CREEP CRACK GROWTH IN A CrMoV THROTTLE VALVE PRESSURE VESSEL

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ABSTRACT

Severe circumferential cracking was detected in several CrMoV forging weld HAZ's in an operating power station. To provide some assurance for continued operation, a pressure vessel test was undertaken in the CEGB's Pressure Vessel Testing Facility at Marchwood Engineering Laboratories. During testing at temperature and pressure, the vessel was continuously monitored using potential drop equipment, strain gauges and acoustic emission techniques. In addition, ultrasonic testing, residual stress and strain measurements were carried out at inspection periods. During the first 3000 hours at plant conditions, 540°C and 159 bar, creep crack initiation and growth were detected but over a subsequent 4000 hours the cracks remained dormant. Increasing first the temperature to 565°C then the pressure to 350 bar produced no change over the next 10,000 hours. The test was therefore terminated and the vessel weldment subjected to a full metallographic examination. The results obtained at the power station conditions are discussed and shown to correlate well with events subsequently occurring on plant. Finally, the eventual dormant nature of the cracks is considered and it is concluded that this arose because the crack tip grew into refined regions of the HAZ and because the welding residual stresses relaxed with time.

KEYWORDS

Crack propagation, creep properties, elevated temperature, heat affected zones, metallography, pressure vessels, residual stress, steels.

INTRODUCTION

Severe circumferential cracking was detected in the weld heat affected zones (HAZ's) of CrMoV steel closed die forged valve components in a CEGB power station operating at 565°C and 159 bar. In the most extreme case, a defect that formed either during stress relief or during 500 hours operation subsequently propagated by fatigue and brittle fracture to give a final defect extending three-quarters of the way around the circumference of the ∿400mm diameter forging and penetrating 50mm into the 70mm wall thickness. This component was removed from service but numerous other cases existed where creep cracks had grown to a depth of about 10mm in the weld HAZ's of similar components. A number of factors may have contributed towards the creep cracking, such as susceptible material composition and inadequate post weld heat treatment. However, the integrity of the defective components during continued operation of the power station was the most immediate concern.

The significance of the defects was assessed using a CEGB procedure (Heaton, Whittle & Oates, 1974) based on

$$\dot{a} = A K^{n} \qquad (1)$$

where $\dot{a}$ is the creep crack growth rate, $m.h^{-1}$,
K the linear elastic stress intensity factor, $MN.m^{-3/2}$,
and A and n material temperature dependent constants, 1×10^{-13} and 6 respectively.

Assuming a constant residual stress of 60 $MN.m^{-2}$, calculation showed that a 10mm deep defect with an aspect ratio of 10:1 would double in depth in 500 hours and produce failure in less than 1000 hours. However, since the then existing weld repair procedures could not guarantee a crack free solution the operating temperature was downrated to 540°C to reduce crack growth rates. A policy of complete replacement, as soon as new components were available, was also implemented. In addition, to give advanced warning of any crack growth that might arise during the interim operation of defective components, a cracked throttle valve containing the most severe defects was removed from the power station and converted into a self-contained pressure vessel for testing at the CEGB's Marchwood Engineering Laboratories.

This paper presents the results of the contingency work carried out at power station operating conditions and of additional experimental testing under more arduous conditions of temperature and pressure. The implications of these results are discussed for the operating power station and the events observed during testing are compared with those subsequently encountered in other valves which remained in service. Finally, the results of metallographic examination are considered and the effects of HAZ microstructure and residual stress are discussed in terms of creep crack growth and arrest.

PRESSURE VESSEL DESIGN & TESTING PROCEDURE

The main concern in producing a pressure vessel from the throttle valve component was that the metallurgical structure and thermal history of the cracked regions should not be affected by the manufacturing procedure. Consequently, care was taken to ensure that extraneous stresses, such as bending during handling or thermal stresses during welding, were minimised. Details of the pressure vessel design are shown in Fig.1(a). The steam inlet adaptor pipe was closed by welding on a hemispherical cap at such a distance that the welding procedure would not affect the forging weld HAZ cracks, while the valve body was sealed primarily by means of a shrunk-in mild steel plug. After manufacture of the pressure vessel, ultrasonic examination of the forging HAZ cracks was carried out and confirmed that the initial defects, shown in Fig. 1(b), were unaffected.

Testing was carried out in a purpose built Pressure Vessel Testing Facility (PVTF) where the vessel was heated in an air circulation bell furnace and internally pressurised with steam. During the test, crack growth was monitored continuously using the dc potential drop technique across the deepest original defect. Single channel acoustic emission monitoring was also employed to detect activity in the vessel in general (Clark, 1979). In addition, capacitance strain gauges were used to monitor displacement across the circumferentially shortest original crack. Intermittent inspections were also carried out at ambient temperature. On these occasions, creep strains were determined at three diametral locations, the adaptor

pipe, the weld centre line and 60mm below the weld in the forging, from micrometer measurements taken across reference centre pop locations. Residual stress measurements were also made in various regions of the weldment using the hole drilling technique (Beaney & Proctor, 1974). The PVTF has been described previously (Eaton & Rowley, 1972) as have the associated measuring methods (Coleman, Fidler and Williams, 1976).

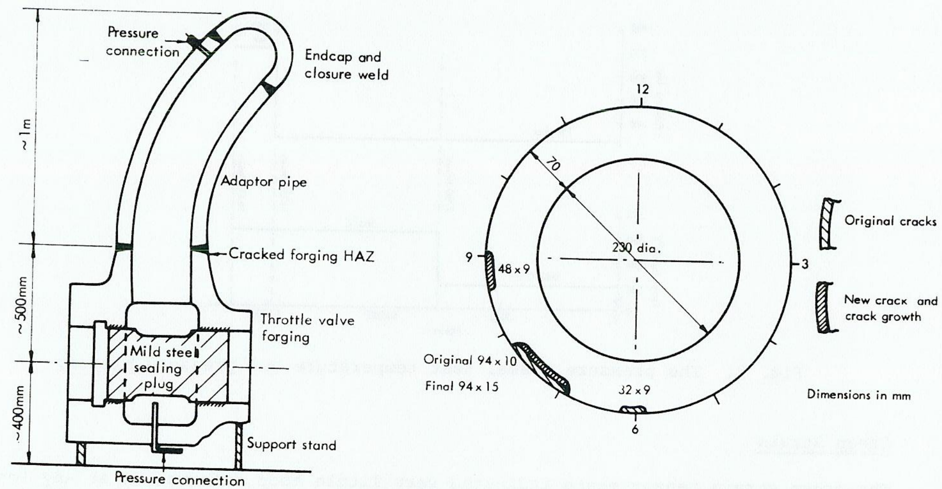


Fig. 1. (a) Pressure Vessel Design (b) Location of Forging HAZ cracks

TEST HISTORY & RESULTS

The pressure vessel temperature and pressure test history are shown in Fig. 2. The first period of testing provided about one year of contingency cover to the power station, which was also operating at 540°C and 159 bar. Subsequent testing at 565°C was aimed at providing further information relevant to normally operating plant, while increasing the pressure to 350 bar was a deliberate attempt to generate more creep crack growth data.

Crack Monitoring

After 1800 hours at operating plant conditions, the acoustic emission count rate increased by a factor of 5 on the background level and inspection at 2000 hours revealed that a new crack had initiated at position 9, Fig. 1(b). Over the next 1000 hours, the potential drop equipment indicated that about 5mm growth had occurred at the deepest original defect although no additional acoustic activity was detected. Non-destructive inspection at 3100 hours confirmed that the defect had grown to a maximum depth of about 15mm, Fig. 1(b). During the remaining period of testing at 540°C and all subsequent testing at 565°C, no further crack initiation or growth was detected by any of the monitoring or inspection techniques.

Residual Stress

The residual stresses in the forging HAZ and immediately adjacent forging and weld metal were measured on eight different occasions. The axial residual stress in the forging HAZ was of particular interest with respect to circumferential HAZ creep crack growth. In the as received condition, this was 130 MNm^{-2}, which reduced to 50 MNm^{-2} after 7740 hours at 540°C and reached -15 MNm^{-2} after a further 8000 hours at 565°C. In the other locations, the axial stresses were always less than the forging HAZ values and decayed to about half their as received values after testing at 540°C, reaching effectively zero at the end of testing.

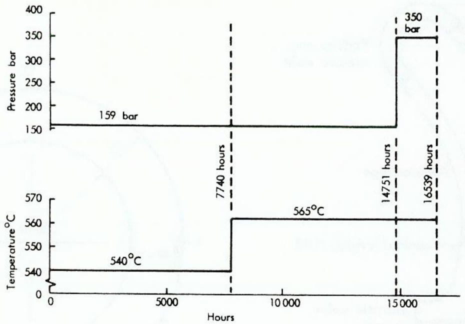


Fig. 2. The pressure vessel test temperature and pressure history

Creep Strain

The creep strain measurements indicated very little hoop deformation at any location. After testing at 540°C, the maximum strain recorded was 0.1% across the weld centre line and reached 0.12% after the 565°C test period. Similar strains were observed in the adaptor pipe, whereas, in the forging HAZ only 0.05% strain was found. These low strains are not surprising since, by design, normal plant conditions should not produce more than 1% strain in 10^5 hours. The increased pressure of 350 bar did not generate any changes outside ±0.012%, the accuracy of the measuring technique.

METALLOGRAPHIC EXAMINATION

The forging to pipe weldment was removed as a complete ring and sections for metallographic examination were obtained by slicing the ring through sound and defective areas of the weld. These were examined initially using light microscopy but, where appropriate, further samples were prepared for scanning electron microscopy (SEM).

Macroscopic

The same general features were observed on all sections examined, Fig. 3(a), and were typical of CrMoV components welded with 2CrMo manual metal arc (MMA) electrodes in a horizontal-vertical manner (weld centre line horizontal, pipe centre line vertical). The forging being the lower face was welded with the electrodes almost normal to the interface and was filled with the root runs plus about 7 beads. On the pipe side the electrodes were roughly parallel to the interface and about 14 beads overlapped along this fusion boundary.

Macrocracking was only observed in sections taken from the three defective regions, Fig. 1(b), and was confined to the forging HAZ adjacent to the top weld bead, Fig. 3(a). At positions 6 and 9, single straight cracks normal to the surface were observed starting adjacent to the fusion boundary and finishing close to the parent material/HAZ interface. These cracks had a depth of 7mm which agreed with the

ultrasonic maximum size assessment of 9mm. Similar observations were made between positions 7 and 8, but in addition discontinuous cracking, following the fusion boundary curve, but still remaining normal to the pipe surface, gave rise to a stepped crack appearance. Here, a 15mm deep crack had been expected from the ultrasonic examination but again macrocracking only extended to about 7mm.

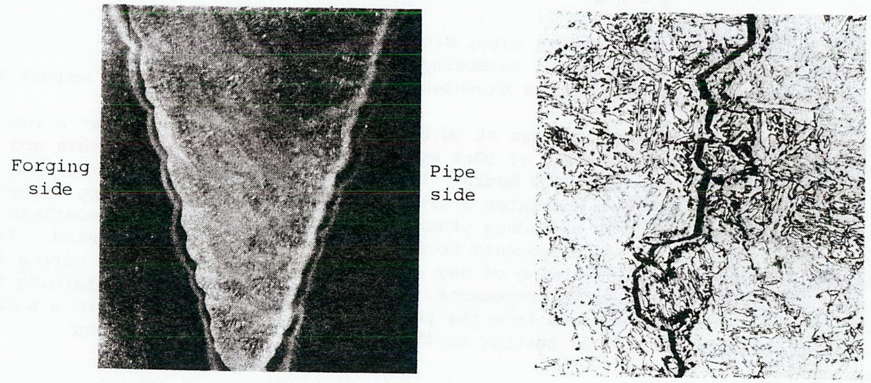


Fig. 3. (a) Forging to pipe weld, x 0.8. (b) HAZ intergranular creep crack, x 200

Microscopic

The normalised and tempered forging and pipe were predominantly ferritic with ~20μm grain size, while the weld metal contained coarse columnar bainitic grains with interbead refinement. Both HAZ structures ranged from coarse grained bainite, ~150μm, adjacent to the fusion boundary to refined bainite, <10μm, adjacent to the parent materials. The radial distribution of coarse grains was distinctly different on the two sides of the weld, the forging side containing about 80% distributed in continuous lengths from 5.5 to 13.5mm, while the pipe side contained 67% distributed in lengths from 2.5-6.0mm.

In the macrocracked regions of the forging HAZ, the cracks started in the coarse grained bainite, Fig. 3(b) and propagated normal to the pipe surface for about half their length. Where single cracks were present, the cracks continued in this direction finishing in the refined extremity of the HAZ. For stepped crack regions, cracking reinitiated in the coarse grains following the fusion boundary curve. SEM revealed that, where the cracks ran into the refined structure, branching occurred and widely dispersed creep cavitation was found ahead of the crack, Fig. 4. In contrast, in the coarse grained region the cracks followed a singular path with microcracking and cavitation down to the depth of the first fusion boundary cusp, generally on grain boundaries at right angles to the pipe surface. Cavitation was also found adjacent to the second weld bead and in some positions, particularly between 7 and 8, linked to give microcracks 15 to 20mm below the pipe surface. This corresponded to the position where ultrasonics had indicated a 15mm maximum depth crack. Below the second weld bead depth extensive examination failed to reveal any further cracking or cavitation.

Examination of the nominally sound regions of the forging HAZ revealed small microcracks and cavitation adjacent to the top weld bead, and incipient cracking in the form of grain boundary networks of cavities in the second weld bead HAZ. Similarly, on the adaptor pipe side microcracks were observed in the top weld bead HAZ with cavitation occurring down to the depth of the fourth weld bead. On each side of the weld therefore, the top third of the HAZ contained creep damage, while the remainder appeared clear.

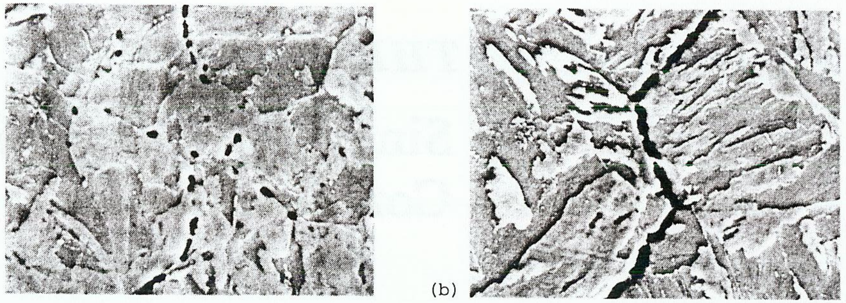
(a) (b)


Fig. 4. SEM's of (a) Dispersed cavitation in refined HAZ and (b) Cracking in the coarse grained HAZ x 1000

DISCUSSION

The throttle valve weldment contained in the pressure vessel had completed the equivalent of 5,000 hours operation at 540°C while in the power station. It was similar to 16 other components but, since some had been repaired immediately the HAZ cracking problem arose, at the start of the pressure vessel test 13 were in their original uncracked condition. It was to assure the integrity of these welds that the contingency test was undertaken.

Plant Implications

Testing at 540°C and 159 bar showed that crack initiation and growth occurred to a depth of 9mm in 2000 hours and that similar defect depths extended to a maximum size of 15mm after a further 1000 hours, these times being equal to total running times at 540°C of 7000 and 8000 hours, respectively. After subsequent testing, equivalent to continuous operation for a year at 540°C and a year at 565°C, no further crack initiation or growth was detected. By comparison, the power station components gave between 7000 and 10,000 hours operation at 540°C before cracking was detected in 6 different welds. This shows good agreement with the pressure vessel test. On the basis of the pressure vessel data the majority of these cracks which were less than 10mm deep, were allowed to remain in service. One exception was a 12mm deep crack detected during a mid-winter period, that was allowed to remain until a planned spring outage. At that time, when it was then repaired, the crack had grown 5mm, comparable with the growth experienced in the defect between positions 7 and 8 in the pressure vessel. Thus, the pressure vessel data was able to contribute to the continued safe operation of the power station and was entirely consistent with the cracking incidence later observed on plant.

Creep Crack Growth

Since rapid crack growth and failure did not occur, either in the pressure vessel test or the power station, it is clear that the original defect growth assessment was very conservative. Accepting that a LEFM approach is not strictly applicable to a time dependent creep process, conservatism stems particularly from two factors. Firstly, the constants in equation (1) are based on small uniaxial tests on 2¼Cr1Mo

(Siverns & Price, 1970) not CrMoV HAZ in a heavy section component. Secondly, residual stresses are assumed to be uniformly distributed, non-relaxing, primary stresses and a value of 60 MNm^{-2} is used throughout, whereas the pressure vessel data has shown that on the surface alone this drops effectively to zero during testing. Some allowance for material composition difference can be made by using

$$\dot{a} = 2.1 \times 10^{-8} K^{3.4} \quad (2)$$

which is based on ½CrMoV (Neate & Siverns, 1973). However, even assuming that the residual stress had dropped to zero during stress relief, and the only stress acting was a uniform axial stress resulting from an internal pressure of 159 bar, equation (2) still predicts that the 10mm deep defect would have reached a depth of 30mm by the end of testing.

Despite the absence of significant growth data, a number of important observations can be made. Irrespective of when it formed, macrocracking was always confined to the top weld bead HAZ. This coincides with the position of maximum residual stress (Fidler, 1977) and consequently is the region where most creep damage would be expected. In the throttle valve, inadequate stress relief, a material high in vanadium and susceptible to stress relief cracking (Murray, 1967) and a welding procedure generating large coarse grained regions (Alberry, Rowley & Yapp, 1978; King, Middleton & Townsend, 1975) have all combined, such that in the forging HAZ damage has reached a critical level resulting in extensive macrocracking. In contrast, in the pipe HAZ the problem is reduced to microcracking.

Creep Crack Arrest

The macrocracks in the forging HAZ all arrested in the refined microstructure, either adjacent to the parent material or close to the first fusion boundary cusp. This indicates that the refined regions are more resistant to creep crack growth. This agrees with uniaxial data showing refined regions to be an order of magnitude more resistant to crack growth than coarse regions (Gooch & King, 1980), and clearly affects any assessment based on a single material model. In addition, the macrocracks reached a significant size because the welding procedure produced extended coarse grained regions. However, on the pipe side, the HAZ contained coarse grained regions only half the length on average of those on the forging side. Consequently, if a macrocrack had developed here it would have been arrested at half the size of those in the forging HAZ.

The absence of sufficient driving stress must also have contributed to the observed crack arrest. In addition to the surface stress decaying with time, it is known that the through thickness distribution changes from tensile to compressive in thick section weldments (Fidler, 1977), and this alone would lead to a reduction in crack growth rate and, finally, to arrest. At the power station, fatigue and thermal stresses were present during the early operation but operating procedures were modified to reduce these stresses. This being the case, the pressure and residual stresses in the pressure vessel test matched those at the power station and it is clear that under these stresses alone, macrocracks do not propagate beyond the first weld bead HAZ. However, this does not preclude crack extension at much greater times when terminal life conditions are being approached.

CONCLUSIONS

1. The throttle valve pressure vessel test produced data that supported the continued operation of power station components containing defects.

2. Creep crack growth assessments using relationships based on LEFM were very conservative.

3. Creep crack damage was confined to the top third of the weld HAZ and, in particular, macrocracking was limited to the forging HAZ adjacent to the top weld bead.

4. Creep crack growth was arrested by the refined microstructure of the weld HAZ. In addition, the decay of welding residual stress, both through the thickness of the weldment and with time at temperature, contributed to this crack arrest.

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REFERENCES

Alberry, P.J., T. Rowley and D. Yapp (1978). Control of metal-arc weld quality by deposition sequence. Conference on Advances in Welding Processes, The Welding Institute, Cambridge. pp. 105-116.

Beaney, E.M. and E. Proctor (1974). A critical evaluation of the centre hole drilling technique for the measurement of residual stresses. Strain, 10, 7-14.

Clark, J.N. (1979). Acoustic emission monitoring of a throttle valve pressure vessel. CEGB Note R/M/N1074.

Coleman, M.C., R. Fidler and J.A. Williams (1976). Crack growth monitoring in pressure vessels under creep conditions. In Detection and Measurement of Cracks. The Welding Institute, Cambridge. pp. 40-44.

Eaton, N.F. and T. Rowley (1972). Experimental evaluation of creep behaviour of welded vessels. International Institute of Welding, Colloqium, Toronto.

Fidler, R. (1977). The complete distribution of residual stresses in a ½Cr½Mo¼V/2CrMo main steam pipe weld in the as-welded condition. CEGB Report R/M/R261.

Gooch, D.J. and B.L. King (1980). Creep crack growth in controlled microstructure CrMoV heat affected zones. Welding Journal, 59, 10s-18s.

Heaton, M.D., M.J. Whittle and G. Oates (1974). The non-destructive examination and fracture mechanics assessment of CrMoV weldments. CEGB Report NW/SSD/RR/331/74.

King, B.L., C.J. Middleton and R.D. Townsend (1975). Prevention of heat affected zone and weld metal cracking through control of microstructure in CrMoV-2¼CrMo weldments. CEGB Report RD/L/R1919.

Murray, J.D. (1967). Stress relief cracking in carbon and low alloy steels. Brit. Weld. J., 14, 447-456.

Neate, G.J., and M.J. Siverns (1973). The application of fracture mechanics to creep crack growth. International Conference on Creep and Fatigue in Elevated Temperature Applications, Philadelphia 1973 and Sheffield 1974, 234.1 - 234.9.

Siverns, M.J. and A.T. Price (1970). Crack growth under creep conditions. Nature, 228, 760-761.