TYPE IV CRACKING IN LOW ALLOY STEEL WELDMENTS

J D Parker*

Type IV cracking is a major cause of in-service failures in low alloy steel weldments. Review of the plant failures in a range of steels shows that damage develops in a region of low creep strength under the action of high system loads. The quantification of Type IV behaviour in the laboratory is more dependent on specimen geometry than test duration with failures occurring at approximately 50% of the life expected for the parent under the same conditions. Traditional plant inspection methods may be non-conservative since microdamage develops below the weldment surface and then propagates rapidly to form major defects.

INTRODUCTION

In many cases, design approaches for high temperature plant do not take direct account of the weldments present. Component geometry is based simply on the application of a representative operating stress to the relevant base material properties at an appropriate temperature. Despite the simplicity of these design methods, the vast majority of plant weldments operates for extended periods without the development of cracking. However, significant damage and in-service failures have been detected with some welds. In particular, for weldments in $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V steel, cracking has been reported at the transition between the heat affected zone (HAZ) and the base metal, after about 80,000 to 100,000 hours of operation. This damage has been described as Type IV (1). Initially it was reported that $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V steel was particularly susceptible to this form of damage since the thermal ageing caused by welding resulted in significant softening of the steel. Thus, although this reduction in strength was accompanied by an increase in ductility, failures with low overall strain resulted from the action of high axial or bending stresses in a soft zone (2). More recently, damage of this form has been identified in 1Cr$\frac{1}{2}$Mo and 2$\frac{1}{4}$Cr1Mo steel welds (3, 4). Furthermore, damaged welds are not associated with a specific plant type, manufacturer or country. Thus, the risk of Type IV damage must be assessed for weldments in high energy plant. Indeed, because the cracking develops in a continuous zone parallel to the weld, for circumferential butt welds the potential exists for rapid catastrophic failure.

* Department of Materials Engineering, University College, Swansea, UK

FACTORS AFFECTING DAMAGE

Detailed investigation of Type IV cracks in ex-service weldments has shown that grain boundary voids are associated with the macroscopic defect. The presence of these voids clearly identifies the predominant damage mechanism as long-term, high-temperature creep. Furthermore, since the microscopic and macroscopic damage occurs predominantly on grain boundaries perpendicular to the vessel axis, the principal stress responsible for crack development appears to be parallel to the vessel axis. For cylindrical components loaded by internal pressure, the maximum principal stress is in the hoop direction. The observations from ex-service weldments thus demonstrate that axial or bending system loading must be present for Type IV cracking to occur.

Creep processes are known to depend on stress, σ, temperature, T, and microstructure. Laboratory uniaxial test programmes on specific microstructures have shown that rupture life, t_f, and creep rate, $\dot{\varepsilon}_s$, can be described by an equation of the form

$$\dot{\varepsilon}_s \propto \frac{1}{t_f} = A\sigma^n \exp\left(\frac{-Q_c}{RT}\right) \qquad \text{... (1)}$$

where A, n and R are constants and Q_c is the activation energy for creep.

Uniaxial test programmes have also been carried out on specimens manufactured from thick section welds with testpieces machined from material sections perpendicular to the weldment. The performance of these "cross-weld" tests should generate the data required to quantify Type IV cracking. However, in tests on weldments in CrMoV steel, for lifetimes up to ~50,000 hours, the majority of failures occurred in the weld metal (5). This behaviour is not simply related to scatter in test data since even with strict control of base material and welding consumables similar results have been found in other test programmes. Long-term creep rupture data for $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V parent, 2$\frac{1}{4}$Cr1Mo weld metal and cross-weld samples are shown in Figure 1. In all cases, the cross-weld samples failed in the weld metal exhibiting properties typical of the all weld metal samples.

Thus, even in long-term programmes under controlled conditions, these laboratory test data are not representative of service behaviour. Recently, a rational explanation for these uniaxial results has been developed (6). It appears that for samples containing zones of different creep strength, the testpiece geometry can determine the failure location and fracture life. Thus, for samples where the weaker zone is wide compared to the specimen thickness, failures occur in the weaker zone. However, as the width of the weaker zone decreases with respect to sample thickness, the creep behaviour of this zone is constrained and laboratory test results are typical of service. This model accurately predicted the results given in Figure 1 (6). Furthermore, using this approach, large-section, cross-weld testpieces with $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V parent and 2$\frac{1}{4}$Cr1Mo weld metal have been tested and successfully reproduced failures typical of Type IV cracking (7). Analysis of these thick-section data has permitted the stress and temperature dependence of the Type IV rupture life to be established. Thus, values of n and Q_c of 3.5 and 400 kJmol^{-1} were obtained. These data agree with published information for tests carried out on samples of single microstructures (8). This agreement demonstrates that although details of the fracture process are specific to Type IV cracking, the deformation and fracture mechanisms are similar to those expected for creep in $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V steel.

METHODS OF DAMAGE ASSESSMENT

Assessment of the current condition of plant welds should be based on non-destructive inspection methods. Since Type IV cracking develops after the initiation and growth of creep voids, one attractive approach for assessment involves evaluation of any creep voids present using metallurgical replicas (9). Provided correct techniques are applied, these replicas accurately reproduce the microstructure and damage levels in weldments and can reliably identify detail of 1μm or less in size. Models relating creep voids to life have been suggested, permitting either qualitative (9) or quantitative (10) assessment of conditions. While the qualitative procedures were largely based on service observation, the quantitative methods have been developed using laboratory data. Examination of ex-service welds containing Type IV damage has shown that the number of voids and the distribution of voids varies even for nominally similar weldments operating under similar stress and temperature conditions (11, 12). Furthermore, recent evidence suggests that Type IV cracks may be initiated below the component surface, Figure 2. If this is generally the case, then application of replica techniques will provide non-conservative assessment of condition.

Alternative methods must be developed to provide a better overall assessment. Measurement of detailed microhardness or local strain appears to offer the potential for at least semi-quantitative assessments. Consideration of Figure 3 shows detailed microhardness measurements taken from an ex-service weldment. The results from location A represent a damaged location with location B indicative of an undamaged region of the same weldment. Clearly, the data from location A reveal a reduction in hardness at the region containing creep damage. Detailed analysis of these data indicate that local softening does occur as damage develops. However, it is interesting to note that microhardness data from the region where no creep voids are present exhibit no evidence of local softening. Consideration of similar data from a range of low alloy steel weldments shows that in general microhardness readings do not reveal a "soft" zone even in HAZ locations susceptible to Type IV creep damage. Thus, it appears that the development of Type IV damage is related to the existence of a region of low creep strength rather than any softening process. Whilst the local reduction in creep strength may be associated with coarsening of carbides, the rate of creep deformation is known to increase at very fine grain sizes (8). Therefore, since fine grain sizes will lead to increased hardness values, the measurement of local microhardness should not be used to provide unambiguous information regarding the creep strength of a specific microstructural zone.

Techniques for measurement of local strain have been suggested based in the deformation of surface grid. Indeed, these methods have been successfully applied to monitor localized strain at grain boundaries or between material zones of different strength. Successful application of these approaches requires that the grid can withstand extended periods at high temperatures and that the grid material does not modify the local deformation patterns. An alternative approach to determination of creep strain involves changes in grain shape. In situations where relatively large strains are developed, measurements of changes in grain shape have accurately mapped the actual deformation pattern. Present evidence suggests that Type IV damage is associated with large local deformation. Work to assess the capabilities of changes in grain shape for the relevant HAZ microstructure is in progress.

CONCLUDING REMARKS

Type IV cracking represents a significant problem in assessing the long-term creep behaviour of low alloy steel weldments. This form of damage has been shown to form in the HAZ of a range of weldments where the material has been heated to about the AC_1 by the welding thermal cycle. It appears that this thermal cycle is directly responsible for the development of a susceptible microstructural zone. This zone is not "soft" as originally suggested (2). Instead the fine grain sizes developed, in combination with modifications to the carbide precipitates present, lead to a region of reduced creep strength. Thus, rapid strain develops in a local zone of fine grain size. Moreover, because of the fine grain size, interlinkage of cavities is difficult and high densities of creep voids develop before the onset of microcracking. Reliability assessment is therefore critical since the transition from damage on a microscopic scale to the formation of major macroscopic cracking or component failure is short. Indeed, recent evidence suggests that such assessment is further complicated since the regions of first damage may be subsurface (3, 4) so that traditional inspection methods may not give an accurate assessment of condition.

Testing of cross-weld samples in the laboratory may be used to provide quantification of Type IV rupture behaviour provided the samples used develop conditions of constraint similar to those encountered in thick-section, plant weldments. The effects of specimen geometry and the size and distribution of the microstructural zones present exhibit a much greater effect on performance than test duration. It is interesting to note that provided the correct degree of constraint is developed by the testpiece geometry laboratory Type IV failures were developed in tests of approximately 1000 hours. Conversely, Type IV rupture did not occur in other tests even though the durations approached 50,000 hours. The mechanisms of deformation and failure associated with Type IV damage are similar to those identified for creep in low alloy steels. However, it appears that for a given combination of stress and temperature, the time to develop Type IV cracks is about half that expected for the parent material under the same conditions.

Additional laboratory research programmes of large cross-weld samples and thick-section tubes under internal pressure and end load are in progress. These tests will fully quantify the effects of HAZ microstructures on Type IV cracking behaviour and establish quantitative methods for assessment of in-service weldments.

REFERENCES

(1) Schuller, H.J., Haigh, L. and Woitscheck, A. "Cracking in the weld region of shaped components in hot steam lines", Der Maschinenshaden, 47, 1974, pp.1-13.

(2) Price, A.T. and Williams, J.A. "The Influence of welding on the creep properties of steels" in "Recent Advances in the Creep and Fracture of Engineering Materials and Structures", Edited by B. Wilshire and D.R.J. Owen, Pineridge Press, U.K., 1982.

(3) Westwood, H.J., Clark, M.A. and Sidey, D. "Creep Failure and Damage in Main Steam Line Weldments", Fourth Int. Conf. on "Creep and Fracture of Engineering Materials and Structures", Edited by B. Wilshire and R.W. Evans, 1990.

(4) Parker, J.D. and Preston, J., to be published.

(5) Mayer, K.H. and Konig, H. "Creep behaviour of Welded Joints in Ferritic Heat-Resistant Steel Castings", IIW Commission IX, 1983.

(6) Williams, J.A., Trans. ASME, 104, 1982, pp.36-40.

(7) Gooch, D.J. and Kimmins, S.T. "Type IV Cracking in $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V/2$\frac{1}{4}$Cr1Mo Weldments", Third Int. Conf. on "Creep and Fracture of Engineering Materials and Structures", Edited by B. Wilshire and R.W. Evans, Inst. of Metals, U.K., 1987.

(8) Evans, R.W. and Wilshire, B. "Creep of Metals and Alloys", Inst. of Metals, U.K., 1985.

(9) Neubauer, B. "Assessment of Creep Damage using Non-destructive Metallographic Measurements", First Int. Conf. on "Creep and Fracture of Engineering Materials and Structures", Edited by B. Wilshire and D.R.J. Owen, 1981.

(10) Shammas, M.S. "Metallographic methods for predicting the remanent life of ferritic coarse-grained weld heat affected zones subject to creep cavitation", Int. Conf. on Life Assessment and Life Extension, VGB-KEMA-CRIEPI-EPRI, 1988.

(11) Arnswald, W., Blum, R., Neubauer, B. and Poulsen, K.E. "Lifetime expectancy assessment through surface investigation", VGB-Kraftwerkstechnick 59, 1979, pp.581-586.

(12) Van Zyl, F.H., Int. J. of Pressure Vessel and Piping, 50, 1992, pp.1-3.

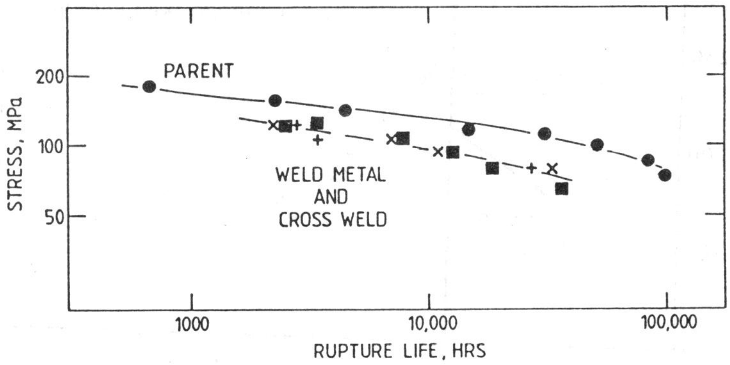

Figure 1. Comparison of the long-term creep rupture behaviour of $\frac{1}{2}$Cr$\frac{1}{2}$Mo$\frac{1}{4}$V steel, 2$\frac{1}{4}$Cr1Mo steel weld metal and cross-weld tests from weld joints

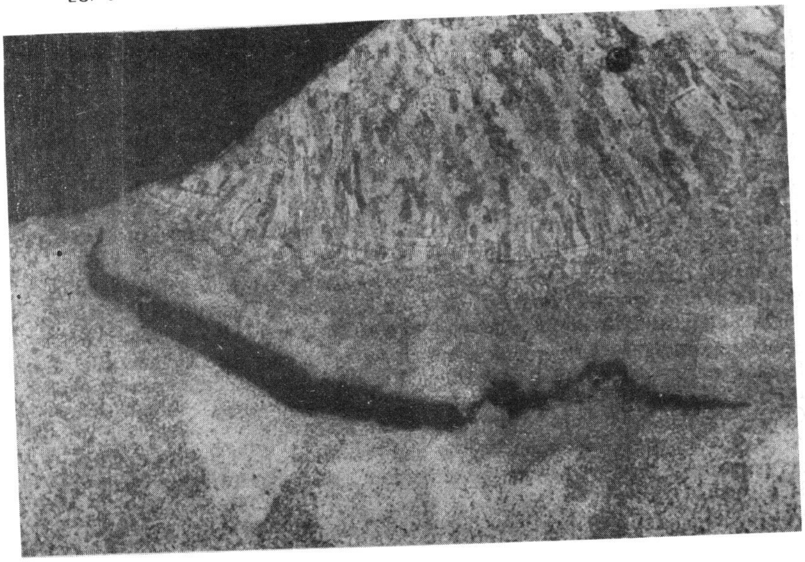

Figure 2. Type IV cracking revealed by metallographic preparation of an ex-service weldment

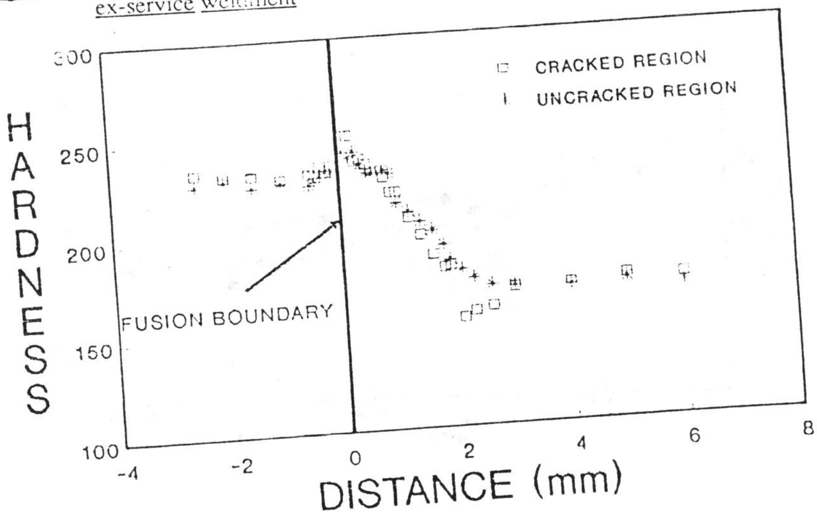

Figure 3. Variation of microhardness readings across the HAZ of an ex-service weldment, data A are from a damaged location, with B results from an undamaged region