Creep and Fatigue Crack Growth in Tubes at High Temperatures

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ABSTRACT

Fracture mechanics experiments have been performed with several types of standard specimens and thick walled tubes made of Alloy 800. The aim was to demonstrate the transferability of creep and fatigue crack growth data at high temperatures.

In the creep crack growth experiments, steam reformer tubes were provided with an external 360°-crack in circumferential direction. The loading condition was axial tension with superimposed internal pressure at 800°C. As a result of the experiments it was found, that creep crack growth can be described by means of the energy rate integral C*.

The fatigue crack growth experiments have been performed with a thick walled tube with an external 180°-surface crack. It was loaded at a frequency of 5 Hz in four point bending. The evaluation of data was done on the base of several approximation methods from literature. Most of these methods are conservative.

INTRODUCTION

In order to demonstrate the transferability of fracture mechanics data in the high temperature regime (550 °C to 850 °C), creep crack growth (CCG) and fatigue crack growth (FCG) experiments have been performed with several specimen geometries. Beside standard specimens (1" CT, 1/2" CT, 1/2" CCP), thick walled tubes were tested in some experiments.

Seven tubes of 120 mm o.d. and 10 mm w.th. were tested before in fatigue crack growth experiments with pure tension. The results of these experiments were published elsewhere (Rödig et al., 1987) and shall not be considered in this paper. The work of this paper deals with the following experiments:

- CCG: tubes of 120 mm o.d. and 10 mm w.th. with an external circumferential crack (360°), loaded in tension and internal pressure at 800 °C.

- FCG: tubes of 197 mm o.d. and 23.5 mm w.th. with an external circumferential crack (180°), loaded in four point bending at 550 °C.

For both groups, additional reference experiments were performed with 1/2"CT-, 1"CT-, and 1/2"CCP-specimens.

MATERIAL

The test material for all experiments was the austenitic alloy X 10 NiCrAlTi 32 20 (Alloy 800) with the chemical composition (wt%):

C :	0.073	Fe:	Bal.	Ni:	30.7	Cr:	20.05
Al:	0.25	Ti:	0.31	Mn:	0.64	Si:	0.3

The standard specimens were taken from sheet material. The crack plane orientation was T-L in accordance with ASTM-E 399.

For the calculation of C*, the constants B and n of Norton's creep law

$$\dot{\epsilon} = B\,\sigma^n \qquad (1)$$

were required. They were obtained from supplementary creep experiments as $n = 5.3$ and $B = 1.9 \cdot 10^{12}\ h^{-1}\ MPa^{-n}$.

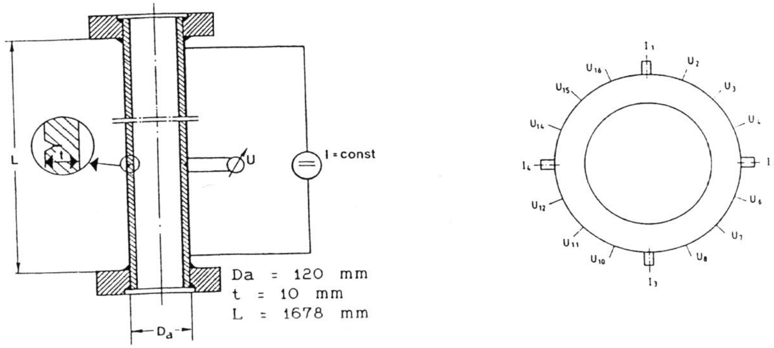

Fig. 1. Reformer tube with circumferential crack, connections for DCPD

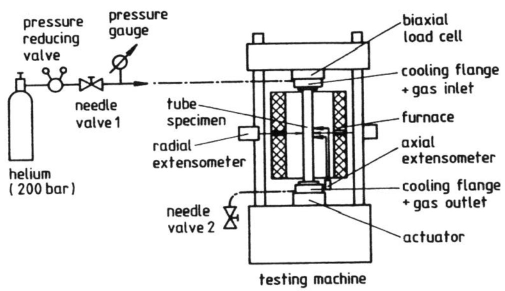

Fig. 2. Schematic diagram of the testing system

CREEP CRACK GROWTH EXPERIMENTS

Experimental Details

The standard specimen tests were carried out in an electromechanical testing machine. The system is provided with an induction heating and has a maximum load of 100 kN.

The reformer tubes of 120 mm o.d. and 10 mm w.th. were provided with a circumferential notch of 2.5 to 3 mm depth (cp. Fig. 1). Before the high temperature experiment was started, the tubes were provided with a fatigue crack at room temperature up to a/t = 40 %.

For testing the steam reformer tubes, a servo-hydraulic testing system with 500 kN maximum load and with a 7-zone tubular furnace was used (cp. Fig. 2). The tubes were passed through the top and bottom of the furnace. Load cells and testing cylinders were protected against excessive heat by cooling flanges. These cooling flanges also served to introduce the internal pressure by helium. The needle valve 1 protects the pressure reducer upon failure of the tube. Needle valve 2 represents an artificial leak and is adjusted to a very low flow rate. This mode of operation ensures a more accurate control of the pressure reducer and simultaneously compensates for small leaks in the pressure system.

The crack length was determined using the DC potential drop (DCPD) technique. While this method is widely employed for CT specimens, extensive preliminary work and calibrations were required for its application to tubes. The measuring current of 80 A was applied at four points near the flanges (cp. Fig. 1). Voltage was measured at 16 positions across the circumference. The DCPD-technique was calibrated using a dummy tube with circumferential saw cut. The location of the potential monitoring position was optimized with regard to sensitivity and noise margin.

Calculation of the loading parameters K_I and C*

The K_I values for the CT specimens were calculated from the equation

$$K_I = \frac{F}{D\,W}\,Y \qquad (2)$$

where F is the load, D the specimen thickness and W the specimen width. The function Y was taken from ASTM-E 399 for the CT-specimens and from the EPRI-handbook (Kumar et al., 1984) for the tubes.

The tube specimens exhibited non-uniform crack growth across the circumference. For the calculation of K_I the crack shape was idealized, and the assumption of a fully axisymmetric crack front was made.

C* was calculated using the equation (Riedel and Wagner, 1984):

$$C^* = \eta\,\dot{v}\,\sigma_{net} \qquad (3)$$

With σ_{net} = net section stress, and $\dot{v}$ = crack opening displacement rate. For the CT-specimens $\eta = 2$ can be assumed. For tube geometries with circumferential flaws, no solutions for η are given in literature. For this reason, finite-element simulations were carried out for this specimen geometry loaded by internal pressure p and superimposed tensile stress F

(Rödig et al., 1988). The C* values were determined for the maximum initial crack length a = 3.6 mm, the minimum initial crack length a = 2.6 mm, and for an average crack length a = 3.05 mm from the line integral. η was determined by equating the numerically obtained value of C* with eq. (3). The values of ϑ were used from those points at which the opening measurements were actually taken in the equipment.

As in the case of standard specimens, η only depends on the crack depth to a very limited extend. A change in crack depth by 30 % causes a change in η by 3 %. An average value of η = 1.35 has been determined. This value was used for the calculation of C* in the CCG experiments with tubes.

Results

Two tests were performed on steam reformer tubes to study creep crack growth. In both cases, the tensile load was superimposed by a constant internal pressure. The load conditions were:

- int. pressure: 40 bars, tensile stress: 5 MPa (tube no. AYJ-1.3)
- int. pressure: 50.4 bars, tensile stress: 26 MPa (tube no. BCD-EN1)

During the experiment the crack length was continuously measured by means of the DC potential method. For the tube AYJ-3.1 the variation in crack length at the radial positions U_1 and U_{13} which show the largest amount of crack growth, is shown in the left part of Fig. 3. Up to about 200 hours, the crack growth velocity decreases and then remains approximately constant. The right part of Fig. 3 shows the crack opening displacement at the same circumference positions.

In view of the decreasing crack growth velocity, it does not appear meaningful to plot da/dt vs. K_I. Moreover, a calculation of the transition time t_1 according to Riedel and Wagner (1984) shows that crack growth should be definitely C*-controlled. For this reason the crack velocity da/dt was plotted versus C* (Fig. 4). The open symbols represent the calculated C*-values at the positions U_1 and U_{13} of tube no. AYJ-3.1.

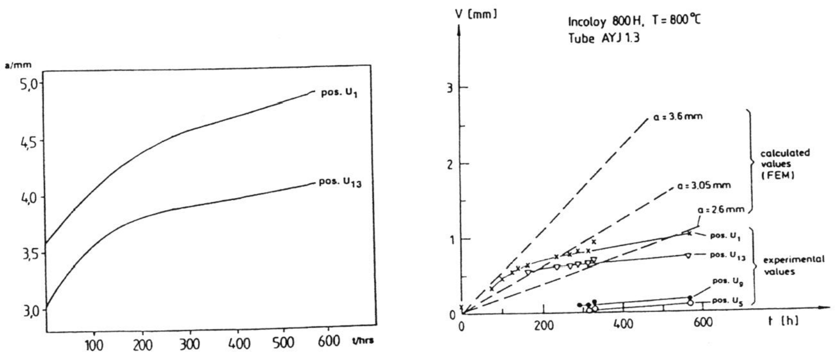

Fig. 3. Progression of crack depth (left) and crack opening displacement (right) at two positions of the reformer tube

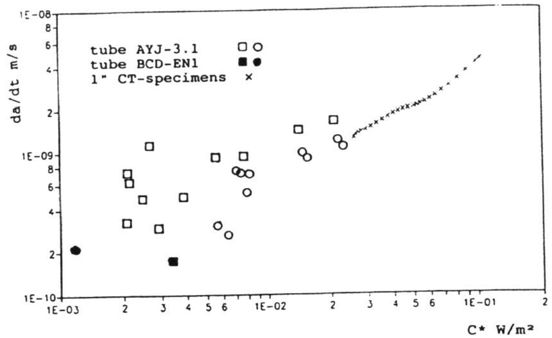

Fig. 4. Crack growth velocity da/dt as a function of C* for reformer tubes and CT specimens

For the tube BCD-EN1 again an evaluation was possible at two circumferential positions. However, the change in crack opening was very small so that it appeared only meaningful to average C* over the entire test period in view of the measuring accuracy. The results of this tube are represented by the filled symbols of Fig. 4.

The CCG-results for the reformer tubes and for the CT-specimens are in good agreement. Therefore it may be assumed that the C* concept is suitable for describing the creep crack growth in Alloy 800 at 800 °C.

FATIGUE CRACK GROWTH EXPERIMENTS

Experimental Details

The standard specimens were tested in a servohydraulic testing system of 100 kN maximum load. The specimens were heated by means of a high frequency generator.

The tubes of 197 mm o.d. and 23.5 mm w.th. were tested in 4 point bending on a stress plate of. The stressing was produced by a servohydraulic actuator of 100 kN max. load. The temperature of 550°C was achieved by heating mats. The tubular specimens were provided with an external 180° cut of 50 % depth, produced by spark erosion (cp. Fig. 5).

As in the case of the CCG experiments (comp. to Chapter 3.1), the crack depth was measured by the DC potential drop method. A current of 80 A was used, and the potential drop was measured at 24 positions around the circumference of the tube.

Calculation of ΔK_I

For the standard specimens, K_I again was calculated according to equ.(2) with Y from Schwalbe (1980) for the CCP-specimens.

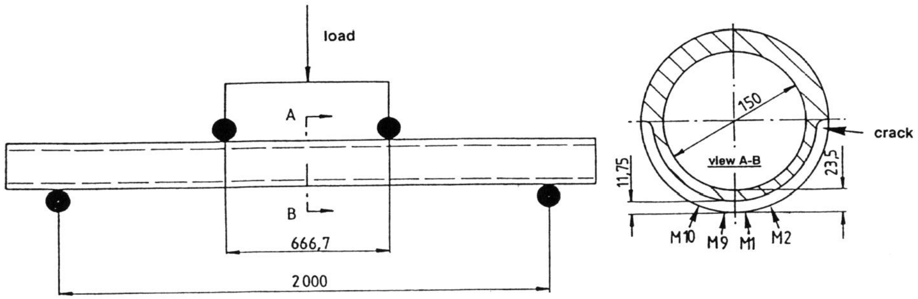

Fig. 5. Schematic diagram of the bending apparatus for fatigue crack growth experiments with tubes

For the calculation of ΔK_I in a tube with a surface crack in circumferential direction, the several approximation methods from literature were considered:

a) calculation by Newman and Raju (1981) for a plate with a surface crack in 4 point bending;

b) equ. (2) with Folias factor for a semi-elliptical surface crack;

c) same as b, but with additional consideration of small scale yielding (methods b and c were described by Schwalbe, 1980);

d) EPRI-solution (Kumar et al. 1984) for an axisymmetric crack in tension (cp. ch. 3.1);

e) finite element calculation of Grebner and Strathmeier (1985) for a surface crack in tension.

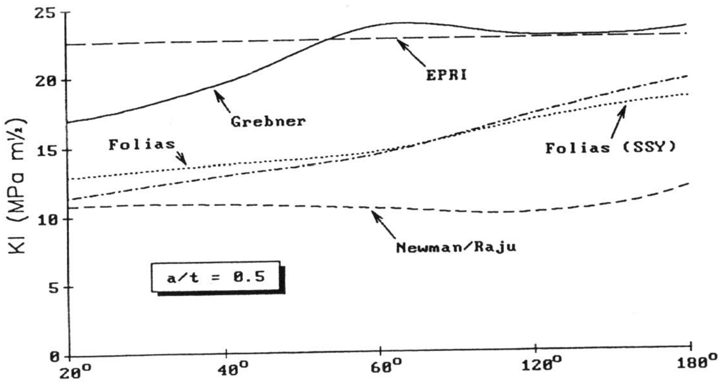

Fig. 6. Calculated stress intensity factor for tubes with circumferential cracks loaded in bending

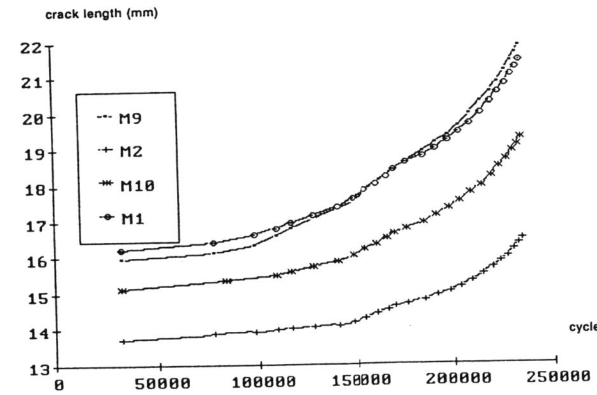

Fig. 7. Progression of crack depth during a fatigue experiment (tube in 4 point bending

Figure 6 shows a comparison of calculated K_I-values for all 5 methods, under the assumption of 50 % crack depth, a crack width between 10 and 180°, and a load of 100 KN.

Results

Figure 7 shows the crack length as a function of cycles at the four potential measuring points (cp. Fig. 5). In the first phase of evaluation, the da/dN vs. ΔK_I-curve only for the regime between 60 and 90 % crack depth was calculated. The results for the two measuring points with the highest bending moments (M1 and M9) agree very well, and hence the same symbol was used in the following diagrams.

The calculation of ΔK_I was done by means of the five equations mentioned above, and da/dN vs. ΔK_I-curves were plotted in Fig. 8. These curves are compared to the scatter band of the CT- and CCP-specimens.

The agreement with the results of standard specimens is poor for all calculation methods. But most of them give conservative results. Method "d" and "e", by which the real crack shape is described best, are in rather good agreement. For these methods the same Paris-exponent is found as for the standard specimens, but the crack propagation rate is significantly lower.

The poor agreement for methods "a" to "c" is thought to be due to the bad description of the real crack front. For method "d" and "e" it is thought to be due to simplified assumptions for the loading conditions (no consideration of bending moments). A finite element calculation considering the actual crack front and loading condition is under progress.

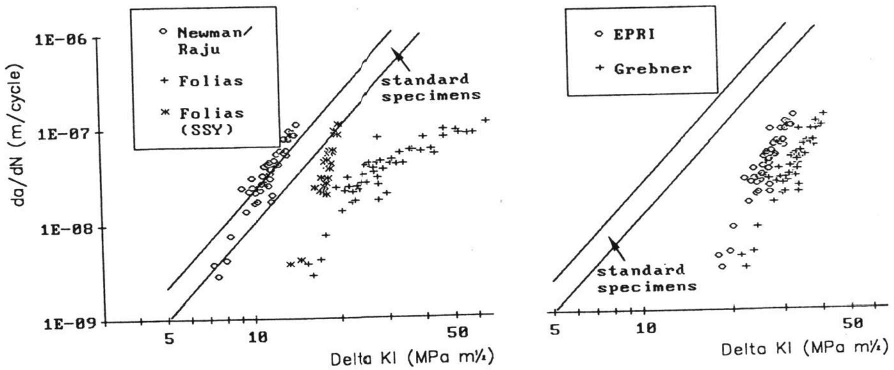

Fig. 8. crack growth rate da/dN vs. loading parameter K_I, calculated by several approximation methods

CONCLUSIONS

The aim of transferring fracture mechanics data for Alloy 800 from standard specimens to components was reached only partially. If the energy rate integral C* is used as a loading parameter, the creep crack growth rates in tubes (loaded by internal pressure and tension) can be described on the base of CT specimen results. The description by means of K_I is unsatisfactory. The transferability of fatigue crack growth data to a tube loaded in four point bending, was less successful. Although most of the methods to calculate K_I give conservative results, the agreement of standard specimens and tubes is poor.

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Part of the investigations reported in this paper have been carried out under the contract of the German Federal Minister for the Environment, Nature Conservation and Nuclear Safety. The minister accepts no responsibility for the correctness, accuracy, and completeness of the information or for the due consideration of the private rights of third parties. Furtheron, the authors want to thank the company Hochtemperatur-Reaktorbau GmbH for their support.