Typical Failures in High Energy Piping Weldments

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ABSTRACT

A review of service experience with low alloy steel piping has shown that a number of damage types are observed. The dominant fracture mode for a particular geometry varies depending on the interaction of stress with constituent microstructures. In view of the variability of structures in weldments, evaluation of component performance requires consideration of local stress redistribution based on specific dimensional and strength characteristics.

KEYWORDS

Low alloy steel; creep fracture; weldments.

INTRODUCTION

Cracks detected in steam piping are usually associated with weldments. Weldment problems arise since even where weldments are produced with weld metal of nominally matching composition to the parent pipe, structural discontinuities are introduced by the thermal cycle associated with the welding process. The variability of microstructures in weldments has been reviewed previously (Coleman, 1978). The observed variations in microstructure also result in differences in creep properties. Thus, it appears that, depending on microstructural form, the creep strength can vary by one order of magnitude even for materials with similar composition (e.g, Parker, 1988).

The manufacture of thick section welds invariably results in the development of residual welding stresses as the molten metal cools and contracts. These stresses may approach the yield strength of the material at room temperature and will relax on reheating to high temperature. Clearly, these stresses relax by development of strain. If, at the temperatures of relaxation, the microstructures present are brittle, then cracking can occur. In order to

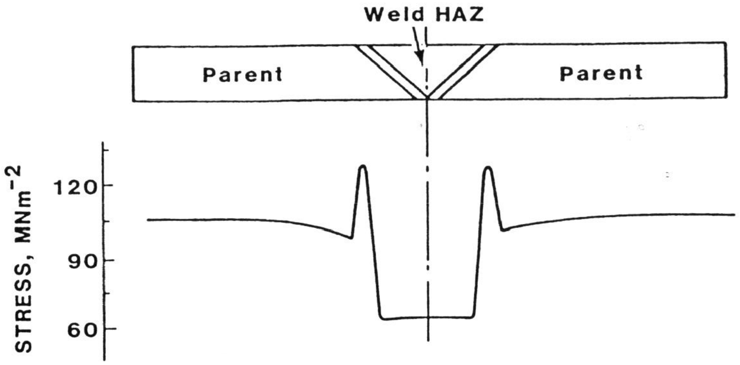


Fig. 1. Redistribution of hoop stress in a girth weld (After Coleman et al., 1985).

Cracking of Dissimilar Metal Welds

Piping may be manufactured from austenitic stainless steel so that a weld joining low alloy ferritic steel to austenitic steel is required. This weld may be made using austenitic steel, nickel based alloy weld metal, or even by producing a graded composition joint (Bagnell, Rowberry and Williams, 1981). Problems encountered with these joints are primarily due to the difference in coefficient of thermal expansion between the austenitic steel and low alloy steel. The effect of the different thermal coefficients of expansion is maximized in welds produced with a stainless filler and damage can develop on prior austenite grain boundaries in the ferritic HAZ adjacent to the fusion boundary. The life of such joints is extended by manufacturing welds with a nickel alloy filler, due to the fact that, in this case, the thermal coefficient of expansion is very nearly the same as in low alloy steel. Some failures have been observed in joints made with nickel based weld metal. These appear to be associated with cavitation developing at the fusion boundary.

CRACKING IN LONGITUDINAL SEAM WELDS

In straight pipe spools, longitudinal seam welds are usually manufactured with a "double-vee" preparation. Metallurgical examinations to date have revealed that creep damage is concentrated at, or adjacent to, the weld fusion interface, although creep damage may occur in the weld metal or HAZ at the inner or outer surface of the pipe. The nature and extent of damage appears to be related to the specific welding procedures followed by the manufacturer. Thus, damage may be concentrated along or between certain weld passes and extend over significant axial lengths. Consequently, the critical damage mode is crack extension or linkup across the wall thickness

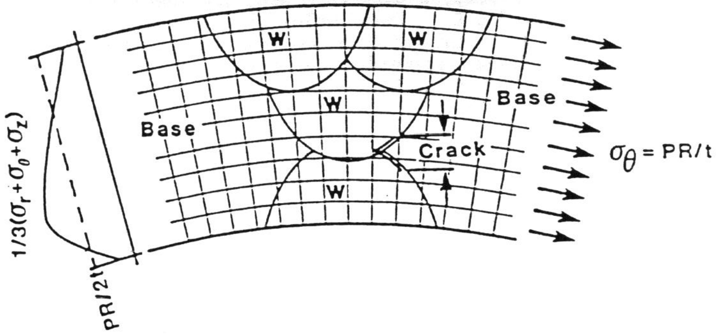


Fig. 2. Redistribution of stress in a longitudinal seam weld (After Wells, 1987).

of the pipe rather than along the length of the seam. This cracking mode can be catastrophic if it leads to rupture of straight lengths of pipe before leakage is detected and preventive measures taken (Becker, Walker and Dooley, 1987).

Finite element analysis modeling seam weld geometries has been reported (Wells, 1986). In situations where the weld metal is weaker in creep than the adjacent base material, the component stress becomes concentrated in the weaker weld metal adjacent to the fusion line. Thus, as illustrated in Figure 2, the location of high stress can occur mid-wall in the cusp area of the weld. This location is coincident with observed service induced cracking.

TYPICAL FAILURES IN NOZZLE WELDMENTS

The main failure modes observed in nozzle welds are illustrated in Figure 3a. These may be listed as :

- Circumferential cracking in the nozzle side HAZ - Mode A
- Circumferential cracking the pipe body - Mode B
- General transverse weld metal or HAZ cracking - Mode C
- Local transverse weld metal cracking, notably in branch/ body welds - Mode D

Circumferential Cracking in the Nozzle Side HAZ

The most commonly observed failure mode in service situations is circumferential cracking in the nozzle side HAZ, Mode A, as shown in Figure 3a. Although the cause of this cracking is uncertain, the presence of systems stresses appears to be important. These systems stresses may be predominantly axial, arising from long range temperature gradients in the improve the weldment ductility, a post weld heat treatment (PWHT) is carried out at temperatures of ~700°C. Thus, welds should enter service with low levels of residual stress and with a tempered structure which is more ductile than in the original as-welded condition. However, relaxation or residual stresses invariably uses some of the creep ductility of the weldment. In cases where ductility is impaired by the presence of trace elements, or by very large grain sizes, then service cracking may still develop. In particular, elements such as phosphorus, arsenic and copper appear to reduce the ductility of 2CrMo weld metal (Wolstenholme, 1976).

Macrocracks have been observed to develop both longitudinally, parallel to the axis of pipe and circumferentially, around the pipe. Assuming that gross defects were not introduced during manufacture, these failures may result from a number of factors.

CRACKING IN CIRCUMFERENTIAL WELDS

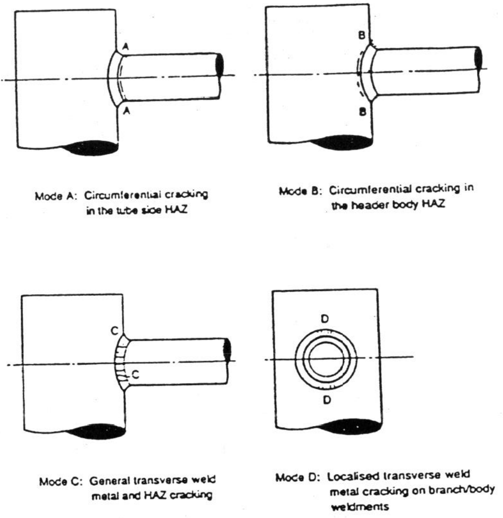
Longitudinal Cracking

Longitudinal cracking in circumferential welds has been detected in the weld metal and in the heat affected zone (HAZ) associated with the weld. The HAZ of low alloy steel welds can be particularly susceptible to crack formation if the welding process results in the formation of a coarse grain bainitic structure. As material adjacent to the fusion boundary experiences high temperatures during weld manufacture, austenite grain growth will occur. Cooling rates are usually such that the resulting transformation structure is coarse-grained bainitic. Coarse grained bainitic material is typically observed to exhibit lower ductility than fine grained bainite.

Examination of weldment behavior by full sized component tests and finite element analysis suggests that longitudinal cracking is a result of the combined high creep resistance and low ductility of this form of structure (Coleman, Parker and Walters, 1985). Thus, it appears that redistribution of hoop pressure stresses occurs such that areas of high creep strength become loaded, Figure 1. The presence of these high stresses is then sufficient to induce cracking.

Circumferential Cracking

Circumferential cracking in the HAZ can occur as a result of residual stresses. However, after extended periods of service, circumferential cracks are usually the result of high system stresses. Stresses of this nature may arise due to bending, thermal gradients, or inadequate pipe support, and will tend to promote failure in areas which are weakest in creep. These stresses may be increased by local geometry. Furthermore, axial or bending stresses are not susceptible to stress redistribution in the same way as pressure stress. Thus, failures may occur in the weld metal if the weld metal material has inadequate creep strength. Alteratively, where the weld metal has matching strength to the parent pipe, cracks may develop in the partially transformed region of the HAZ. In this region, the thermal cycles produced by the welding process are such that some regions transform to austenite. The welding thermal cycle may also result in growth of the carbide distribution present and thus reduce the creep strength of the resultant microstructure (Gooch and Kimmins, 1987).



Mode A: Circumferential cracking in the tube side HAZ

Mode B: Circumferential cracking in the header body HAZ

Mode C: General transverse weld metal and HAZ cracking

Mode D: Localised transverse weld metal cracking on branch/body weldments

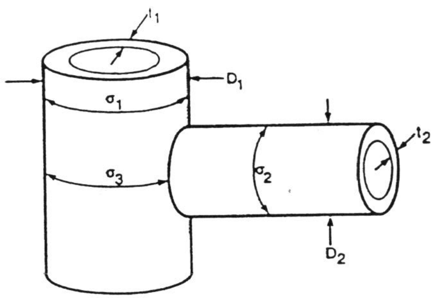
Fig. 3a. A schematic representation of cracking modes in cyclinder/cylinder intersections.

piping or incorrect setting up of hangers, or predominantly bending, due to through wall temperature gradients or inadequate allowance for thermal expansion of the main pipe. In either case, such stresses usually interact with weak microstructures. This effect has been observed in butt welds between forgings and piping where circumferential cracks have developed in the partially transformed regions of the HAZ, as described earlier.

The stresses present in the nozzle side HAZ may be further complicated by the geometry of the weld metal. The wedge shape of the circumferential fillet weld will concentrate stress in the HAZ region, and restrict deformation in the weld metal. Rapid strain accumulation in the adjacent tube can then result in the development of high shear stresses, which interact with the HAZ microstructure to form circumferential cracks.

Circumferential Cracking in the Pipe HAZ

This Mode B damage is shown in Figure 3a and appears to be due to more rapid rates of strain accumulation in the pipe as compared with the tube or pipe connection. Since the maximum stresses in both areas of the component will be in the hoop direction, if the pipe is significantly weaker in creep than the adjacent stub weldment, then the pipe material will creep away from the weld. This deformation then results in cracks in the brittle HAZ material, which propagate under the hoop stress to become part circumferential.



$$\sigma_1 = \frac{P\,(D_1 - t_1)}{2t_1}$$

$$\sigma_2 = \frac{P\,(D_2 - t_2)}{2t_2}$$

$$\sigma_3 = \frac{P\,(D_1 - t_1)}{2t_1} \times \text{fn}\,(e)$$

Where $e = f\left(\frac{D_2}{\sqrt{2D_1 \cdot t_1}}\right)$

P = pressure, t = wall thickness

Mode B failure if $\sigma_3 > \sigma_2 > \sigma_1$

Mode C failure if $\sigma_2 > \sigma_3 > \sigma_1$

Mode D failure if $\sigma_3 = \sigma_2 > \sigma_1$

Fig. 3b. A simplified assessment of stresses in cylinder/cylinder intersections.

Such differences in creep rate do not have to be a result of materials mismatch. Consideration of Figure 3b indicates that, with certain geometries, the hoop stress in the header ligament, σ_3, is greater than that in the nozzle, σ_2. In this case, even with materials of matching creep strength, creep deformation would be expected to accumulate faster in the pipe.

General Transverse Weld Metal or HAZ Cracking

An example of general transverse weldment cracking is shown in Figure 3a. This damage, Mode C, would appear to be due to enhanced rates of strain accumulation in the branch interacting with the adjacent weld metal. The fillet weld will tend to be more creep resistant than the tube or pipe because of the geometry of the weld or the creep properties of the weld metal. If deformation is then more rapid in the nozzle compared to the main pipe, either as a result of the materials properties or the hoop stresses present, case C in Figure 3a, the weld will exert a restraining influence on strain accumulation. Redistribution of stresses will occur so that material of low creep strength 'off-loads' stress to positions of higher creep resistance. It then appears that the weld metal is subjected to increases in hoop stress such that transverse cracking can take place. This damage may then occur in the weld metal or HAZ depending on the creep ductility of the constituent weldment microstructures.

Local Transverse Weld Metal Cracking

This damage, Mode D, is a particular form of the cracking described in the previous section and is usually observed in the welds of pipe intersections, Figure 3a. Under these specific conditions, the hoop stress in the main pipe can be approximated as equal to the hoop stress in the branch pipe, so that $\sigma_2 = \sigma_3$ in Figure 3b. The resultant pattern of deformation then causes a strain concentration at the 12 o'clock and 6 o'clock positions of the weldment.

CONCLUDING REMARKS

From the review of observed cracking modes it is apparent that damage in weldments is rarely a simple function of the stress due to internal pressure. Furthermore, estimates of performance made on the basis of a hoop stress calculated using a thin wall piping formula may underestimate local stresses and therefore, damage.

The pattern of cracking indicates that accurate assessment of weldments must account for specific geometry, microstructure and strength. The manufacture of thick section welds invariably leads to heterogeneity of microstructure and properties.

- For girth welds, the hoop stress due to internal pressure will redistribute based on local creep strength such that locations of high strength will sustain high stress with weaker areas under lower load. Thus, the effect of the stress redistribution will be to improve service performance provided the weldment microstructures have sufficient ductility. In this case, estimates based on nominal hoop stress will usually be conservative.
- In girth welds subject to high tensile or bending load, limited stress redistribution is possible and cracking will occur at the zone of weakest creep strength. In this case, estimates based on nominal hoop stress will usually be nonconservative.
- For longitudinal seam welds manufactured with a 'double-vee', the consequence of weld metal weaker than the adjacent parent is to concentrate the stress, midwall, within the weaker material. In this case, estimates based on nominal hoop stress will usually be nonconservative.
- For nozzles, damage is a function of relative deformation rates at the intersection of the cylinders. Thus, superior performance is obtained for components with compatible stresses and material properties.

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