Creep Crack Growth Verification Testing in Tubular Components

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ABSTRACT

A method is described for determining the creep crack growth (CCG) and stress rupture behaviour of Alloy 800H tubular components containing longitudinal surface defects at 800°C. The presence of the notch is found to systematically reduce the stress to rupture over a wide stress range. Creep crack growth rates derived from potential drop measurements across the notch show consistent K_I and C^* dependence. Comparison with creep crack growth behaviour from conventional specimens confirms that C^* is the most appropriate correlation factor. Finally, attention is drawn to the potential dangers of predicting component CCG behaviour from conventional specimen data for structure sensitive materials such as Alloy 800H and conversely to the potential advantage of the component type CCG tests developed in the present work.

INTRODUCTION

Susceptibility to fracture of components operating at elevated temperatures is manifested not only under cyclic (thermomechanical or mechanical) but also under steady state conditions, where the development and growth of creep cracks can be life limiting. Data covering creep crack growth from either pre-existing defects or from creep damaged material is required by the designer for materials selection and design calculations and by the plant operator to determine the appropriate component replacement time. Such data is conventionally obtained from standard fracture mechanics tests on specimens of the compact tension, centre- or edge-notched type. The suitability for utilising data obtained from standard specimens for the prediction of crack growth in components is not, however, a formality. The metallurgical state of the material may differ between specimen and component and the geometrical dissimilarities lead to the need for assumptions in the analysis route. In order to investigate these differences, crack growth must additionally be studied on components and a special technique has been developed for just such measurements on small tubular test pieces. The material selection for the present investigation was determined by availability of standard fracture mechanics data and applicability of components fabricated from the material in high temperature service. Fracture mechanics data for Alloy 800H was available from a European collaborative research programme, the alloy being a candidate heat exchanger material in HTR technology and of course used in a wide range of high temperature petrochemical processes.

EXPERIMENTAL METHODOLOGY

In order to limit the material structural difference between the component material and that used for establishing the basic creep crack growth data, tube was manufactured from the same cast of Alloy 800H as the plate examined by the EGF Working Party in their round robin programme (Hollstein et al, 1987). As it is known that the difference in forming procedure pronouncedly influences the metallurgical structure of Alloy 800H (McAllister et al, 1987) this factor must still be given consideration in the analysis of the results.

The only other reported creep crack growth test on a component of Alloy 800H refers to growth from a circumferential groove on a pipe subjected to combined internal pressure and axial tension (Rödig et al, 1989). A longitudinal notch was selected as an appropriate configuration for the present case of a crack growing in the wall of a tube subjected to internal pressure only. In view of the influence of machining on the creep properties of Alloy 800H (McAllister et al, 1987) it was decided to prepare the notch by spark erosion. The tubes of 200 mm length were machined from their original 25 mm O.D., 19 mm I.D. to 24.5 mm O.D., 19.5 mm I.D., re-heat treated, and the notch of 15 mm length, 0.3 mm width was eroded to a depth of 1 mm from the outside at the tube centre (Fig. 1). The choice of an axial notch in such a thin wall unfortunately precluded the possibility of generation of a sharp fatigue crack, usually a prerequisite in CCG testing.

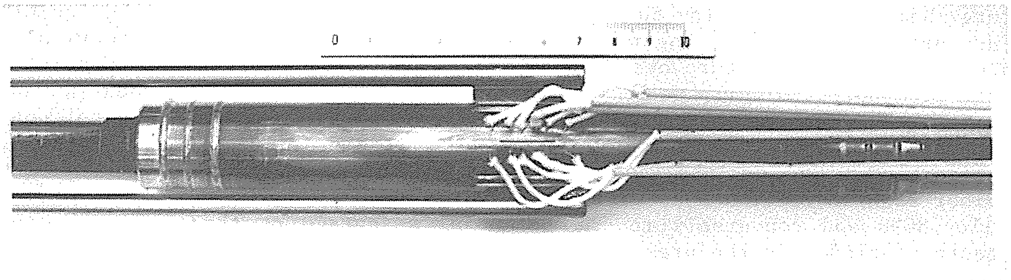

Fig. 1. Notched tubular component with PD probes.

Fig. 1 also shows the arrangement for measuring potential drop across the notch. The supply of a constant direct current across the notch was eventually achieved using rectangular Alloy 800H plates machined to match the tube curvature and electron beam welded on either side of the notch. Finite element analysis shows that the distance of the plates from the notch is sufficient to avoid any influence on the stress distribution either at the notch tip or in the ligament containing the crack. The current leads were welded to these plates and extended to the outside of the furnace. The potential drop was determined using platinum wires spot welded close to the notch, four pairs within the 15 mm length and 2 pairs beyond each end to detect eventual lengthening of the notch.

The test specimens with their electron beam welded end plugs connected to pressure inlet and outlet pipes and instrumented for both potential drop and temperature measurement were tested in one of the J.R.C. internal pressure test cells. The argon pressurising gas was held at the test pressure to ± 0.1 bar and the test temperature to within ± 2°C of the set temperature, in the present series of experiments, 800°C. Test pressures between 147,5 and 101 bar were selected in order to lead to rupture in the range 50 to 3500 hours respectively.

The longest test was interrupted shortly before failure and an additional test was commissioned for interruption in the early stages of crack growth in order to calibrate the potential drop against the creep crack length. This method of calibration using actual creep cracks was preferred to eroding notches of different depths. Data taken from the interrupted tests and from some ruptured specimens away from the position of burst are shown in Fig. 2 where a calibration dependence of approximately $a = (\text{mV})^{0.92}$ can be derived.

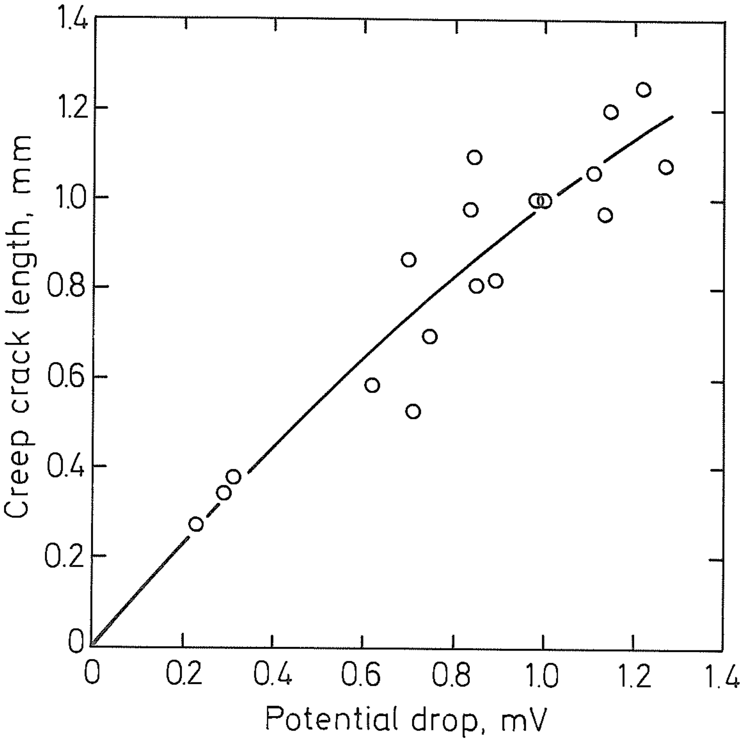

Fig. 2. Creep crack calibration curve.

CREEP RUPTURE RESULTS

In the case of large notches, such as those in notched tensile specimens, the creep rupture behaviour is usually considered in terms of net section stress. However for short narrow notches of the type studied in the present work, the test stress can be considered as that in the un-notched tube wall to allow comparison with baseline data. The stress rupture data for the notched tubes are shown along with the data for two plain tubes in Fig. 3. The reduction in strength due to the presence of the notch is relatively uniform over the stress range employed as also observed by other workers, notably Guest and Hutchings (1973) working on 9%Cr1%Mo steels. Examining the behaviour of internal rectangular notches, they used a modified flow stress concept incorporating a Folias (1964) factor which predicted rather well the influence of notch length and depth on rupture behaviour. Alternative approaches (Miller, 1987) consider local and global collapse strength, the latter being used to estimate reference stress in the subsequent section concerning crack growth behaviour. Applied to the 15 mm long, 1 mm deep notch the values of reduced creep rupture strength calculated from the three approaches all lie in the range 72.5-76.5% of that for plain tube. The straight line in Fig. 3 corresponds to the mean reduction (i.e. 74.5%) from the two plain tube results. Relatively good agreement with the notched tube results can be seen although the plain tube data is clearly insufficient for drawing further conclusions.

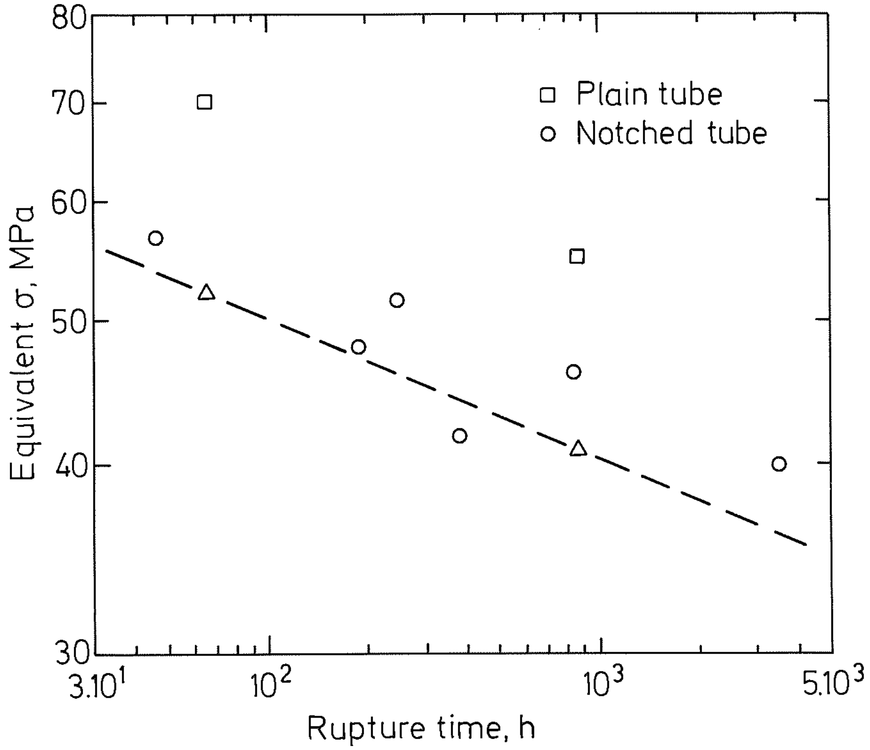

Fig. 3. Reduction in rupture strength of notched tubes compared with predictions from plain tubes.

CRACK GROWTH BEHAVIOUR

Using the relationship between potential drop and crack length it is possible to establish a profile for a developing crack from the potential drop measurements given for the different sensor pairs. An example is given in Fig. 4 for the test at 147.5 bar where the shape of the crack at failure as shown in the fractograph is consistent with the developing, potential drop derived, crack front. The drop in potential occurring beyond the extremities of the notch is caused by limited cracking extending from the notch in the axial direction. A rather long period of slow growth precedes the growth of a major creep crack and this can be seen for four of the tests in Fig. 5 where the maximum measured crack extension is plotted against (normalised) time. The 123 bar test result falls between the 109 and 134 bar curves and is omitted for the purpose of clarity. The proportion of life before the major crack growth commences is apparently independent of the applied load, however the potential drop recorded during this first stage clearly increases with increasing stress. Metallographic examination of the interrupted test-piece suggests that in the lower stress tests the development of creep damage through the ligament ahead of the crack tip occupies most of the life before joining up to form the major creep crack whereas at higher stress the crack presumably initiates early in the test but grows in a less creep damaged ligament.

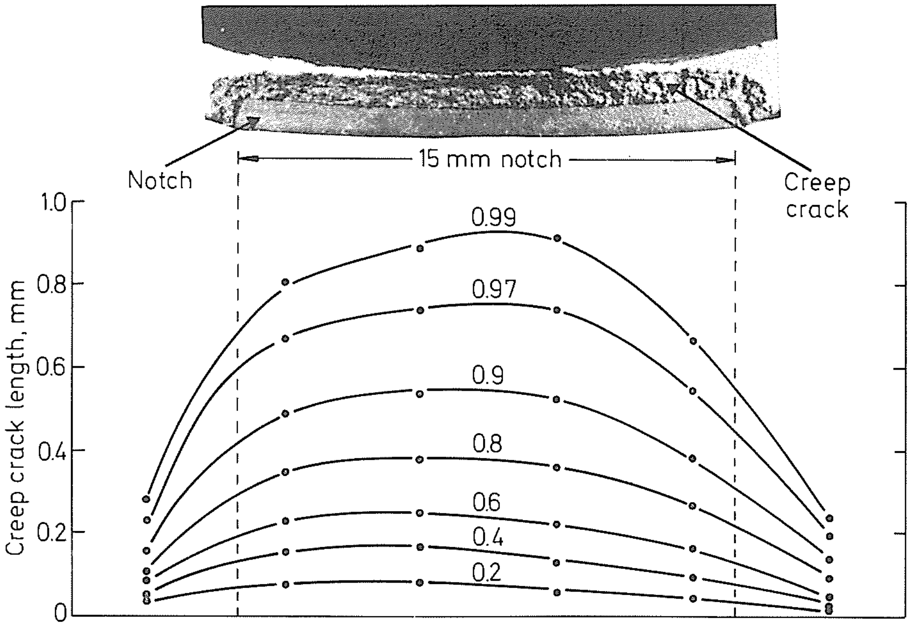

Fig. 4. Crack development profiles for certain life fractions and fractograph at failure for 147.5 bar test.

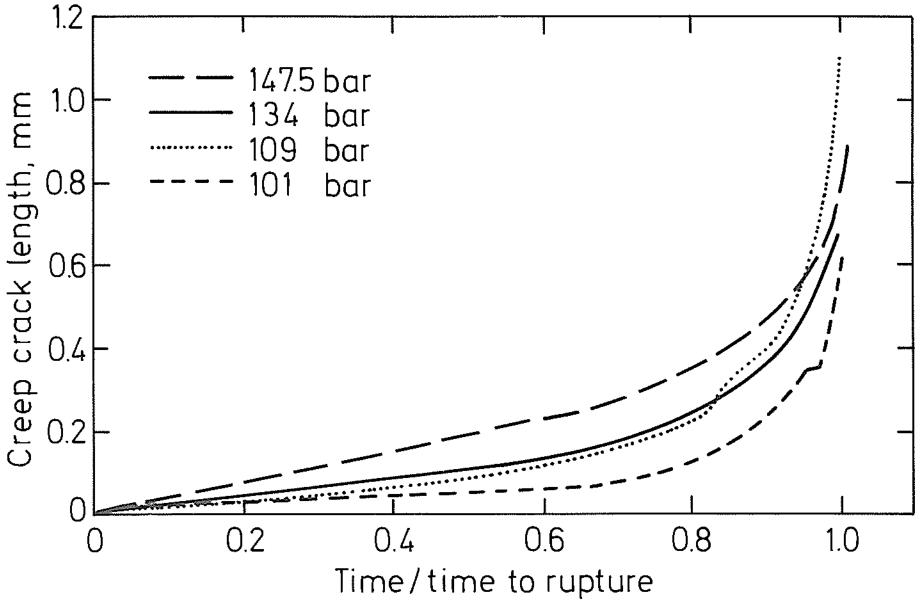

Fig. 5. Maximum creep crack extension dependence on normalized time.

Suitable methods available for analysing the creep crack growth data include K, σ_{net}, C.O.D. and C* but, as the objective is to compare the results with those obtained on the same material using conventional CCG testing, only the stress intensity factor, K, and C* are again selected. In the analysis of the single component test with a circumferential groove only C* is selected due to the decreasing crack growth velocity. Indeed calculation of the characteristic time (Riedel and Rice, 1980) which indicates K or C* control, in the range t_1 = 1-5 hours for Alloy 800H, tubes would point directly to C* being the most appropriate parameter. However in view of the accelerating crack growths observed, an assessment of K is included at least for comparison purposes.

The stress intensity factor along the notch root was calculated by approximating the rectangular to a semi-elliptical profile with the ellipse angle, ϕ, taken as the maximum value of $\pi/2$. this can be expressed in the general form (Raju and Newman, 1982)

$$K_I = \frac{pR}{t}\sqrt{\pi a/Q}\ G_i\ (a/c,\ a/t,\ t/R,\ \phi)$$

where Q is a shape factor for the crack defined as $1 + 1.464\ (a/c)^{1.65}$. Following the analysis of Raju and Newman, the influence coefficients G_i (i = 1-3) due to the different stress distributions were calculated for the present tube geometry. The calculated K_I values and their dependence on crack growth rate are shown in Fig. 6. The component results lie close to each other which is surprising in view of the scatter observed for specimens and the high creep ductility of this alloy. The shaded area defines the range of the standard specimen data and the component data clearly lies at lower K_I values for similar crack growth rates.

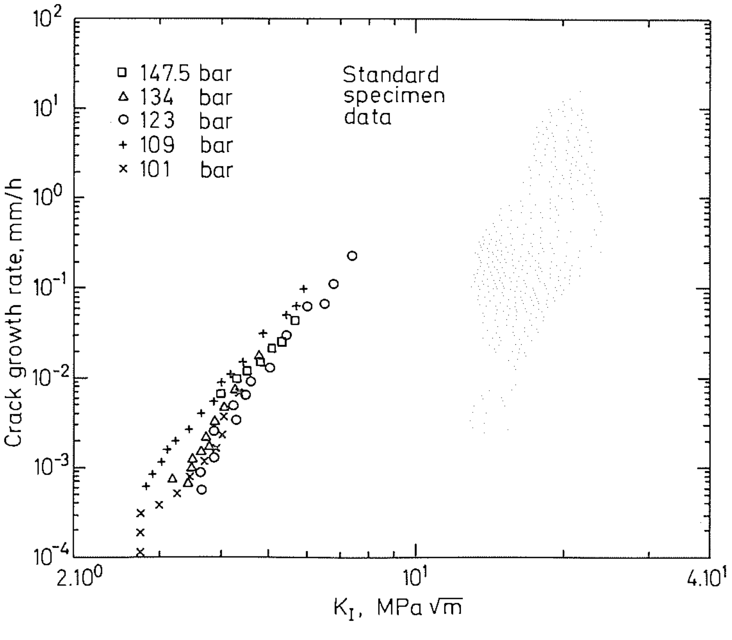

Fig. 6. Crack growth rate of Alloy 800H at 800°C as a function of stress intensity factor.

A method for the determination of C* for tubular notched components is not readily available and a CEGB procedure (Ainsworth, 1988) developed for assessing defective components in the creep range has been followed. This is particularly well suited to practical loading cases such as the tubular components of the present study.

The procedure derives from the fully plastic J solution of Kumar & Shih (1981) and is based on reference stress techniques which require calculation of the stress intensity factor and limit load solution for the defective component along with a power law equation governing creep of the material.

This analysis results in an expression for C* of the form

$$C^* = \sigma_{ref}\, \dot{\varepsilon}_{ref}\, R$$

where R is a characteristic length defined as $(K_I/\sigma_{ref})^2$

The reference stress is obtained from the global collapse pressure for this geometry (Miller 1987)

$$\sigma_{ref} = \frac{pR}{t}\left[1 - a/t + \frac{a/t}{\dfrac{(1+1.61c^2)}{Ra}}\right]^{-1}$$

where p is the test pressure and 2c is the defect length.

The minimum creep rate at the reference point is probably the most influential parameter in determining C* and is derived from the steady state Norton creep law. In order that direct comparison can be made with the specimen test data and with the data from the circumferentially notched tube the identical Norton constants are used i.e. A = 1.45E-19 and n = 6.5. The danger inherent in this choice for this particular alloy will be subsequently discussed. The calculated dependence of the crack growth rates on C* is shown in Fig. 7 where again the range of data from the specimen tests is shaded for simplicity and the result for the circumferentially notched pipe is added. Rather good agreement is obtained which would be expected in view of the low values of characteristic time between K and C* control calculated for this material.

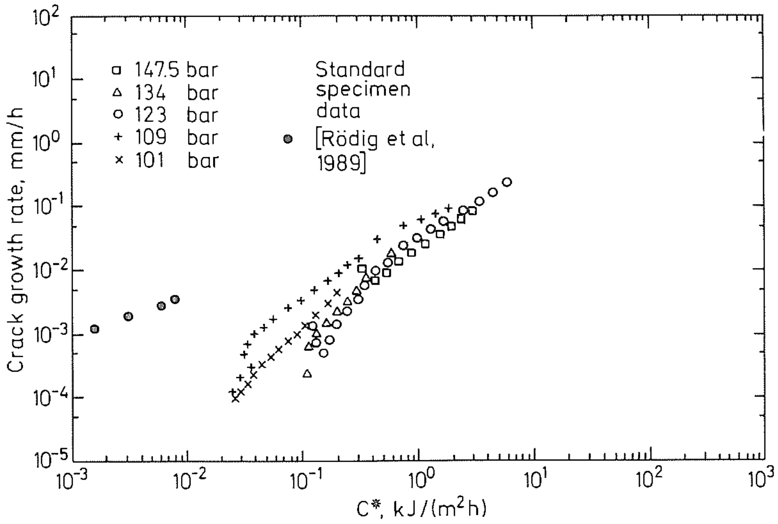

Fig. 7. Crack growth rate of Alloy 800H at 800°C as a function of C* integral.

As mentioned above, a critical aspect in the C* procedure concerns the selection of an appropriate creep equation for the material. In attempting predictions of creep crack growth behaviour in components from specimen data it is assumed that the creep behaviour of the material in component form is essentially the same as in the specimen form. For many ferritic materials this is indeed the case, however some austenitic steels can show anomalies, with Alloy 800H being a particularly sensitive material in this respect but nevertheless useful in illustrating the potential drawbacks.

The European COST 501 action (which included the creep crack growth work) also served to highlight the main factors which influence the creep behaviour of Alloy 800H as follows :

a) Level of test stress, where a distinct transition in creep behaviour was observed for the bar, and
b) Material state, where in the programme the same cast of Alloy 800H was processed into three material forms (bar, plate and tube) with differing mechanical properties.

With regard to test stress level, a significant change in creep constants above and below 50 MPa was observed for the bar. Although most of the CCG tests are carried out at stresses above this level, particular care should be taken when predicting low stress behaviour from high stress CCG data assuming that this transition is also observed for plate and tube material. Nevertheless the close proximity of the CCG curves obtained at different stresses suggests that no transition in creep properties occurs at least within the test stress range.

In the creep crack growth calculations, Norton constants from bar data were used even though the CCG specimens were machined from plate and the CCG components from tube stock. The tensile mechanical properties of these three forms differ widely, and hence difference in creep constants might be expected. The two internal pressure creep tests on unnotched tubes would point to much higher n and lower A values for the tube material compared to the bar data.

As C* is extremely sensitive to values of A and n, the reasonable agreement in CCG behaviour in terms of C* between the specimen and component tests implies that the creep properties of the tube and plate are similar but does not necessarily mean that they are the same as those derived from bar experiments. In fact the results strongly support the choice of the methodology developed in the present work for establishing creep crack growth behaviour in components where there is any doubt concerning the transferability of data from conventional specimen tests.

CONCLUSIONS

Tubular Alloy 800H components containing longitudinal spark machined defects have been creep tested to failure using internal pressure at 800°C. A systematic reduction in stress rupture properties was noted which was of the same order as found in the literature for other alloys. The potential drop method adapted for in situ measurement of the creep cracks emanating from the notches has successfully led to the possibility of directly comparing the creep crack growth behaviour of such components with conventional specimens.
As expected, the stress intensity factor, K_I, is not capable of correlating specimen and component results although, surprisingly, the component tests showed little scatter. The C* approach requires a creep equation for Alloy 800H which is known to be both material condition and stress level sensitive. However using the same Norton creep law constants for both specimens and components leads to excellent agreement of creep crack growth behaviour with the C* method. Notwithstanding the good correlation obtained, a successful component testing methodology could obviate the requirement for specimen obtained data thus avoiding any unnecessary risks in predicting component behaviour for product-form sensitive materials.

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