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Creep lifetime assessments of ferritic pipeline welds

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ABSTRACT: The low alloy ferritic steam pipework in Advanced Gas Cooled Reactor (AGR) power stations operates at temperatures in the creep range. An inspection strategy for continued operation of the pipework has been developed based on estimation of the creep rupture life of pipework weldments and fracture mechanics for demonstrating acceptance of defects. This strategy is described in outline. The estimation of creep rupture life is described in more detail. Validation for the approach is illustrated by comparison with pressure vessel tests and with metallographic examination of components removed from service. The fracture mechanics methods are also described. It is shown that the amount of creep crack growth is dependent on the life fraction at which the assessment is made; crack growth being rapid as the creep rupture life is approached.

1 INTRODUCTION

The steam pipework in AGR power stations operates at elevated temperatures and pressures where creep deformation occurs. To meet this demand, the pipes and associated welds are manufactured from creep resisting steel. In particular, a low alloy steel combination of ½Cr½Mo¼V pipe welded with 2¼Cr1Mo weld metal (CMV weldments) has been used extensively. In general, these pipework systems have operated satisfactorily and, in some cases, for times well in excess of their original design creep lives, 150,000 h or more. However, creep deformation giving rise to Type IV cracking in the low alloy ferritic steel weldments has been encountered from times midway through the plant life and onwards.

Inspection and assessment strategies have, therefore, been put in place to detect Type IV cracking and enable the significance of such damage to be assessed in terms of the continued safe operation of plant. These are described in this paper.

2 PLANT EXPERIENCE

The problem that has developed in CMV weldments after service times of about 50,000 h and onwards involves circumferential cracking in the heat affected zone (HAZ) immediately adjacent to the parent material. During welding, HAZ thermal cycles that reach peak temperatures in the intercritical range cause partial transformation of the matrix and incomplete dissolution of carbides. This produces a microstructure with a fine grain size of spheroidised carbides which results in a narrow band of low creep strength, high ductility material. Under simple pressure stress loading this region has little effect on life when compared with the design intent. However, when additional stresses arise, such as at changes of geometry or terminal locations such as branch or nozzle connections, the presence of the intercritically transformed material leads to the development, of so-called, Type IV damage. Furthermore, if this damage is not detected, crack initiation occurs and growth may proceed rapidly through the band of creep damaged material, leading to the formation of a Type IV crack as shown in Figure 1.

Figure 1 - Type IV Cracking in a CMV Weldment (x 1½)

3 INSPECTION STRATEGY

The inspection strategy for Type IV cracking is based either on a database of previous experience or on a creep life fraction approach. Experience has shown that weldments that might be subjected to additional loadings, such as large bore branch connections or terminal butt welds, are particularly susceptible, while joints such as simple butt welds in plain pipe are least at risk. This was based largely on the analysis of steam leakage incidents and inspection data from fossil fired plant, but has recently been reviewed with regard to its applicability to Nuclear Electric's AGR plant. From this review, inspection requirements have been produced that specify initial inspection times, frequency of inspection and sample size for each category. Such requirements are illustrated in Table 1 for categories of CMV weldment that are most, moderately and least susceptible to Type IV cracking.

CMV Weldment Category	1st Inspection		Subsequent Inspection	
	Sample %	Time kh	Sample %	Time kh
Pipe to pipe butt	10	76-100	10	25
Pipe to steam chests	50	45-65	50	25
Large bore branch	100	48-77	100	25

Table 1. In Service Inspection Requirements for the Detection of Type IV Cracking

From the examples given in Table 1 it is clear that the number of joints targeted for inspection increases as the expectation of Type IV cracking increases. Similarly, the times for the first inspections are shorter for the more susceptible categories, based directly on plant experience. Thereafter, the time for repeat inspections have been justified to follow the operating regime for plant for all categories. The difference in sample size for each category remains the same but would be changed, if appropriate, in the event that cracking was detected.

4 CREEP LIFE ASSESSMENT

In contrast to the above approach based on experience, a preferred option which has now been developed is based on estimation of the creep life fraction using Nuclear Electric's assessment procedure for the high temperature response of structures, R5 (Nuclear Electric 1994). This procedure uses the plant operating conditions, lower bound creep rupture data, system stresses from pipework analysis and nominal or measured pipe dimensions to assess the creep life for individual weldments. Thereafter, these assessed creep lives are used as the basis for targeting the weldment inspection requirements for the plant.

The overall loading, characterised by a magnitude P, is related to a reference stress, σ_{ref}, by

$$\sigma_{ref} = P\sigma_y / P_L(\sigma_y) \tag{1}$$

where P_L is the value of P at plastic collapse assuming a rigid plastic material of yield stress σ_y. Equation (1) has been developed for homogeneous structures (Ainsworth and Budden, 1994). In weldments the differing creep strengths of the weld metal, parent and HAZ materials causes redistribution of stress. Also the rupture characteristics of the constituent materials may differ. Redistribution is addressed by defining, for hoop-dominated loading, a scaling parameter k, which differs between weld zones: k exceeds unity for creep strong materials which tend to pick up stress in creep; conversely $k < 1$ for regions which off-load stress. The factor k can be obtained by computer creep analyses of the component, and values are given in R5 for the CMV weld as well as other common combinations of parent and filler materials. The k factor multiplies the reference stress of equation (1) for calculations of rupture in each zone.

The rupture time is estimated as

$$t_{CD} = t_r(k\sigma_{ref}) \tag{2}$$

where $t_r(\sigma)$ is the lower bound creep rupture life at stress σ. The time to rupture of the complete weldment is taken to be the lowest of the times to rupture for the constituent zones.

The inspection strategy involves comparing a fraction of this assessed creep life with the plant operating times to the next and subsequent planned outages, t_{NO} and t_{SO}, respectively. Experience of creep life assessments has indicated that 80% of life is an appropriate time for inspections to commence, this time being referred to as t_I. The derived inspection strategy is simply illustrated in Figure 2.

In following this route a number of additional factors must be taken into account. Firstly the initial 5% speculative sample inspections of the weldments in any one category should commence at times as indicated from the experiential approach, Table 1. Furthermore, these samples should be on different weldments for each category at each outage. Finally, when the weldment assessed creep life falls between t_{NO} and t_{SO} or below t_{NO}, further justification is required to return the weldment to service, even though inspection has shown it to be clear of damage. Such justification often involves creep crack growth calculations, again using procedures given in R5, which are described below.

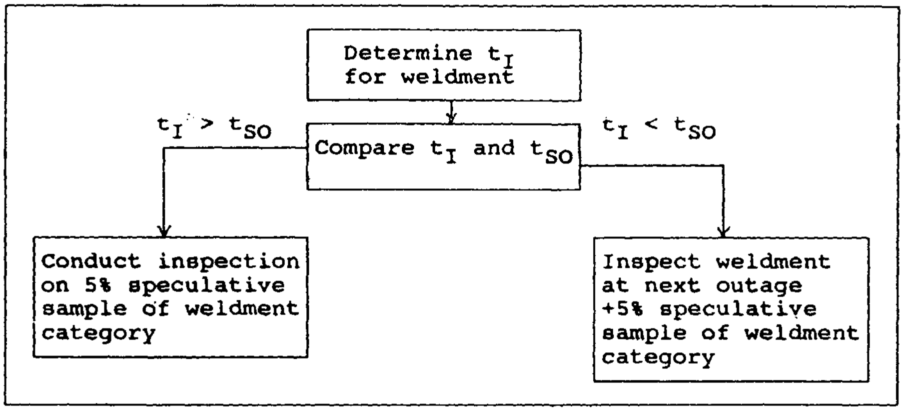

Figure 2. Creep Life Fraction Assessment - Inspection Flow Chart

5 CREEP CRACK GROWTH CALCULATIONS

The basic creep crack growth approach in R5 is to evaluate the creep crack tip parameter C* from

$$C^* = \sigma_{ref}\, \dot{\epsilon}_c\, R' \qquad (3)$$

where σ_{ref} is the reference stress from eqn (1) but allowing for the effect of crack size through its influence on P_L, $\dot{\epsilon}_c$ is the creep strain rate at the current reference stress and R' is a length scale estimated as $R' = (K/\sigma_{ref})^2$ where K is the elastic stress intensity factor. The creep crack growth rate, ȧ, is then obtained from experimental data often presented in the form

$$\dot{a} = AC^{*q} \qquad (4)$$

where A and q are material and temperature dependent constants. For weldments, the reference stress is again modified by the factors, k, discussed in Section 4 and the constants A,q are evaluated for the material zones in which the crack progresses as it grows through the wall.

The strategy for future operation is based on assuming the existence of short shallow defects and calculating the crack growth in the period (t_{SO} - t_{NO}) using equations (3) and (4). Some results are shown schematically in Figure 3. It can be seen that the extent of creep crack growth increases as the time at which the assessment increases. This is a consequence of the creep strain rate in equation (3) increasing as t_{NO} approaches the rupture life t_{CD}. Consequently, replacement becomes a more likely option as the joint approaches its assessed life.

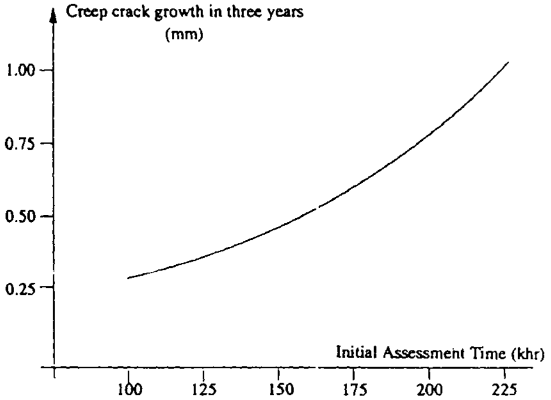

Figure 3. Schematic Result of Creep Crack Growth Calculations

6 VALIDATION

Validation for the creep life and creep crack growth approaches in Section 4 and 5 has been addressed by detailed finite-element analyses and by experiments on test specimens and components, as described in R5. For weldments, a particular example of the validation has been on a welded steam pipe of wall thickness 60mm and outer diameter 350mm operating at 565°C. The pipe was subjected to an internal pressure of 35MPa and failed after 46085h as a result of creep crack growth at a machined defect in a HAZ adjacent to an end-cap. The pipe contained a number of machined defects and results of measured crack depth are compared with the predictions of eqn (3) and (4) in Figure 4. It can be seen that there is good agreement between measured and experimental crack depth and also that the actual vessel failure time is close to the estimated value of t_{CD} which was 46399h.

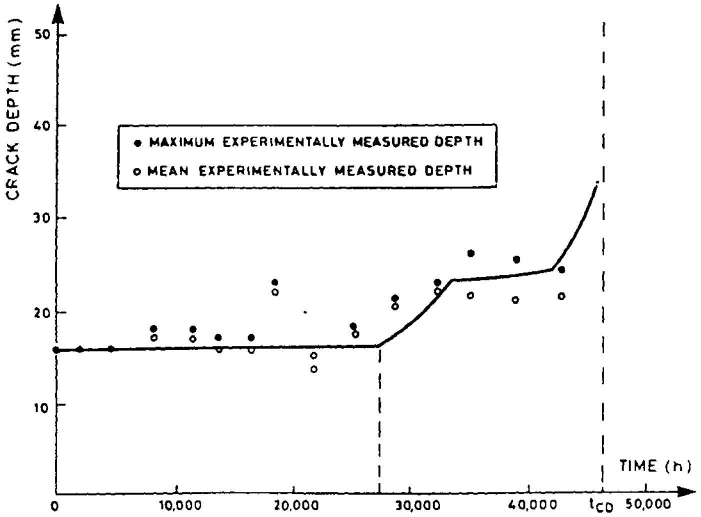

Figure 4. Crack Growth in Pressure Vessel Test

More direct validation on plant has been obtained by quantifying the relationship between creep cavitation damage and the remaining creep life of CMV weldments. Uniaxial test data have been generated for Type IV cracking from which a quantitative relationship between cavity density and creep life has been established. This forms the basis for assessing the significance of creep cavitation detected during the inspection of CMV weldments in Nuclear Electric steam generating plant.

Once creep cavities have been detected, the assessment strategy involves quantifying the density level, through a defined metallographic procedure, then comparing this level with pre-defined, low, medium and high density criteria, to determine the appropriate course of action. This approach is presented in Figure 5. While the detection of medium or high levels of cavity density generates additional work, it affords the opportunity to establish the fitness for service of a weldment without moving directly to repairing all weldments found to contain Type IV creep cavitation.

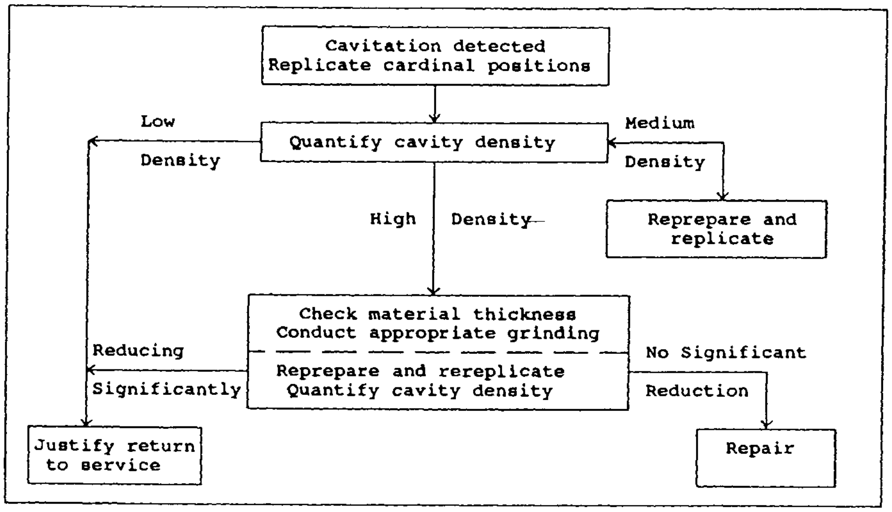

Figure 5 - Route for Assessing the Significance of Type IV Creep Cavitation

This approach has been adopted for a number of years of Nuclear Electric's plant. Following this route and supported by R5 creep crack growth studies, a number of welds have been returned to service and operated safely while others have been nominated for repair.

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