The High Temperature Deformation and Fracture of a Mild Steel Weldment in Heavy Section Low Alloy Ferritic Steel Pipe

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ABSTRACT

The integrity of welded components is important in ensuring the safe and economic operation of high temperature plant. This paper describes the design, testing and examination of a welded pipe component which forms part of a research programme examining weldments operating in the creep regime. Creep stress redistribution and microstructural features are described to explain the weldment behaviour. The significance of the work is then discussed in terms of the need for design and remanent life assessment procedures for weldments.

KEYWORDS

Creep; deformation; fracture; ferritic; weldment; microstructure.

INTRODUCTION

There is considerable economic advantage in continuing to operate components in high temperature plant to times in excess of their original design life. To justify this extension of plant life it is necessary to assess the components and ensure their integrity for future operation. To this end, the CEGB have developed a procedure for boiler header creep life assessment (Bates & Townsend, 1982; Gooch & Townsend, 1986) which is aimed at ensuring the safe operation of plant, identifying plant problems and facilitating a planned replacement programme.

This procedure primarily considers only the parent material sections of headers. However, high temperature plant contains many weldments in steam lines, valves and casings as well as in headers. Furthermore, experience has shown that the first problems invariably arise from cracking in weldments often before the design life is reached. Clearly then, there is a need to understand the performance of welded components operating at high temperatures and, thereby, to develop design and assessment procedures to ensure the integrity of these components throughout their required operating life.

Assessment procedures are currently being developed by the CEGB to ensure the structural integrity of high temperature plant including weldments (CEGB Research, 1988). In support of this the CEGB have undertaken a number of research programmes involving welded full size pipe components addressing specifically the validation of design and assessment procedures for weldments. To illustrate this work, this paper describes part of a programme in which the effects of weld metals of different creep strength are being examined. Creep strain, metallurgical and analytical data are presented relating to the behaviour of a mild steel weld metal and implications for design and life assessment procedures are discussed.

FULL SIZE COMPONENT DESIGN AND TEST CONDITIONS

The component was a ½Cr½Mo¼V pipe, typical of that used in the main steam lines of power stations, containing four circumferential butt welds and forming a self contained pressure vessel. The weld of interest here had been produced using mild steel consumables which, while not typical of power station practice, provided a weak weld/strong parent combination appropriate to the overall scope of the programme. The dimensions of the pressure vessel are given in Fig. 1 which also shows its general appearance when installed for testing in the CEGB's Pressure Vessel Testing Facility (PVTF) at MEL. Full details of the programme and the capabilities of the facility are described elsewhere. (Rowley and Coleman, 1974; Coleman, Fidler and Williams, 1985)

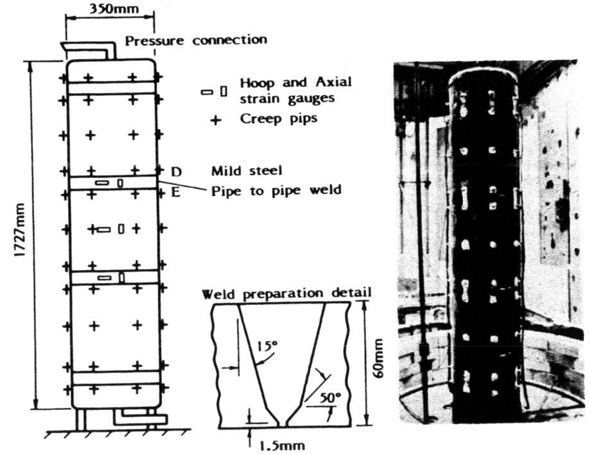

Fig. 1. Main features of the pressure vessel and its general appearance in the PVTF.

The welded pipe was tested at 565°C and internally pressurised with steam at 455 bar. Normal design practice (BS806 and 5500) uses the mean diameter hoop stress in such a component in conjunction with uniaxial stress rupture data and a safety factor to determine an allowable design life. Following this route, the mean diameter hoop stress in the pipe, 110 MPa, applied directly to mean ISO data but excluding any safety factor, predicted lives of 20,000h and about 100h for the parent metal and mild steel weld metal, respectively. On this basis, failure of the welded pipe was anticipated to occur early by axial cracking in the mild steel weld.

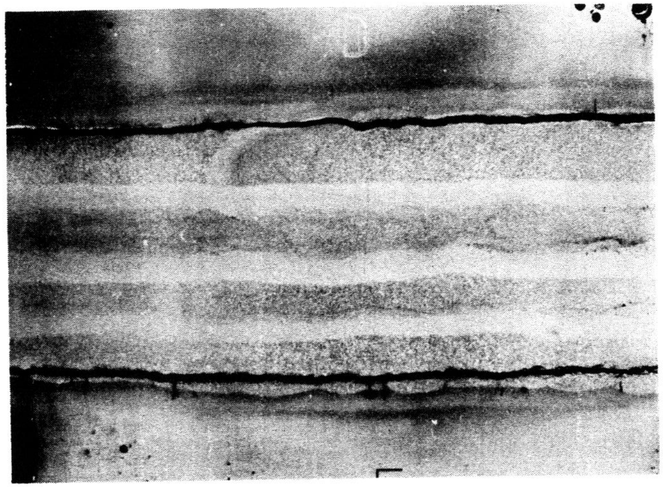

Fig. 2. General view of the cracking on the surface of the mild steel pipe-pipe weldment when the test was terminated at 23671 h.

Continuous monitoring of the component during testing and direct examination during inspection periods at ambient conditions produced creep strain, crack initiation and growth data. After about 24000h circumferential cracking had developed fully in the weld adjacent to both fusion boundaries, Fig. 2, and, based on ultrasonic measurements, had extended to a maximum depth of 40mm through the 60mm thick wall. While no steam leaked from the component it was considered to have failed and the test terminated.

EXPERIMENTAL DATA

The hoop and axial strains determined from measurements across reference positions, creep pips, adjacent to the weldment are shown in Fig. 3. The maximum strains were always in the axial direction and at the end of the test had reached about 3%, compared with about 0.9% in the hoop direction. Furthermore, these data, which came from eight separate hoop and axial positions around the circumference, showed little scatter indicating that the weldment had deformed uniformly. On the basis of strain, therefore, it was considered that cross sections taken from any position would be representative of the weldment.

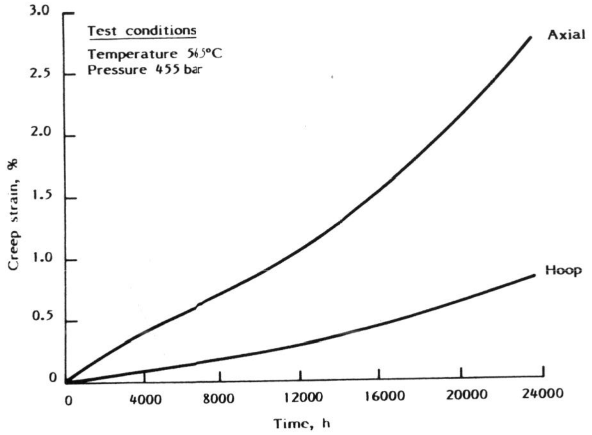

Fig. 3. The average hoop and axial strains obtained from creep pip measurements across the weld.

Circumferential cracking initiated between about 1,500 and 3,500h on the outer surface of the weld metal close to both fusion boundaries and became fully circumferential between 5000 and 9000h. The depth of these cracks was assessed using conventional ultrasonic techniques as 40mm and 10mm at the two interfaces. Magnetic particle inspection showed that some transverse cracks occurred across the heat affected zone (HAZ) and although reaching a maximum length of 6mm, Fig. 2, were generally less than 3mm deep. No cracking was detected in the parent material.

METALLOGRAPHIC RESULTS

Four evenly spaced full cross sections were cut from the weldment and prepared for metallographic examination using conventional grinding, polishing and etching techniques. All sections showed a similar distribution of macroscopic features and were typical of heavily weaved thick section MMA weldments. The weld metal showed irregularly distributed regions of coarse columnar structure in the body of the weld with more uniformly distributed regions in the capping beads. Similarly, the HAZ contained coarse and refined microstructures, with the latter predominant and accounting for about 80% of the cross section.

The cracking features observed are illustrated in Fig. 4, where it is apparent that cracking in the weld metal had extended to a depth of about 40mm but was not continuous. Cracking was detected extending from the surface circumferential cracks and at 6 separate locations through the thickness of the weldment, in all cases adjacent to the fusion boundary.

Cracking from the surface extended continuously for about 10mm, traversing coarse columnar and refined weld metal microstructures, while the separated regions of cracking were confined to coarse columnar regions sandwiched between refined microstructures. In addition some creep cavitation was observed in the refined regions, again close to the fusion boundary. No creep cavitation or cracking was detected in any parent material away from the weldment.

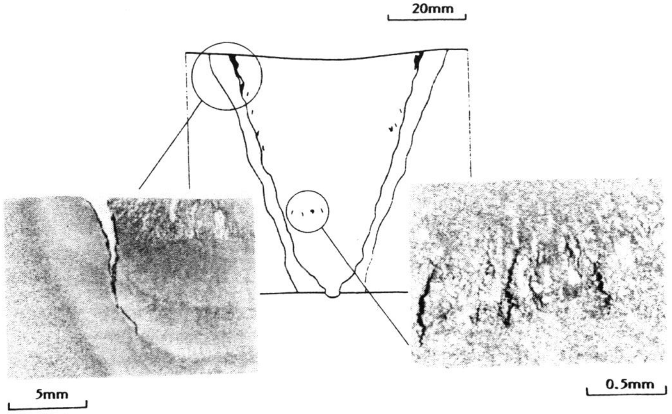

Fig. 4. The distribution of cracking in the mild steel weldment and its macro/microscopic appearance.

The transverse HAZ cracks observed on the surface of the weldment, Fig. 2, were also revealed in some cross sections, but only in the coarse grained regions adjacent to the capping beads. The highly refined microstructure of the HAZ limited the depth of these cracks and they appeared to have no significant effect on the overall failure of the weldment.

STRESS ANALYSIS

Heavy section weldments have previously been studied using finite element stress analysis techniques (Walters and Cockcroft, 1972). A major finding of this work was that significant stress redistribution occurs in a welded pipe component containing materials with differing properties. This finding has been particularly important in the current case and, consequently, the relevant analysis data are presented below.

The stress distribution occurring in the mild steel weldment was calculated using a finite element mesh modelling the weld, HAZ and parent regions of the pipe and assuming elastic-steady state creep behaviour (Coleman, Parker and Walters, 1985). The hoop and axial steady state creep stress distributions across the outside surface of the weldment are shown in Fig. 5. It is clear that considerable changes occur as the result of the presence of a weld with for example, the hoop and axial stress values at the outer surface centre of the weld being 11 and 20 MPa, respectively, compared with those in a plain pipe of 96 and 48 MPa, respectively.

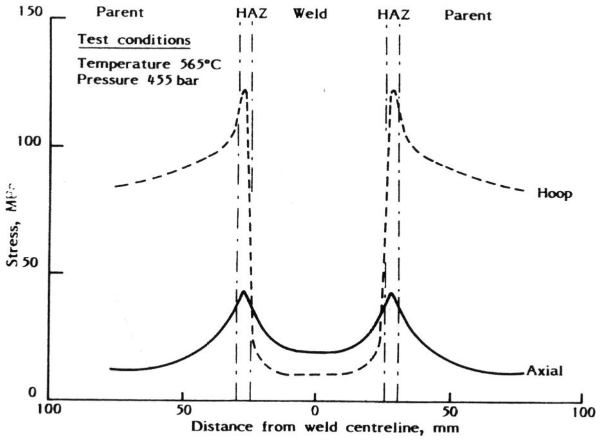

Fig. 5. Steady state stress distribution in the mild steel pipe-pipe weldment from finite element stress analysis data.

DISCUSSION

Two factors combined to generate the failure mode observed in the mild steel weld, the microstructural distribution produced during welding and the creep stress-strain distribution arising during testing.
The coarse columnar grained regions in the weld metal were limited to small separate locations, with the largest regions being in the capping beads adjacent to the fusion boundary, Fig. 4. Since coarse grained microstructures have generally low creep ductility, then the weld metal was predisposed to fail initially by cracks occurring in the separate locations corresponding to the coarse columnar grains. The macroscopic and microscopic observations confirm that this has occurred.

The presence of a brittle microstructure alone, however, is not sufficient to cause cracking. This is apparent since the coarse grained regions in the centre of the weld metal are relatively undamaged while those adjacent to the fusion boundary contain the cracks. The reason lies in the creep stress-strain distribution that occurs in joints comprised of weak weld metal and strong parent metal.

The stress data, Fig. 5, show that in addition to the axial stress being the maximum principal stress in the weld metal, it reaches a peak value of about $36 MNm^{-2}$ at the outside surface fusion boundary position, which is 75% greater than that at the weld centre line. This results in enhanced axial strain with, from finite element data, the steady state axial strain rates at the fusion boundary being 6 times greater than those at the weld centre line. The dominance of the axial stress predicted by the finite element analysis is supported by the experimental strain data shown in Fig. 3, where axial strains dominate the deformation behaviour throughout testing, averaging about 3% across the weld metal at failure compared with about 0.9% in the hoop direction. Additionally, a predicted concentration of stress and strain close to the fusion boundary is borne out by the observation of cracking in the coarse columnar microstructure which led, eventually, to the observed failure mode.

Low alloy ½Cr½Mo¼V pipe material are normally welded with 2¼Cr1Mo consumables and not the significantly weaker mild steel used in this work. Clearly, it would be inappropriate to apply the current findings to normal plant. However, the results do indicate a number of factors that should be given due consideration in the design and assessment of weldments.

The current design procedure for welded pipes operating at elevated temperatures effectively ignores the presence of the weld. For this particular research test a design life of 20,000h was calculated for the pipe component without applying any safety factors. However, examination of the pipe after 24000h revealed no creep cavitation or cracking, which supports the view that the code for pipework, even without safety factors, is pessimistic. Moreover, if the mean diamter hoop stress, 110MPa, is applied to mild steel weld metal rupture data then the "design" life would be 100h. Comparing this with the actual life of 24000h is a further illustration of the pessimism of this approach.

To improve this situation it is clear that account should be taken of the stress redistribution that occurs in welded components. In the present work, for example, the maximum principal stress from the weld metal was 35 MPa. Applying this to mild steel creep rupture data indicates a life of 20,000h which is a sensibly pessimistic estimate of the component life.

Full size component test programmes are underway in the CEGB examining remanent life assessment procedures and techniques (eg Hepworth and Williams, 1988; Shammas, 1988) although the work described here was not directed specifically at this topic. Nevertheless, it has provided useful data relevant to this area. Two findings in particular are worthy of mention. Significant stress redistribution occurs in weldments such that the maximum principal stress direction and location may be quite different to that in a plain pipe. Inspection and monitoring procedures which, inevitably, must form part of any assessment route should take account of this knowledge to identify the regions of weldments most at risk. Secondly, the presence of creep cavitation, micro or macrocracking, while representing end of life on a local scale does not in itself signify the end of useful life for the heavy section welded component. The work detailed above clearly illustrates this with significant cracking being detected after only 10% of the total life.

CONCLUDING REMARKS

The welded pipe component consisting of mild steel weld metal in a low alloy, ½Cr½Mo¼V, steel pipe failed by circumferential cracking in the weld metal adjacent to the fusion boundary. This behaviour has been explained by taking account of the microstructural variations and considerable stress redistribution that occurs in welded components.

The close relationship that exists between weldment structure, stess distribution and behaviour is recognised. Accordingly, the current work involving full size components, in common with numerous other CEGB programmes, is directed towards improving both design and assessment procedures for welded structures operating at elevated temperatures.

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