CREEP CRACK GROWTH AND CONSTRAINTS IN WELDMENTS

T. Vilhelmsen *ELSAMPROJEKT A/S, 7000 Fredericia, Denmark*
G. A. Webster *Imperial College, London SW7 2BX, England*

ABSTRACT

This paper is concerned with creep crack growth in the heat affected zone of a weldment (HAZ). The paper presents creep crack growth testing results obtained on modified 9Cr steel (P91). The test program is addressing creep crack growth in the heat affected zone by testing welded compact tension specimens in which the crack was growing along the intercritical zone. The constraint effect arising due to the presence of different material properties was studied numerically, and different methods for estimating a fracture mechanics parameter for the case of a welded specimen were investigated by means of finite element analysis.

KEYWORDS

Creep, crack, welding, Type IV.

INTRODUCTION

In recent years power stations have faced increasing demands for environmental protection. This has led to increasing interest in new technologies which can improve the efficiency of power production, and thereby reduction of CO_2 emissions. One way of improving the efficiency is to build power plants with advanced steam cycles. Another option is to increase steam temperatures and pressures. In Denmark, a study of advanced steam cycles has been undertaken by ELSAM/ELSAMPROJEKT, and the study has shown that a thermal efficiency of 47.5% or even higher can be achieved with a steam temperature of 580°C and a pressure of 300 bar (Kjær, 1990). Two power plants of this type will enter into operation in Denmark in 1997. These advanced steam conditions can only be reached if material with higher creep strength than the well known 21/4Cr1Mo or 12CrMoV steels are used for thick walled components. 12CrMoV has been used for a number of years with good service experience, but the maximum achievable steam conditions are in the range of 560°C/250 bar.

Experience shows that, creep failures of components are almost exclusively located in the weldments due to wrong welding procedures or simply due to a changed microstructure in the base material as a result of heat generated during the welding process. A strict quality control system should be able to rule out failures caused by wrong welding procedures, whereas a damaged microstructure is an inherent problem which cannot be solved by simple measures.

FRACTURE MECHANICS AT HIGH TEMPERATURES

Analogue considerations show (Landes *et al.*, 1974) that the path independent J-integral for plasticity (Rice, 1968) can be used to quantify the stress field around a creep crack tip:

$$\sigma_{ij} = \left(\frac{C^*}{I_n C r}\right)^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta,n) \qquad 1$$

Thus, C* can be presented in the form:

$$C^* = h_1(a/w,n)(w-a)\sigma_0\dot{\epsilon}_0\left(\frac{P}{P_0}\right)^{n+1} \qquad 2$$

where σ_0, $\dot{\epsilon}_0$, C and n are material constants. P is the applied force and P_0 is a normalising load, often calculated as the limit load. The quantity h_1 is tabulated for different geometries and different values of n, eg. Kumar *et al.,* 1980. C* can also be estimated by using the reference stress method (Ainsworth, 1982; Webster *et al.*, 1994):

$$C^* = \sigma_{ref}\dot{\epsilon}_{ref}\left(\frac{K}{\sigma_{ref}}\right)^2 \qquad 3$$

This expression is independent of creep behaviour, therefore, any creep law or even raw creep data can be used. For a CT specimen, C* is estimated from the load line displacement rate:

$$C^* = \frac{P\dot{\Delta}}{B W} F \qquad 4$$

where B is the thickness, F is a function of n and geometry. The product $P\dot{\Delta}$ can be regarded as the total energy dissipation rate within the specimen.

There are many models in the literature which suggest proportionality of the creep crack growth rate and C* raised to some power e.g. Nikbin *et al.* (1984, 1986):

$$\dot{a} = (n+1)\frac{\dot{\epsilon}_0}{\epsilon_f^*}\left(\frac{C^*}{I_n\sigma_0\dot{\epsilon}_0}\right)^{\frac{n}{n+1}} r_c^{\frac{1}{n+1}} \qquad 5$$

where ϵ^*_f is the failure strain and r_c is the creep process zone.

CREEP FAILURE OF WELDMENTS

Service experience has shown that the creep life of a component is limited by the strength of the weldment since the final failure of components almost always occurs here. These failures are linked with a changed microstructure brought about by the heat input into the base material during welding. Failures are often located in a narrow zone next to the weld material. The different kinds of failure which can occur in weldments are classified into four types according to there location. The so-called Type IV cracking covers cracks located in the intercritical zone. It has been reported, Blum (1988), that type IV cracking has been responsible for 25% of all creep damage in the past 20 years in Danish power stations where the remaining 75% was due to improper welding procedures.

The uniaxial creep properties are also changing for the different zones of the weldment e.g.

Metcalfe *et al.* (1993) found the minimum strain rate at 600°C and 100MPa for P91 weld material, Intercritical HAZ material and Coarse grained HAZ material compared to the base material:

$$\dot{\epsilon}_{WM} = 0.09\,\dot{\epsilon}_{BM}\ ,\quad \dot{\epsilon}_{IC\text{-}HAZ} = 64\,\dot{\epsilon}_{BM}\quad \text{and}\quad \dot{\epsilon}_{CG\text{-}HAZ} = 3\cdot 10^{-6}\,\dot{\epsilon}_{BM}$$

Where index BM is referring to base material. It is evident from this study that there is a large difference in uniaxial creep properties across the zones.

CREEP OF WELDED CT-SPECIMENS

The present study is simulating Type IV cracking using P91 (Iseda *et al.*, 1988) by performing creep crack growth tests on CT-specimens machined from a welded pipe such that the notch is placed in the intercritical zone of the weldment, Fig. 1.

The ability of C* estimated from load line displacement data to characterise the stresses local to a crack tip at a material interface is investigated by comparing the value calculated from load line displacement data C^*_{LL} (or C*LL) with the value obtained from a contour integral around a crack tip C^*_{int} (or C*int) both values are calculated using a multi-material finite element model. C*LL is the total dissipated energy rate for the whole specimen. Three different regions were included in the finite element model of the interface ie. weld, intercritical zone and base material, where the coarse grained HAZ region was given the properties of the weld material. The material data for the individual zones were taken from Eggeler *et al.* (1994) for P91 at 600°C.

Two C* values are calculated for each loading 1) C*int from the contour integral and 2) C*LL from the load line displacement. Fig. 2 serves as examples of the calculated C*int values for two different net section stresses. The bars indicate the C* values obtained if the specimen was homogeneous weld, base or IC-HAZ material, respectively. The horizontal line marked C*int correspond to the value obtained by integration along the contour. Note that the value from integration along the contour is almost equal to the value for the base material. This point is discussed later.

The final result for the multi-material model is presented in Fig. 3 as the ratio of the C*LL to C*int, ie. the ratio of C* estimated from load line displacement to C* calculated by contour integrals, this ratio is about 0.9. It can therefore be concluded that the traditional way of estimating C* from experimental data for a homogeneous specimen will provide a good representation of the stresses local to the crack tip for a specimen with the crack growing along a type IV region.

As mentioned earlier the contour integral was almost equal to the value which would be found if the material data of the base material were used. Whether or not this is a coincidence is investigated with the following parameter variation. Two extreme situations were calculated, the first case is for material 1 in Fig. 4 equal to weld material and material 2 is HAZ, thus a weak HAZ surrounded by the strong weld. This situation is referred to as weld-HAZ-weld interface. The result of this analysis is given in Fig. 5 along with the inverse situation where a strong weld is enclosed by a weak HAZ (HAZ-weld-HAZ), the bars indicate the C* value obtained for a homogeneous specimen with material properties equal to weld material and intercritical HAZ, respectively.

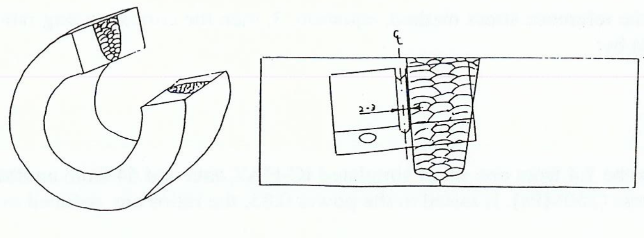

Fig. 1 Positioning of the CT-specimens cut from the pipe simulating Type IV cracking. Internal diameter of the pipe is 241 mm, wall thickness is 56 mm

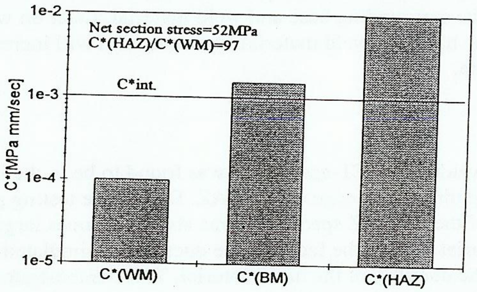

Fig. 2 The contour integral from the multi-material Finite Element model (C*int) compared to the values obtained assuming a homogeneous specimen made from weld, base and IC-HAZ material. The net section stress is 52 MPa

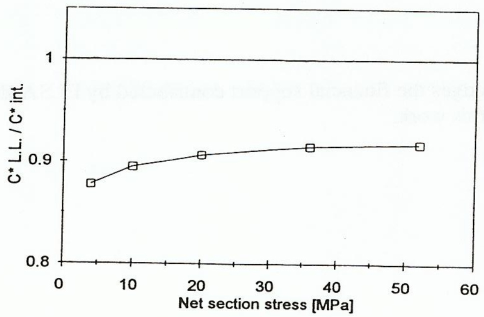

Fig. 3 Ratio of C* in the mulit-material model calculated from load line displacement to contour integration as a function of net section stress

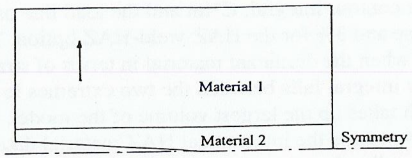

Fig. 4 Symmetric model used for a parameter variation where two different materials combinations are used. Combination 1: material 1 is IC-HAZ and material 2 is weld material (HAZ-weld-HAZ). Combination 2: material 1 is weld material and material 2 is IC-HAZ (weld-HAZ-weld). Model size is w=50mm and the distance from the symmetry line to the interface is 2mm

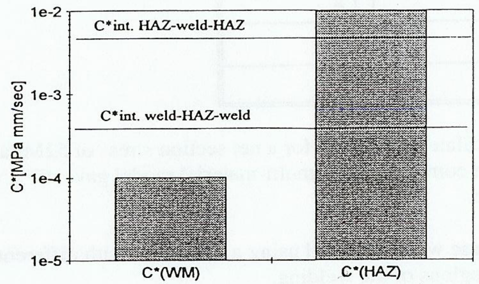

Fig. 5 The contour integral falls between the homogeneous results, closest to the material which is occupying the largest volume of the model

The difference between the contour integral, C*int and the load line parameter C*LL was 13% for the weld-HAZ-weld case and 3% for the HAZ-weld-HAZ option. This indicates that the best prediction is obtained when the dominant material in terms of strain rate is occupying a larger volume. The contour integral falls between the two extremes in both cases, but it is closer to the material which takes up the largest volume of the model. It is therefore concluded that it would be conservative to use the intercritical HAZ material data for calculating C* since this zone occupies only a small volume and has weak properties. It can further be concluded that an under matched filler material would increase C* compared to an over matched filler.

A summary of all C* values calculated for the multi-material model is given in the table below

$C^*\times10^3$ [MPa*mm/sec]	Reference stress	Kumar and Shih
Base material	4.12	1.8
Weld material	0.23	0.1
IC-HAZ	20.6	10

Table 1 Summary of all calculated C* values for a net section stress of 52MPa using material data from Eggeler (1994). In comparison the multi-material model gave: C^*_{int} =1.05e-3 and C^*_{LL}=0.96e-3, MPa*mm/sec.

C* for the reference stress case was calculated using a FE model with different material properties for the different regions of the welding.

A conservative estimate would be the result if the weakest of the materials was used for calculating C* (about 20 times the contour integral value from table 1). A less conservative estimate will result from the base material creep parameters. Note that the reference stress estimate and Kumar value are in good agreement when the base material properties are used.

COMPACT TENSION TESTING RESULT

A number of creep crack growth experiments were performed in the following configurations: P91 Base material and P91 IC-HAZ. These results were obtained with a net section stress in the range of 38MPa which corresponds to a reference stress of about 150MPa (assuming plane strain and a/W=0.5). Curve fitting of the experimental data gave the relative result for the intercritical zone specimens relative to the base material specimens:

$$2 \leq \frac{\dot{a}_{IC-HAZ}}{\dot{a}_{BM}} \leq 3.2$$

The ductility of the IC-HAZ material has been found to be about a factor of 1.5 larger than for the base material, (Eggeler *et al.* (1994) and Metcalfe *et al.* (1993)). The IC-HAZ crack rate was therefore expected to be lower and not higher than for the base material, equation, 5. This shows that the IC-HAZ region is constrained by the surrounding material resulting in a larger cracking rate. Therefore, the creep properties of the different zones will have a relatively larger influence on the cracking rate since the creep strain rates differ more than the ȧ vs. C* relations.

If C* is estimated by the reference stress method, equation, 3, then the corresponding ratio of C* values can be given by:

$$\frac{C^*_{IC-HAZ}}{C^*_{BM}} = \frac{\dot{\epsilon}_{IC-HAZ}}{\dot{\epsilon}_{BM}}$$

This ratio was found to be 7.4 from one set of simulated IC-HAZ data and 64 from another data set at the reference stress (150MPa). If raised to the power 0.85, the ratios are reduced to 5.5 and 34, respectively.

The creep crack growth test showed that IC-HAZ material had a faster cracking rate compared to the base material but a longer incubation period. This behaviour can be explained by the spread of creep after load application. Shortly after the specimen is first loaded creep strain will be present locally near the crack tip and elastic strains are dominating elsewhere. In this situation the specimen is acting in an almost homogeneous fashion because only little creep strains have accumulated in the surrounding base and weld material. Later on when creep strains are accumulating in the base and weld material, the constraint will increase which in turn increases the cracking rate.

CONCLUSIONS

The actual crack path in the welded P91 CT-specimens was found to be in the intercritical zone closer to the fine grained zone than to the edge of the HAZ. During the testing program it was found that the cracking rate of the IC-HAZ specimens was about 2.5 times larger than the cracking rate of the base material despite the fact that the ductility of simulated intercritical HAZ material is larger than the ductility of the base material. This demonstrates the presence of a constraint effect in the HAZ causing the cracking rate to become larger for the IC-HAZ specimens compared to the cracking rate of the homogeneous base material specimens.

It has been demonstrated experimentally that the C* value for a crack situated in the intercritical HAZ can be well estimated by using the material properties of the base material. This is useful for practical purposes when a welded structure containing a creep crack is to be assessed.

ACKNOWLEDGMENTS

The authors greatly acknowledges the financial support contributed by ELSAM and ELSAMPROJEKT towards this work.

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