is especially ductile at 600°C. While at 550°C, deformation was found to play a less significant role than crack growth (2), it is evident from figure 2 that this is not the case for the present argon tests. The hydrogen tests have proceeded in a much more brittle manner however, with a discrete crack progressing through the ligament without much accompanying deformation. It is surprising then that, in the PD output for all tests types, very similar trends are seen. The PD output has been interpreted in figure 5 in terms of crack extension for the hydrogen tests, although it more accurately reflects only the loss in cross sectional area for the argon tests. Aside from detecting axial crack growth in hydrogen tests, no obvious difference between test types is discernible from the curves, belying the different physical processes. It can be argued that as both types of damage lead to failure, there is still considerable merit in the PD method which reflects their progression. Extra information in the form of strain measurements at the defect would be needed to indicate the particular form of damage during the test.

In order to develop analytical routes for the prediction of notched component behaviour it is necessary to correlate the rates of damage evolution, normally taken to be crack growth, with those measured on conventional laboratory specimens. Of existing methodologies to describe both component and conventional specimen data, the C* Integral would be expected to apply to the present material on consideration of the Riedel-Rice (13) characteristic time which is only a few hours. For CT specimens tested in air this parameter has been calculated from measurements of load line displacement during tests. The data fits well within the bounds of other standard specimen data gathered for this material by Saxena (14). Because of the amount of deformation occurring in the argon pressurised tubular specimens, even real crack extension data derived would be expected to lie outside the range of validity of C*, while application of the method to results from the hydrogen tests can be considered valid.

In the absence of displacement measurements on the components a procedure proposed by Ainsworth (11) based upon reference stress has been adopted to calculate C* as

$$C^*=\zeta\, \varepsilon_{ref}\, K_1^2/\sigma_{ref}$$

where ε_{ref} is defined as the minimum creep rate at the reference stress, and K_1 the elastic stress intensity factor. ζ is equal to 1 under plane stress conditions, but taken as 0.75 for plane strain conditions in the present work. The appropriate limit load solutions have already been described, with the value of ε_{ref} being deduced from the Norton relationship obtained from uniaxial creep data at 600°C. An expression for the stress intensity factor was taken from the literature (15).

The dependence of crack growth rates for the hydrogen tests on C* is presented in figure 6, along with the upper and lower bounds of conventional specimen data. The tests are identified by the reference stress calculated using MPS as the MSRC. Due to similar evolutions in PD, the crack growth rate/C* curves for the argon tests are actually quite comparable, but are not appropriately interpreted by this method due to the highly ductile material behaviour. Correlation of the hydrogen results is quite good, with two of the tests falling within or close to the band for much of the test time. The higher stress test, carried out on the thinner tube, falls outside but mostly parallel to the band. Although no conclusions should be drawn from the comparison of the hydrogen and air results due to the differences in material ductility (which is also related to specimen geometry), the close interrelation between the C* derived hydrogen results is clearly encouraging.

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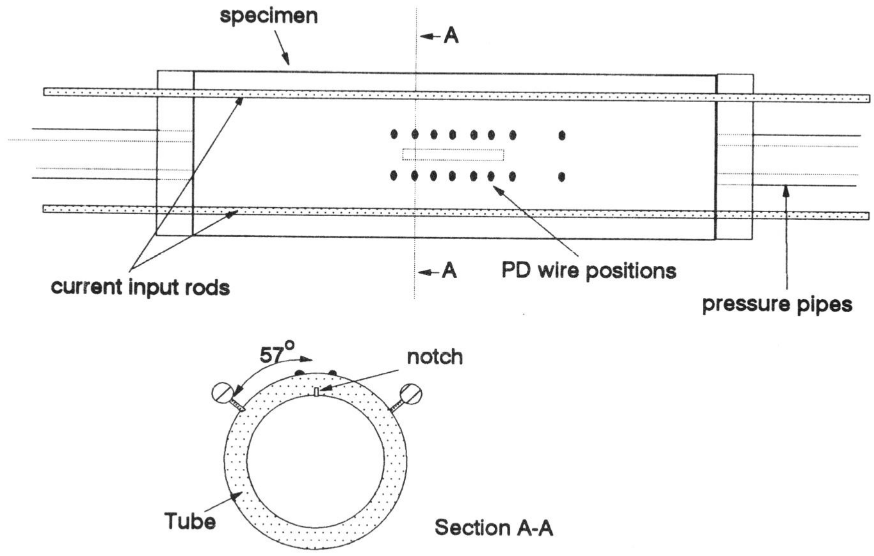

Figure 1 Configuration used for potential drop measurement.

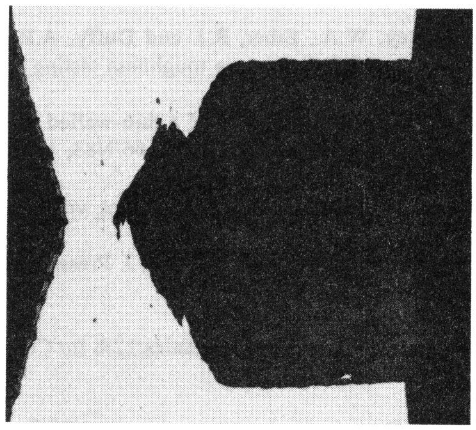

Figure 2 Cross section of specimen tested in argon, taken at the notch (×16).

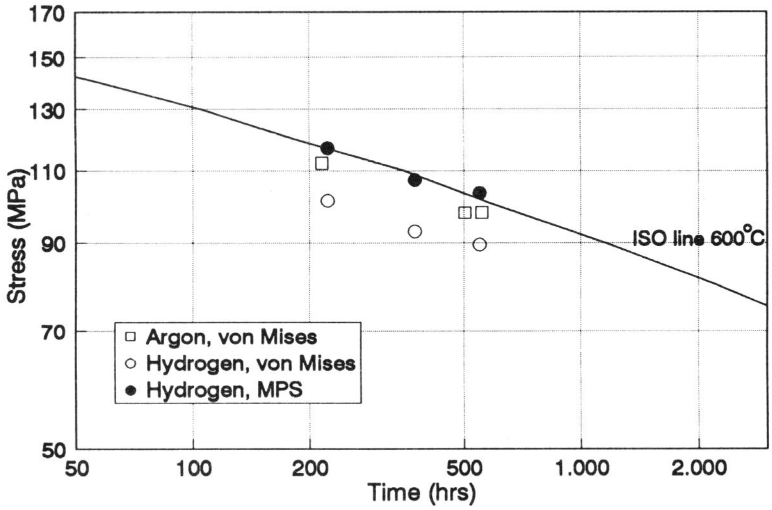

Figure 3 Notched tube stress rupture results.

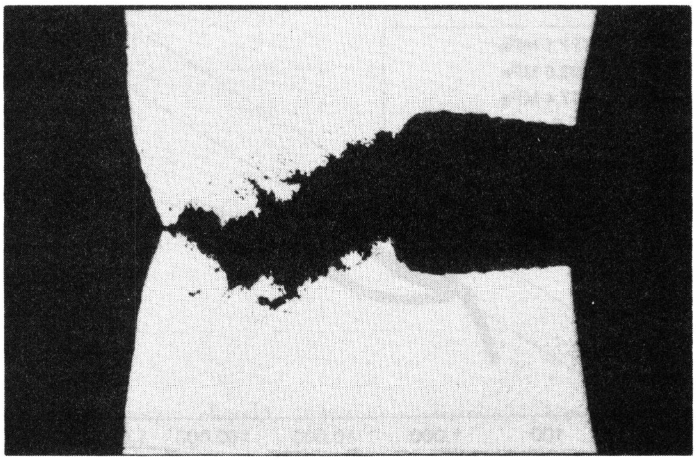

Figure 4 Cross section of specimen tested in hydrogen, taken at the notch (×16).

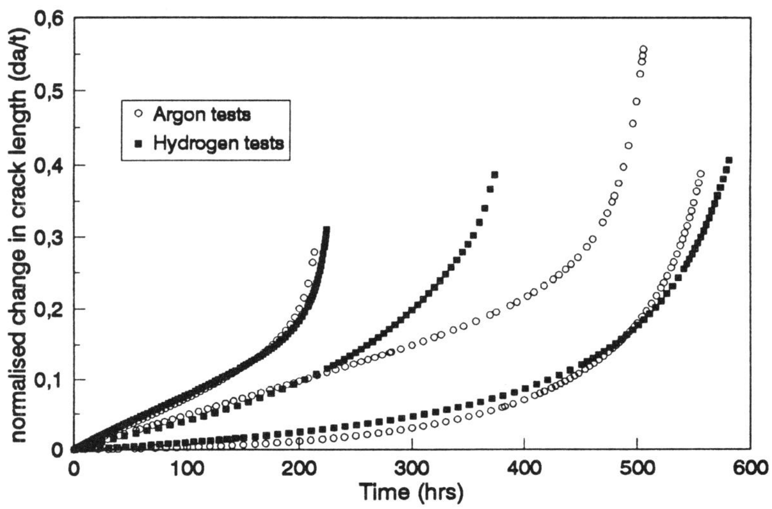

Figure 5 Crack growth in notched tubes, inferred from potential drop output.

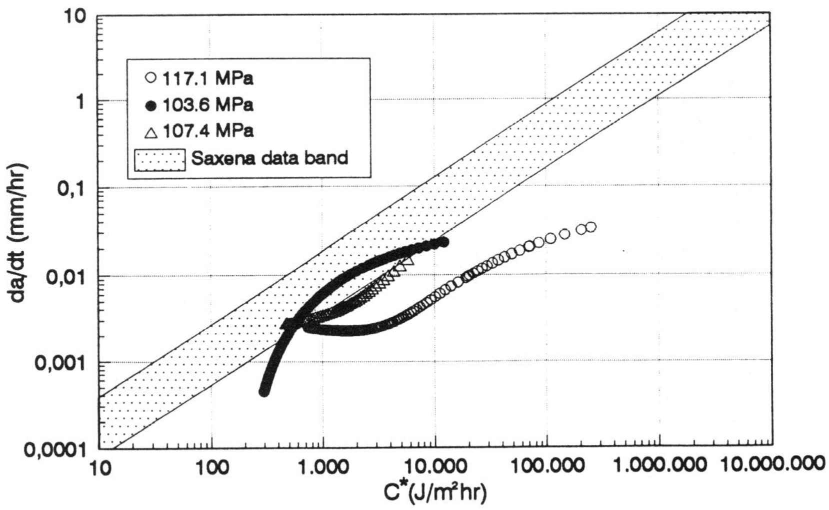

Figure 6 Creep crack growth rate dependence on C* for tubes tested in hydrogen.