RESEARCH OF WELDING EFFECT ON STRUCTURAL INTEGRITY AT HIGH TEMPERATURE

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ABSTRACT

The invention of fusion welding technology has brought on a revolutionary change in manufacturing industry which enables the construction of large scale high temperature plants in chemical, petrochemical and power generation industries. However, among the failure cases of high temperature components, premature failures of weldments have taken a large percentage that indicates the detrimental effect of welding on structural integrity. The accurate prediction of the high temperature behaviour of welded components is thus becoming increasingly important in order to realise an optimised design and maintenance of a plant life. In the present paper, recent research activities on high temperature behaviour of welded structures are briefly summarised. A local deformation measuring technique is proposed to determine the creep properties of weldment constituents. A damage mechanics approach is introduced to study the life reduction and ductility reduction due to the presence of a weld in high temperature structures. Finally, the high temperature creep crack growth in weldments is discussed.

Key Words: Welding; life assessment; creep; damage mechanics; fracture mechanics, ductility; multiaxility; high temperature; design code

1. INTRODUCTION

The development of design theory for structure integrity can be largely divided into several stages and are illustrated in Fig. 1. It has been seen that the fusion welding technology has brought on a revolutionary change in manufacturing industry that enables the construction of large scale high temperature plants in chemical, petrochemical and power generation industries. However, it has also been well aware that the premature failures of weldments are a common occurrence that indicates the detrimental effect of welding on structural integrity.

The integrity of welded structures has thus been a problem entangling engineers and researchers since it was introduced into industries. Some simple rule-based design principles were made available in design codes earlier in 1950s. Fatigue strength data of weldments were also comparatively well documented for normal temperatures in the 1980s[1]. At elevated temperatures, however, there are only limited results, which can benefit the design and life assessment purposes. The failure of weldments at high temperature remains unfortunately a larger percentage. The technical difficulties in designing weldments at high temperature are two-folds: the metallurgical complexities and time-dependent features of failures. It is now widely recognised that the integrity of weldment at high temperature is the 'last link' in the path towards the reliable and safe design of structures[2].

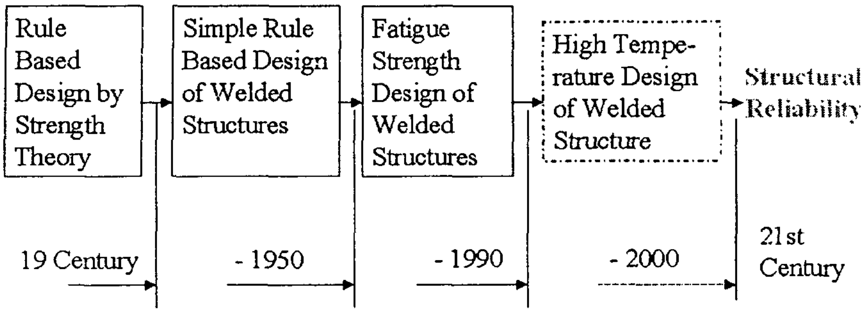


Fig. 1 Development of Design Principles for Welded Structures

In the past several decades, many countries have put great efforts into the investigation of the effect of welding on the structural integrity of high temperature installations. In the context of design method, the ASME Code Case N-47[3] took into account the welding effect at high temperature for the first time in 1987. This is a significant improvement in the design methodology[4]. However, deficiencies exist in the definition of the weldment strength reduction factor (WSRF) which takes no multiaxial effect into account and is only applicable to the weldments of relatively lower weld metal strength. The applicability of stain limit in the code is also questionable. Research efforts on creep stress and strain evaluation of a welded tube[5], creep crack propagation rates in a welded pressure vessel[6] and remnant life assessment of seam welded pipework[7] have resulted in a fairly comprehensive British R5 route[8]. Other guidelines such as French RCC-MR rule[9] have also taken the weld into consideration.

In the development of the design codes and life extension technology for ageing plants, the life assessment methodology is the nucleus. Due to time-dependent features of failures, the life assessment generally requires long term tests on small specimens or components at high temperature for at least one percent of the service life (1,000 hrs of 100,000 hrs service life) to ensure the extrapolation accuracy[10]. For weldments previous work were mostly done on single weld metal specimens or cross-weld specimens[11-14]. However, this is generally not sufficient to understand the high temperature behaviour of a complete weldment. The cross-weld specimen may be used to compare relative strength but is not capable to predict the life of the weldment due to the multiaxility existed in actual welded components[15]. The component tests would have been very desirable if they were technically feasible and not too costly. There are unfortunately only few test cases on components[5, 16, 17]. The alternative way is to do laboratory tests on small specimens and then extrapolate the results via certain constitutive laws to engineering components by numerical simulations[16]. Major progresses have been achieved in recent years in this respect. Techniques for long term measurement of local deformation of constituents of weldments are developed[18, 19]. A semi-analytical method is proposed to calculate the creep stresses in circumferential welds of pipes[20]. Damage mechanics approaches are incorporated in the study of creep damage development in weldments[21, 22]. The calibration results are used to evaluate the weldment strength reduction factors and strain allowances through some simple expressions[16, 23].

In the present paper, our recent research work on local deformation measuring technique is introduced. The weakening effect of weldments on high temperature structures is studied in terms of a damage mechanics approach. High temperature creep crack growth behaviour in weldments is also discussed.

2. LONG TERM MEASUREMENT OF LOCAL DEFORMATION OF CONSTITUENTS OF WELDMENTS

The extrapolation of our knowledge from short time to long time and small scale (one dimension) to larger scale (3- dimension) requires first a material databank from small specimen and then a good constitutive model. The weldment is actually a combination of different material zones: parent metal, intercritical structure, fine grain and coarse grain heat affected zones (HAZ) and weld metal. Each zone may exhibit quite different material properties, which leads to great difficulties in understanding the creep behaviour of a complete weldment[21]. In order to obtain the necessary material data, some conventional tests were done separately on parent metal, weld metal and simulated HAZ which was obtained by thermal cycle simulation[24]. More recently an impression creep test technique was developed to determine the creep law of HAZ material in terms of a transformation via reference stress technique[19]. These represent indirect measurement of the material creep properties. In the present work a direct measurement of local deformation in the weldment has been made possible.

2.1 Principles for Local Deformation Measurement

In consideration of difficulties of measuring long-term creep deformations in small zones, a new method has been developed in high temperature technology division of Nanjing University of Chemical Technology. The basic idea is to use optical fiber to conduct light and one ends of the fibers as measuring marks. By measuring the displacements of the marks the deformation of different zones are obtained. The measuring system is shown in Fig.2, which utilises the merits of quartz optical fiber, advanced long distant microscope and computer image analysis techniques. Deformation measurement is carried out by the following procedure: (1) quartz optical fibers are stuck to the measured specimen by using ceramic gum, and served as dot-shaped marks; (2) laser is transmitted through the fibers to the specimen surface where the light marks are received by a long distant microscope and imaged on CCD's target; (3) the mark information is transferred onto a computer by A/D converting with the help of image processor; and (4) the received digital images are automatically processed by a special purpose software designed by us.

The selected quartz optical fiber has an outer diameter of 140μm and a core diameter of 110μm. It is possible to arrange 3 -4 fibers in a region as small as 1 mm. The fibers can thus be stuck to the narrow regions of weld metal and HAZ of a weldment. The feasibility of the method is verified by two examples.

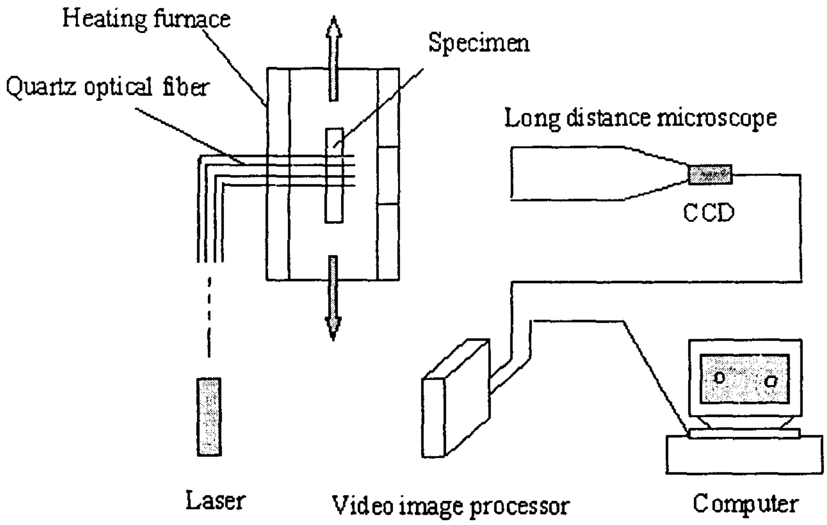


Fig.2 Measuring system of local creep deformation

2.2 Measurement of deformation of weld metal in HK-40 reformer tubes

Plate type cross-weld specimens were produced from welds of HK-40 tubes. In order to measure creep deformation of weld metal, a waisted cross-weld specimen is designed. Stuck marks are shown in Fig.3. The specimen has a thickness of 3 mm.

Uniaxial creep tests were performed in air at a temperature of 850°C with stresses in the range of 40~50MPa, the temperature difference was maintained within ±3°C. Six quartz optical fibers were stuck onto the waisted weld region of three cross-weld specimens. The creep deformation of the weld metal was obtained by measuring local deformation between the optical fiber marks, the creep curves in the form of creep strains versus time are shown in Fig.4. The minimum creep strain data of weld metal is obtained, and compared with that of base metal from Reference[25] in Fig.5.

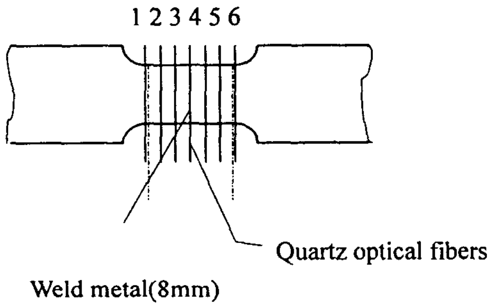


Fig.3 HK-40 cross-weld specimen and stuck fibers

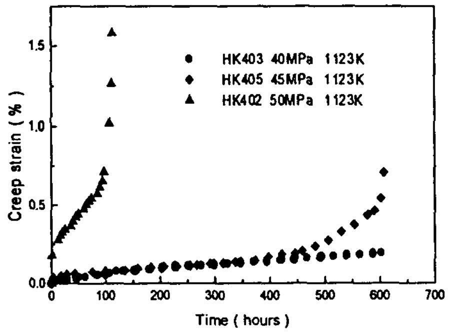


Fig. 4 Creep curves for weld metal of cross weld specimens

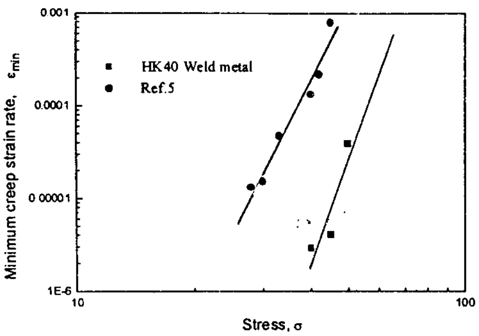


Fig. 5 Minimum creep strain rate for base, and weld metal of HK-40 tubes at 850°C

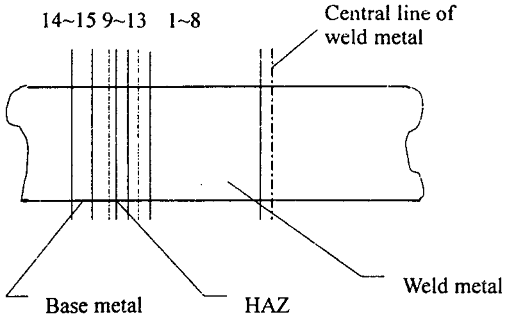


Fig.6 Schematic diagram showing the shape of 1Cr0.5Mo cross-weld specimen

Fig.6 indicates that weld metal has a lower creep strain rate than the base metal when subjected to the same stress. Therefore, the HK-40 weldment is essentially a creep-hard weld where notable stress concentration may occur.

2.3 Measurement of deformation in constituent parts of 1Cr0.5Mo cross-weld specimens

The developed method is also applied to measuring creep deformation of different parts in 1Cr0.5Mo cross-weld specimens. Plate type cross-weld specimens including the parent metal, the weld metal and the HAZ were machined from the weldment. Specimen thickness is 3mm. 15 quartz optical fibers were stuck onto the regions of base metal, weld metal and HAZ respectively, as shown in Fig. 6. Uniaxial creep tests were carried out at 550°C with stresses from 110 MPa~165MPa.

The measured creep strains versus time are shown in Fig. 7, 8 and 9 for the base metal, weld metal and HAZ respectively. The minimum creep strain rates with applied stress are shown in Fig. 10. Test results show that the base metal exhibits a higher creep strain rate at high stress levels compared with the weld metal and HAZ, while the weld metal exhibits a higher creep strain rate than the base metal and HAZ at lower stress levels (less than 120MPa). Although it is creep-hard at high stress levels, the weld metal is creep-soft at low stress levels for post weld heat treatment condition.

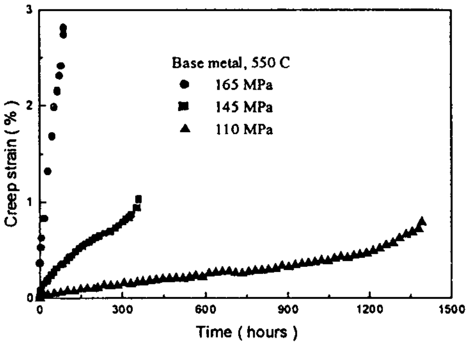


Fig.7 Creep curves of base metal of 1Cr0.5Mo cross-weld specimen

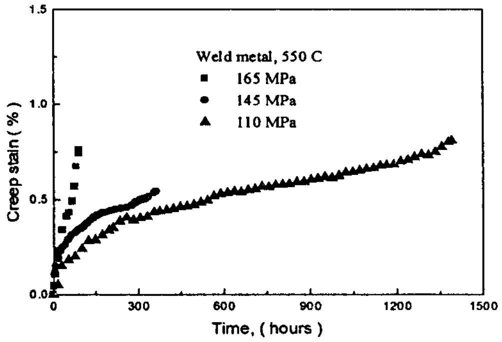


Fig.8 Creep curves of weld metal of 1Cr0.5Mo cross-weld specimen

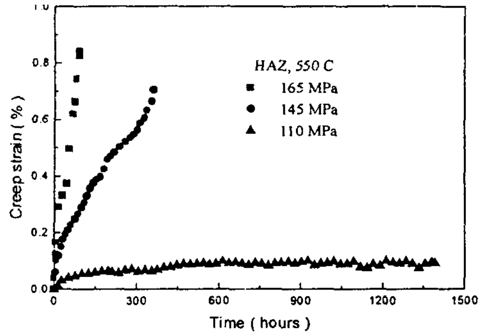


Fig.9 Creep curves of HAZ of 1Cr0.5Mo cross-weld specimen

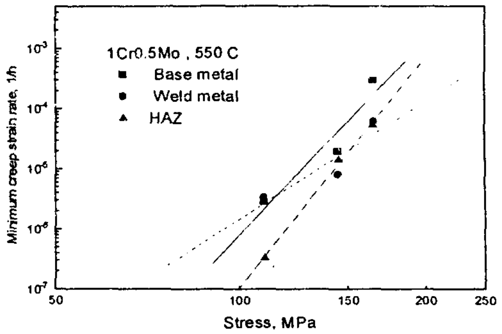


Fig.10 Minimum creep strain rate for the base metal, weld metal and HAZ of 1Cr0.5Mo cross-weld specimen

It is seen that the local creep deformation of the base metal, weld metal and HAZ in the cross-weld specimens can be accurately acquired by the present method. The acquired information on the creep deformation of each part of a weldment give the basic features of a weldment such as creep-soft or creep-hard, at low and high stress levels. But the conventional uniaxial creep tests only give an averaged deformation over the gauge length.

3. CONTINUUM DAMAGE MECHANICS APPROACH FOR CREEP BEHAVIOUR OF WELDMENTS

When the material data of the constituents of a weldment are available, the continuum damage mechanics (CDM) approach would be an appropriate tool to circumvent the difficulties in the high temperature test of full scale welded components. The damage concept was first proposed in a pioneering paper by Kachanov (1958)[26] and accomplished by Robatnov(1968)[27]. An inherent discrete process of material degradation was modelled by a continuous variable. The damage was generalised as an internal state variable in the context of irreversible thermodynamics later in 1970s by Lamaitre and Chaboche[28]. What was lost in accuracy in modelling the deterioration was then gained in computational simplicity. The CDM was introduced to study the creep behaviour by Hayhurst[29] and by Tu for design considerations[21, 23].

3.1 *Constitutive Model*

A constitutive model derived from a multi-phase composite assumption is used to describe the damage localisation in the weldment[30].

The constitutive equations are expressed as

$$\left.\begin{aligned}
\frac{d\varepsilon_{ij}}{dt} &= \frac{3}{2} B\sigma_e^{\,n-1} S_{ij}\left[(1-\rho)+\rho(1-D_\rho)^{-n}\right] \\
\frac{dD_\rho}{dt} &= g\frac{A}{\phi+1}\frac{\left[\alpha\sigma_1+(1-\alpha)\sigma_e\right]^{\upsilon}}{(1-D_\rho)^{\phi}} \\
D_{cr} &= 1-(1-g)^{1/(\phi+1)}
\end{aligned}\right\} \qquad (1)$$

where ε_{ij} is the strain tensor, S_{ij} the stress deviator, σ_I and σ_e are the maximum principal stress and the effective stress, their combination, $\alpha\sigma_I + (1-\alpha)\sigma_e = \sigma_r$, is a mixed multiaxial rupture stress, α is a material constant ranging from zero to unity, D and D_{cr} are the damage variable and critical damage; B, n, A, and υ are the material constants relating to the minimum creep strain rate and rupture behaviour; ρ is the volumetric ratio of the damage phase, which may corresponds to the boundary cavitation, g and ϕ are the constants accounting for the material damage performance. Local rupture is postulated to occur when the rupture equation, $A\sigma_r^{\upsilon}t = 1$, is satisfied. A finite element method software for boundary value problems (Σ-FEM) is coded with the above constitutive equations. The time-integration is carried out by using Euler method. The time step is controlled by both strain rate and damage rate criteria.

3.2 Damage Development in Weldment of HK 40 Furnace Tubes

The weldments of HK 40 furnace tubes are generally believed to be reliable. However, our recent dissection of furnace tubes which had been in service for more than 15 years revealed damage concentration occurred almost inevitably in the weldments. Continuum damage mechanics approach is used to obtain the general understanding of the damage behaviour of the weldment. The studied hydrogen reformer furnace tube had been in service for 9,000 hours and was removed for destructive inspection from in a refinery. The tube has a diameter and thickness of 127×12 mm. The whole furnace tube of 12 meters is fabricated by welding together 4 to 5 short tubes. A mixture of hydrocarbon and steam of about 500°C enters the tube from the top inlet. Hydrogen-rich gas is produced during the chemical reaction and then leave the outlet to gas collector at about 850°C. The internal pressure is about 2 MPa.

Using the material data from the optical measurement on the weld and conventional creep test on parent metal[25], the material constants for the constitutive equation (1) are obtained and are listed in Table 1, where stress and time units are MPa and hour respectively.

Table 1 Material Constants for HK40 Weldment

Location	B	n	A	υ	g	ϕ	ρ	D_{cr}	α
PM	1.034E-14	6.526	9.167E-11	4.375	0.908	1.238	0.014	0.656	0.25
WM	8.569E-25	11.475	1.495E-16	7.971	0.92	3.00	0.043	0.656	0.25

A quarter of the welded tube is modelled according to its symmetrical nature. As the weld metal is very hard as compared with the parent metal, significant stress concentration is found in the weld. After 10,000 hours, the inner side of the weld has a stress about twice as the parent metal. Damage is thus found preferentially occurred in the inner side of the weld and then developed into the outer surface. Fig.11 illustrates the damage distributions in the weldment at 96,000 hours and 110,000 hours respectively. The damage in the parent metal is relatively lower. It attains only about 50% when the weld metal is fully damaged. This is verified in the dissection of the furnace tube. Fig. 12 shows the cavities in the weld metal (a) and in the parent metal (b). It is obvious that damage is prone to the weld. Some other research also indicates that the weld may have a higher damage rank[31]. We thus believe that the weldments may become the weak link in HK 40 furnace tubes in the later period of service life.

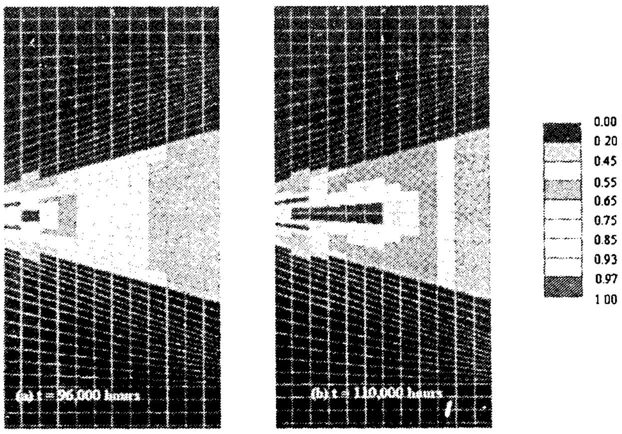
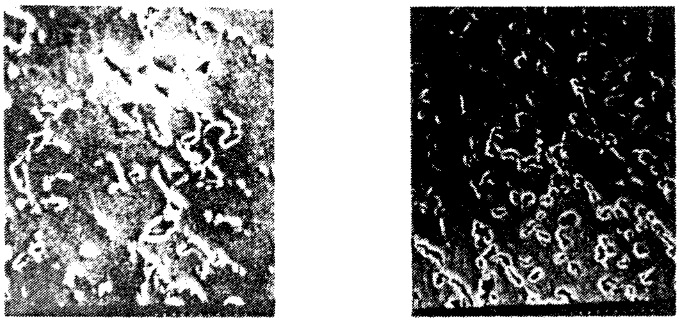


Fig.11 Damage distributions in the weldment at (a) 96,000 hours and (b) 110,000 hours



(a) (b)

Fig. 12 Cavities in (a) weld metal and (b) parent metal, SEM x 700

3.3 Damage Development in Weldment of 0.5Cr0.5Mo0.25V Main Steam Pipe

A weldment of 0.5Cr0.5Mo0.25V steel at T-joint pipe component of the main steam pipe from a power plant is investigated. The welded pipe has an outer diameter of 273 mm and a thickness of 23 mm. The weld profile is assumed as a V-shaped one of an angle of 45° and a root width of 4 mm. The loading condition is assumed to give the same stress level($\approx$ 120 MPa) as the weld region in the T-joint. This is achieved by a 3-D creep stress analysis on the T-joint. The service temperature and pressure are taken as 530°C and 21.5 MPa, respectively. Creep testing was performed on the weld and the parent metals for both severe damaged and almost undamaged materials[32]. The testing results show that the weld metal has higher creep strength and lower strain rate than the parent metal. The weldment is thus a hard weld. The obtained material constants for Eq.(1) are given in Table 2, where stress and time units are MPa and hour respectively. The derived creep curves of the parent and the weld metal and HAZ are shown in Fig. 13.

Table 2 Material Constants for 0.5Cr0.5Mo0.25V Weldment

Location	B	n	A	υ	g	ϕ	ρ	D_{cr}	α
PM	$8.495\text{x}10^{-37}$	14.45	$7.963 \text{ x } 10^{-32}$	12.65	0.725	1.472	0.0053	0.408	0.43
HAZ	$7.726\text{x}10^{-35}$	13.72	$7.04 \text{ x } 10^{-30}$	12.0	0.797	1.340	0.0055	0.494	0.43
WM	$2.196\text{x}10^{-36}$	13.93	$1.467 \text{ x } 10^{-29}$	11.54	0.817	2.207	0.0188	0.411	0.43

The finite element simulation shows that after 97,000 hours one element in the weld on the outer surface close to the fusion line attains the critical value which indicates that the element is seriously damaged. The predicted damage profile is in good consistence with the practical observation. Fig.14 shows the damage profile across the weld section and Fig.15 is the metallographical observation of the damage across the weldment. The damage in the weld grows much faster than that in parent metal. When the damage in the weld metal reaches the critical value, the parent metal is only exhausted to a relatively small percentage of 26%. The damage has caused severe strain concentration in the weld metal. Fig.16 illustrates the strain accumulation in the weldment. It is seen that the parent material is in the secondary stage when the weld metal enters the tertiary creep. Although the weld metal has longer creep life than the parent metal when subjected to the same uniaxial load, the damage occurs first in it due to the stress redistribution in the pipe component. It is worth mentioning that the general finite element method fails to predict the high strain concentration, and inversely gives smaller strain in the weld region. The above results also indicate that the parent metal is not fully made use of in the structure and will have considerable lifetime left. It should be possible to increases the availability of the structure by an appropriate repair procedure.

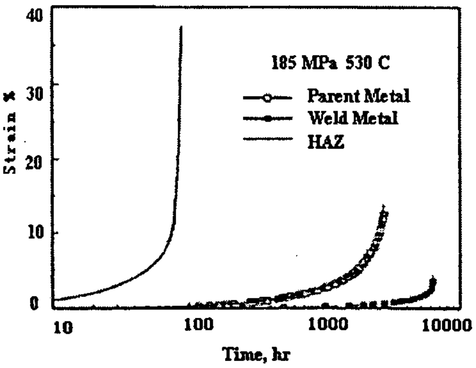


Fig. 13 Derived creep curves for the parent metal and the weld metal and HAZ

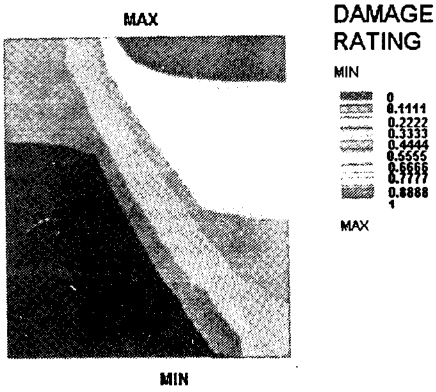


Fig. 14 Damage profile across the weld section

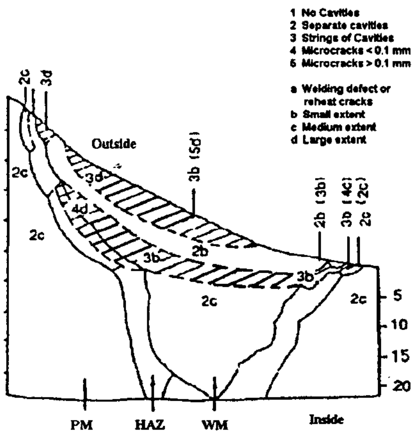


Fig.15 Metallographical observation of the damage across the weldment

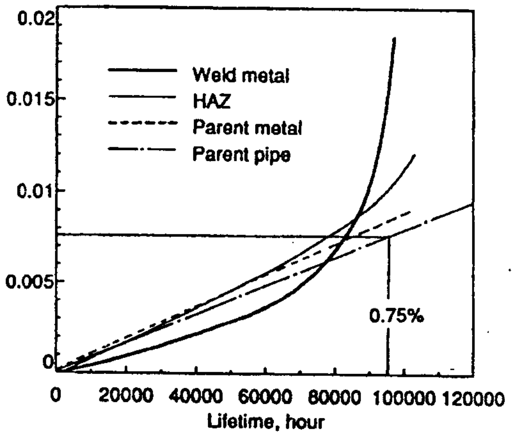


Fig. 16 Strain accumulation in the weldment

For the comparison purpose, damage analysis is also performed on a reference parent pipe that has the same geometry as the welded one. The previous finite element model is used, When the element at the outer surface reaches the critical damage value, the creep time is about 280,000 hours. With reference to this lifetime, one can see that the life of the pipe is shortened by a factor of about 3 due to the presence of the weld. The required weldment strength reduction factor can accordingly be found which is about 0.90.

4. FRACTURE MECHANICS CONSIDERATION OF CREEP CRACK GROWTH IN WELDMENTS

The plant assessment experiences indicated that in the majority of cases where creep crack initiation and growth occurs, defects predominate in and in the vicinity of welds. However, creep crack growth (CCG) studies have mostly concentrated on homogeneous materials where the crack growth rate is correlated with $C^*(t)$ in the extensive creep regimes according to ASTM E1457[33], and with C_t in the transition regime from small scale creep to extensive creep[34]. There are two major concerns about the CCG at the weldments. One is fracture mechanics parameters and the other the crack growth rates in the inhomogeneous materials. They are illustrated with following examples.

4.1 Effect of Metallurgical Inhomogenity on Fracture Mechanics Parameters

As the mechanical properties vary significantly across the weldment, the stress redistribution is generally not negligible, which influence the evaluation of fracture mechanics parameters. To quantify the effect, a single edge notched specimen (SENT) manufactured from the weldment in the HK 40 furnace tubes of the same geometry is studied. Finite element method is used in the analysis. The material constants in Norton's creep law are given below:

B= 1.034E-14	n = 6.526	for parent metal
B= 8.569E-25	n = 11.475	for weld metal

In order to have a comparison, two cases are considered: one is a single material model of weld metal only and the other the combination of parent and weld metal. The crack has a length of 5mm and the specimen a width of 12 mm. The change of C(t) with time is given in Fig. 17. When the time is small, there is little change of the stress and creep zone ahead of the crack tip is very small. No interaction occurs between the crack tip stress field and the redistributed stress due to material mismatch. Thus the two-material weld model predicts the same value as the single material model (the curves from different contour integrals overlap). With the passage of time, however, the hard weld metal will be on-loaded and soft parent metal off-loaded. This will enhance the stress field around the crack tip which leads to a larger C* value in the stationary creep. It is thus seen that the converged curve of the two-material model deviates from that the single material model and the corresponding value is about **3.2 times** larger. This means that the creep crack growth rate may be under-estimated by ***2 –3 times*** *if the effect of material mismatch is not taken into* consideration.

Similar studies are performed on the weldment of a HK 40 furnace tube subjected to an internal pressure of 2.5 MPa. A circumferential crack is assumed in the inner side of the weld. An axisymmetric model with the same mesh as the SENT specimen is used in FEM computations. It is found if the fracture assessment is based entirely on the weld metal properties, the C* parameter may be underestimated by more than **100 times** when compared with the results of two-material weldment model. However, in the small scale creep, the difference between the C(t) values is not significant.

Another interesting example is when the crack is located in the interface of weld and parent metal

The finite element simulation shows that after 97,000 hours one element in the weld on the outer surface close to the fusion line attains the critical value which indicates that the element is seriously damaged. The predicted damage profile is in good consistence with the practical observation. Fig.14 shows the damage profile across the weld section and Fig.15 is the metallographical observation of the damage across the weldment. The damage in the weld grows much faster than that in parent metal. When the damage in the weld metal reaches the critical value, the parent metal is only exhausted to a relatively small percentage of 26%. The damage has caused severe strain concentration in the weld metal. Fig.16 illustrates the strain accumulation in the weldment. It is seen that the parent material is in the secondary stage when the weld metal enters the tertiary creep. Although the weld metal has longer creep life than the parent metal when subjected to the same uniaxial load, the damage occurs first in it due to the stress redistribution in the pipe component. It is worth mentioning that the general finite element method fails to predict the high strain concentration, and inversely gives smaller strain in the weld region. The above results also indicate that the parent metal is not fully made use of in the structure and will have considerable lifetime left. It should be possible to increases the availability of the structure by an appropriate repair procedure.

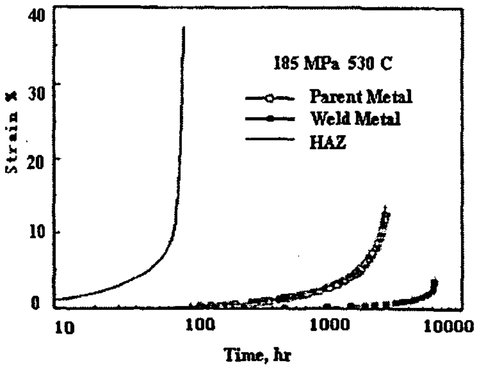


Fig. 13 Derived creep curves for the parent metal and the weld metal and HAZ

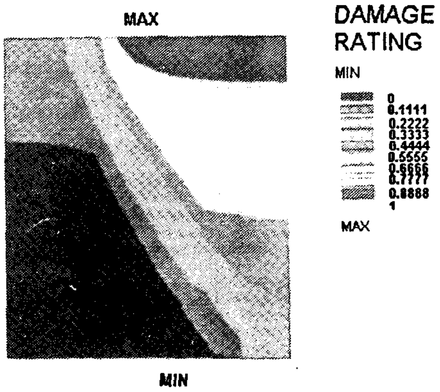


Fig. 14 Damage profile across the weld section

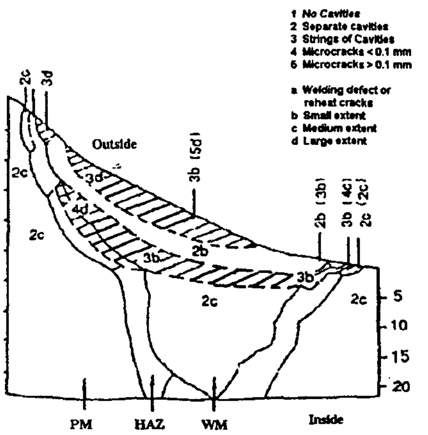


Fig.15 Metallographical observation of the damage across the weldment

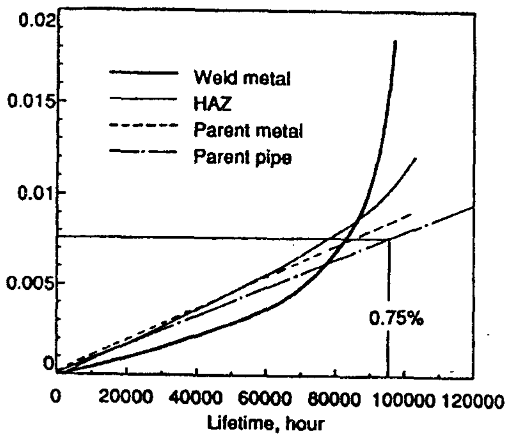


Fig. 16 Strain accumulation in the weldment

For the comparison purpose, damage analysis is also performed on a reference parent pipe that has the same geometry as the welded one. The previous finite element model is used, When the element at the outer surface reaches the critical damage value, the creep time is about 280,000 hours. With reference to this lifetime, one can see that the life of the pipe is shortened by a factor of about 3 due to the presence of the weld. The required weldment strength reduction factor can accordingly be found which is about 0.90.

4. FRACTURE MECHANICS CONSIDERATION OF CREEP CRACK GROWTH IN WELDMENTS

The plant assessment experiences indicated that in the majority of cases where creep crack initiation and growth occurs, defects predominate in and in the vicinity of welds. However, creep crack growth (CCG) studies have mostly concentrated on homogeneous materials where the crack growth rate is correlated with C*(t) in the extensive creep regimes according to ASTM E1457[33], and with C_t in the transition regime from small scale creep to extensive creep[34]. There are two major concerns about the CCG at the weldments. One is fracture mechanics parameters and the other the crack growth rates in the inhomogeneous materials. They are illustrated with following examples.

4.1 Effect of Metallurgical Inhomogenity on Fracture Mechanics Parameters

As the mechanical properties vary significantly across the weldment, the stress redistribution is generally not negligible, which influence the evaluation of fracture mechanics parameters. To quantify the effect, a single edge notched specimen (SENT) manufactured from the weldment in the HK 40 furnace tubes of the same geometry is studied. Finite element method is used in the analysis. The material constants in Norton's creep law are given below:

B= 1.034E-14 n = 6.526 for parent metal
B= 8.569E-25 n = 11.475 for weld metal

In order to have a comparison, two cases are considered: one is a single material model of weld metal only and the other the combination of parent and weld metal. The crack has a length of 5mm and the specimen a width of 12 mm. The change of C(t) with time is given in Fig. 17. When the time is small, there is little change of the stress and creep zone ahead of the crack tip is very small. No interaction occurs between the crack tip stress field and the redistributed stress due to material mismatch. Thus the two-material weld model predicts the same value as the single material model (the curves from different contour integrals overlap). With the passage of time, however, the hard weld metal will be on-loaded and soft parent metal off-loaded. This will enhance the stress field around the crack tip which leads to a larger C* value in the stationary creep. It is thus seen that the converged curve of the two-material model deviates from that the single material model and the corresponding value is about **3.2 times** larger. This means that the creep crack growth rate may be under-estimated by **2 –3 times** if the effect of material mismatch is not taken into consideration.

Similar studies are performed on the weldment of a HK 40 furnace tube subjected to an internal pressure of 2.5 MPa. A circumferential crack is assumed in the inner side of the weld. An axisymmetric model with the same mesh as the SENT specimen is used in FEM computations. It is found if the fracture assessment is based entirely on the weld metal properties, the C* parameter may be underestimated by more than **100 times** when compared with the results of two-material weldment model. However, in the small scale creep, the difference between the C(t) values is not significant.

Another interesting example is when the crack is located in the interface of weld and parent metal which may represents the case of fusion line crack. Parametric FEM computations are performed on CT specimens[35]. Modifications on the current formula for C_t parameter are made. In the case that the creep strain rate of the weld metal is 10 times larger than that of the parent metal, for instance, the C* value of the two material weld model is found about 20 times larger than that of single parent metal model but about 2 times less than that of the single weld metal model, as shown in Fig. 18. Some other computational work on the HAZ crack has indicated similar results[36]. These results give us a warning that it may be dangerous to do high temperature fracture assessment on the weldment defect only based upon weld metal or parent metal properties.

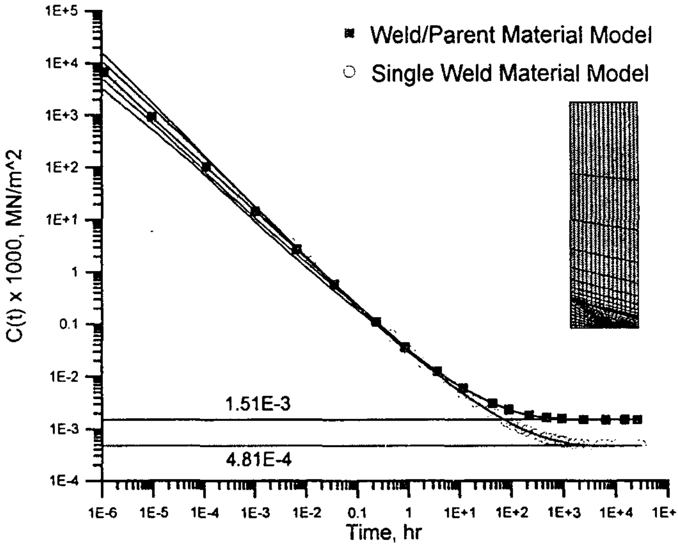


Fig. 17 Change of C(t) vs. time in SENT specimen (a=5mm, W=12mm)

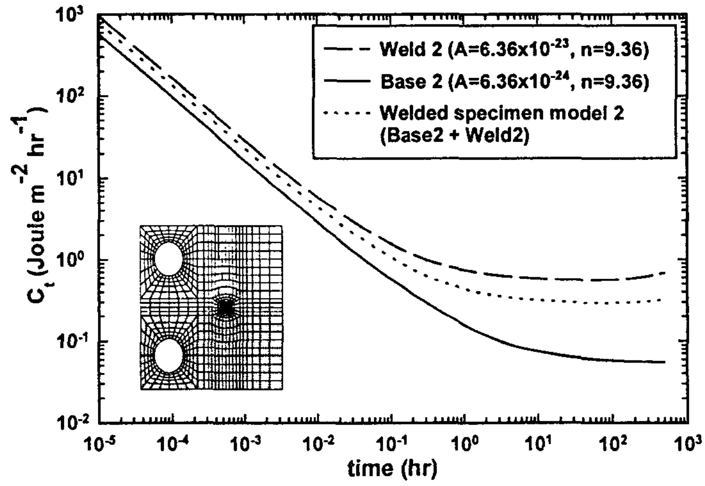


Fig. 18 Change of C(t) vs. time in CT specimen

4.2 Creep Crack Growth Rates in Weldments

Considerable research efforts have been taken for the creep crack growth rates in recent years[37]. A European Commission supported project 'SOTA' has been carried out aiming at harmonising creep crack growth testing and data analysis techniques for welds. Some initial co-operation between China and Korea has also been performed on the creep crack growth rates in new and old weldments. Fig. 19 shows the creep crack growth rates from tests on service exposed HK 40 furnace tubes[38]. In order to better simulate the cracking states of the furnace tubes, C-shaped specimen is used for parent part of the tube while SENT specimen used for the weld metal. The C* parameters are calculated according to ASTM E1457 with the measured load line displacements. It is seen that the weld has higher creep crack growth rates. This attributes partly to the higher pre-damage level in the weld which is proved in our previous damage simulations.

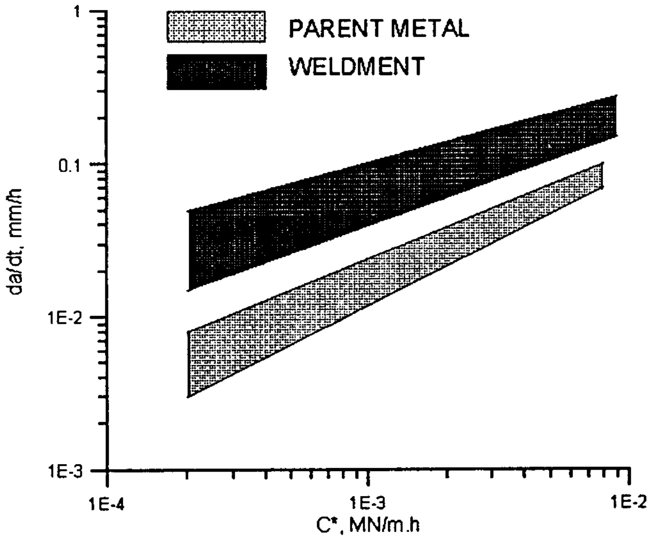


Fig. 19 Creep crack growth rates of service exposed parent and weld metal of HK 40 furnace tubes

It should be pointed out that the comparison of CCG between the weld and parent metal might not make much sense when the accuracy of the measured fracture parameters is not well clarified. Thus a re-examination of the applicability of ASTM E1457 for the weldments should be carried out.

5. CONCLUDING REMARKS

In the present paper, recent research activities on high temperature behaviour of welded structures are briefly summarised. A local deformation measuring technique is proposed which allows the direct measurement of the creep properties of weldment constituents. A damage mechanics approach is introduced to study the life reduction due to the presence of a weld. The high temperature creep crack growth in weldments is also studied. It is found that the material mismatch in a weldment may have significant influence on the damage development and creep crack growth rates of the weldment.

Although progresses have been made in recent years in research of the welding effect on structural integrity at elevated temperatures, further efforts are still needed to dissolve the 'last link' in the path to the reliable design of welded structures. The following aspects should be given a first priority in research:

Failure Case Study and database development

The failure cases from plants are of particular importance to the improvement of new product design. The premature failures of weldments in-service indicate the weakest links of components in plants. They represent hence the lower bound of life scatter. If the weldment design is based on the creep behaviour of the weakest welds, the design is certainly in the safe side. A serious lack of useful information concerning the high temperature performance of weldments is obviously an obstacle to improve the weldment design. Further experimentation and database development for various weldments are required.

Strain Allowance

The methods for the evaluation of inelastic strains are not clearly specified in the current codes. One, for instance, may use creep constitutive equations with or without primary creep. Different analysis approaches will certainly end up with different values of the accumulated inelastic strain. There is then a lack of clear cut of the strains for the life design and extension. The stress multiaxility also has influence on the strain criterion.

Fatigue-Creep Interaction Effect

The damage summation rule should be modified when the welding effect is taken into account. The allowable strain range reduction factors have not yet been available for the evaluation of the fatigue life.

Fracture Mechanics Considerations

The defect acceptance criteria are usually formed based on the individual weld metal rather than the composite weld. As it has been known that there are always stress disturbances across a weld, the defect in different positions will exhibit different growth behaviours. It is suggested the study of fracture parameters of different weld compositions should be first carried out and re-examination of the applicability of ASTM E1457 for the weldments be performed.

Probabilistic Evaluation of the Weldment Strength Reduction Factors

Finally, in consideration of scatter nature of the high temperature life of a structure[39], especially when the weldments are involved, it is preferable that the design and life assessment of welded structures be based on probabilistic methods. The reasonable weldment reduction factors should give 'acceptable risks of failure' for structures of different importances[40].

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REFERENCES

1 Maddox, S.J., *Fatigue Strength of Welded Structures*, Abington Publishing, 1985

2 Penny, R. K., Private Communication, April 1994

3 ASME Code Case N-47, *Class 1 Components in Elevated Temperature Service*, ASME, New York, 1987

4 Corum, J.M., Evaluation of Weldment Creep and Fatigue Strength-Reduction Factors for Elevated-Temperature Design, *ASME Trans. J. Pres. Ves. Technol.*, **113** (1991)

5 Coleman, M.C., Parker, J.D. & Walters, D.J., The Behavior of Ferritic Weldment in Thick Section 1/2Cr1/2Mo1/4V Pipe at Elevated Temperature, *Int. J. Pres. Ves. & Piping*, **18** (1985) 277-310

6 Coleman, M.C., CEGB Report, TPRD/M/1234, 1255/M82, 1982

7 Bissell, A.M., Cane, B.J. and Delong, J.F., Remnant Life Assessment of Seam Welded Pipework, Proc. Int. Conf. Life Assessment and Extension, 13-15 June 1988, The Hague, Netherlands, Vol. **2**, 1988, 203-211.

8 Nuclear Electric plc, *An Assessment Procedure for the High Temperature Response of Structures, Procedure R5 Issue 2*, UK, 1997

9 RCC-MR, *Design and Construction Rules for Mechanical Components of FBR Nuclear Islands*, Published by AFCEN, June 1985

10 Viswanathan, R. And Foulds, J., Accelerated Stress Rupture Testing for Creep Life Prediction - Its Value and Limitations, *ASME Trans. J. Pres. Ves. Technol.*, **120** (1998) 105-115.

11 DeWitte, M. and Cossement, G, Creep Behavior of 2.25Cr1Mo Base Material and Weldments, VGB-Conf. "Residual Service Life 1992", Mannheim, 6-7 July 1992, 38. 1-38. 28.

12 Laha, K., Rao, K.B.S. and Mannan, S.L., Creep Behaviour of Post Weld Heat Treated 2.25Cr-1Mo Ferritic Steel: Base, Weld Metal and Weldments, Mater. Sci. Eng. **A129**, 1990, 183-195

---

13 Wu, R., Storesund, J., Sandström, R. and Von Walden E., Creep Properties of 1Cr0.5Mo Steel Welded Joints with Controlled Microstructures, Welding in the World **30** (1992) 329-336.

14 M.Prager, Issues in Life Assessment of Chrome-Moly Welds, *Serviceability of Petroleum, Process and Power Equipment, PVP-Vol.239,* ASME, New York, 1992, 253-265

15 Tu S.-T., Gong J.-M. and Ling X., Mechanical Behavior of Laboratory Cross-Weld Specimen and its Relation with the Practical Cases at Elevated Temperature, *Proceedings of 3rd Sino-Japan Bilateral Symposium on High Temperature Strength of Materials,* CMES, 1998, 264-271

16 Tu, S.-T., and Sandström, R., The Evaluation of Weldment Creep Strength Reduction Factors by Experimented and Numerical Simulations, *Int. Pres. Ves. & Piping,* **57** (1994) 335-344

17 Dhalla, A.K., Influence of Welding Factors on Creep-Rupture Cracking at Elevated Temperature, *ASME Trans. J. Pres. Ves. Technol.,* **113** (1991) 194-209.

18 Gong, J. -M., Tu S.-T., Xia, J. and Ling, X., A New Method for Measuring Long-Term Creep Deformation in a Small Region, *Proceedings of 3rd Sino-Japan Bilateral Symposium on High Temperature Strength of Materials,* CMES, 1998, 113-119.

19 Hyde, T.H., Yehia, K.A., and Becker, A.A., Application of the Reference Stress Method for Interpreting Impression Creep Test Data, *Mater. at High Temperature,* **13** (1996) 133-138

20 Sandström, R., and Tu, S.-T., The Effect of Multiaxiality on the Weldment Creep Strength Reduction Factors in High Temperature Creep, *Trans. ASME. J. Pres. Ves. Technol.* **116** (1994) 76-80

21 Tu, S.-T., Wu, R., and Sandström, R., Design against Creep Failure For Weldments in 0.5Cr0.5Mo 0.25V Pipe, *Int. J. Pres. Ves & Piping,* **58** (1994) 345-354.

22 Hall, F. R. & Hayhurst, D. E., Continuum Damage Mechanics Modeling of High Temperature Deformation and Failure in a Pipe Weldment, *Proc. R. Soc. Lond,* **A, 433** (1991) 383-403

23 Tu, S.-T. and Sandström, R., Numerical Simulation of Creep Exhaustion of Weldments and Some Design Considerations, *Proc. 5th Int. Conf. on Creep and Fracture of Engineering Materials and Structures,* B. Wilshire and R. W. Evans eds., Institute of Materials, 1993, 695-704.

24 Sandstrom, R. and Ivarsson, B. Creep deformation and rupture of butt-welded tubes of cold worked 316 steel, Met. Techn. 7 (1980) 440-448

25 Wen,Y., M.Sc. Thesis 1990, Nanjing Institute of Chemical Technology (in Chinese)

26 Kachanov, L.M., *On Creep Rupture Time,* Izv. Acad. Nauk SSSR, Otd Tech. Nauk, No.8, 1958

27 Rabotnov, Yu,N., *Creep Problems in Structural Members,* North-Holland, Amersterdam, 1969

28 Lemaitre J. and Chaboche, J.L., *Mecanique des Materiaux Solides,* Dunod, Paris 1985.

29 Hayhurst, D.R. and Perrin, I.J., CDM analysis of creep rupture in weldments, *Proceedings of the 10th Conference on Engineering Mechanics.* Vol.1, May 21-24 1995, ASCE, 393-396

30 Liu, Y., Ph.D. Thesis, Southwestern Jiaotong University, Chengdu,1990

31 I.Le May, T.C.da Silveria and C.H. Vianma. Criteria for the evaluation of damage and Remaining life in reformer furnace tubes. Int. J. Pres. Ves. & Piping, **66**(1/3)(1996) 233-241

32 Sandström, R., Wu, R. and Storesund, J., Through thickness distribution of Creep Damage in a Service Exposed Double T-Joint of 0.5Cr0.5Mo0.25V Steel, Pressure Vessel Technology I, Proc. ICPVT 7, VDTUV, 1992, 772-789

33 ASTM Standard E1457, Standard test method for measurement of creep crack growth rates in metals, 1992

34 Saxena, A. and Liaw, P.K., Remaining Life Assessment of Boiler Pressure Parts-Crack Growth Studies, EPRI-CS 4688, Electric Power Research Institute, Palo Alto, Ca., 1986

35 Yoon, K.B., Shim, H.W. and Shin, Y.E., A Computational Study on Ct Parameter for Weld Interface, 1998 Annual Meeting of Korean Welding Society, 29-30 Oct, 1998.

36 Segle, P., Andersson, P. And Samuelson, L., A Parameteric Study of Creep Growth in Heterogenous CT Specimens by Use of Finite Element Simulations, Proc. Int. HIDA Conference: Creep and Fatigue Crack Growth in High Temperature Plant, 15-17 Apr. 1998, Paris France, s2-17

37 McCarthy, P.R., Shibli, I.A. and Raynor, D., A Survey of European Creep Crack Growth Data Generation from Weldments and Recommendations for a Draft Code of Practice7, ibid. S2-12

38 Gong, J.M. and Tu, S.T., Damage Analysis for Service Exposed HK 40 Furnace Tubes and Creep Crack Growth Rates Assessment, NJUCT-Failure Analysis Center Report HTT9705, 1997

39 Penny, R.K. and Weber, M.A., Robust Methods of Life Assessment during Creep, *Int. J. Pres. Ves. & Piping,* **50** (1992) 109-131.

40 Dai, S.H. and Wang M.O, *Reliability Analysis in Engineering Application,* Noshhand Reinhold, New York, 1992