A Review of Methods to Estimate Creep Damage in Low Alloy Steel Power Station Steam Pipes

C. Maharaj^{*}, J. P. Dear[†] and A. Morris[‡]

^{*}[†]Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK

[‡]Technical Head Integrity, E.ON UK, Power Technology, Ratcliffe-on-Soar, Nottingham, NG11 0EE, UK

^{*}c.maharaj06@imperial.ac.uk; [†]j.dear@imperial.ac.uk; [‡]andy.p.morris@eon-uk.com

ABSTRACT: For large complex structures such as power stations, refineries and other processing plants, cost effective operation is essential. With power stations, failures of components without prior warning can have serious consequences for personnel on site and be extremely expensive in terms of both losses in generation revenue and repair costs. The ability to monitor and assess the evolution of damage is critical to maximising plant availability and to minimise the risk of failures that pose a threat to personnel safety. This paper relates to the methods used to estimate creep damage in service aged low alloy steel steam piping. Welds and the extrados of bends in steam pipes are a particular problem with regards to measuring for the onset and progression of creep failure. Existing techniques will be discussed with respect to traditional site based and laboratory testing and assessment. Emerging strain monitoring techniques will also be described and evaluated that include point-to-point measurement and two-dimensional mapping of creep strain across the weld zone and other creep susceptible components of power-station steam piping.

KEY WORDS: creep, welds, high temperature steam pipes, condition monitoring

NOMENCLATURE:

AE	- Acoustic Emission
API	- American Petroleum Institute
ARCMAC	- Auto-Reference Creep Management And Control
BS	- British Standard
CCD	- Charge-Coupled Device
CDM	- Continuum Damage Mechanics
CMV	- Cr (0.5wt%), Mo (0.5wt%), and V (0.25wt%) Steel
DIC	- Digital Image Correlation
DSLR	- Digital Single-Lens Reflex
ECR	- Extensometer Calibration Rig
FATS	- Focused Annular Array Transducer System
FE	- Finite-Element
HAZ	- Heat Affected Zone
LED	- Light-Emitting Diodes
LPA	- Linear Phased Array
MPC	- Materials Properties Council
NPL	- UK National Physical Laboratory
SEM	- Scanning Electron Microscope
TOFD	- Time Of Flight Diffraction
UT	- Ultrasonic Testing
σ	- Stress
ε_x	- Strain in the x-direction (horizontal)
ε_y	- Strain in the y-direction (vertical)
A	- Manufactured reference distance on the gauge (3mm)

- $B(t)$ - Distance between two outer targets on the gauge as a function of time
- G_L - Installed gauge length (mm) between the weld pins
- t - Creep exposure time
- T - Temperature
- 2D - Two-Dimensional
- 3D - Three-Dimensional

Introduction

The onset and progression of creep processes in power station pressurised low alloy steel steam pipes need to be identified at an appropriate time to minimise the risk of what can become very expensive catastrophic failures. Material technology has much improved but as yet creep failure processes remain a key problem in many components as well as pressurised steam pipes. An important requirement is to have knowledge of the development of creep damage, to give the power-station maintenance staff sufficient time to respond with repairs or replacements. Inherent weakness in parent material, shortcomings in welds and other features can be some of the potential sites for early creep failure. The maintenance of power station pressure systems on UK plant requires that invasive site inspections are undertaken during regular overhauls to determine plant condition, according to a pre-planned outage inspection schedule. Inspection based assessment procedures have proved to be the most reliable means of evaluating the condition of plant to-date. However, there is great potential to reduce the scope of these site inspection activities during overhauls if reliable systems for monitoring the health of components can be developed and validated.

There are many examples of plant failures on power stations, with the majority resulting only in commercial loss. As an example Viswanathan [1] described where a catastrophic hot reheat pipe failure occurred at a power station in 1986 resulting in an estimated litigation and downtime costs of US\$400 million dollars (1986 values).

In the current economic environment, there is a need to maintain the availability of aged plant, whilst ensuring that safety is not compromised. With well-planned and effective maintenance, many of these large fossil fired stations are exceeding more than

30 years of service. This is a considerable achievement as these power generation plants were initially designed for 20 years of service.

In the UK, power stations have operated in a deregulated market for several years, consequently operational demands are prone to change at relatively short notice to maximise commercial revenues. Present economics of most aged plant may not allow for total upgrade of creep susceptible low alloy steel pipes. It is therefore important that a condition monitoring strategy evolves to ensure present competitiveness and future survivability of plant. Therefore, the inspection and maintenance requirements must be re-evaluated and continuously optimised over time. This paper offers insight into the methods being currently researched and applied to estimate creep in low alloy steel power station steam pipes. An optimised combination of any of these methods can become an effective creep condition monitoring strategy.

Review of Creep Processes

This section reviews the research of others relating to creep processes in low alloy steel materials that have been used for steam pipe manufacture.

Creep

Creep is the plastic deformation of a material that is subjected to a stress below its yield stress when that material is at a high homologous temperature (ratio of operating temperature to the melt temperature in K). The homologous temperature for creep processes is usually greater than $\frac{1}{3}$.

Creep processes can be subdivided into three categories: primary, steady state (secondary) and tertiary. This is illustrated in Figure 1A but it is to be noted that the steady state creep regime often occupies the largest proportion of the total creep life. The effect of increasing the stress and temperature on creep strain versus time behaviour is shown in Figure 1B. In the steady state creep regime, the strain rate tends to be constant or nearly so. In the tertiary regime, high strains will start to cause necking in the material as for a uniaxial tensile test. This necking will cause an increase in the local stress of the component and this further accelerates failure. Eventually, the material will pull apart in a ductile manner about defects in the solid. These defects could be precipitates at high temperatures or grain boundaries at lower temperatures. The end of the steady state creep regime is often taken as the end of serviceable life of a component.

Low Alloy Steels used in Power Plant Piping

The development of low alloy steels for elevated temperature service began after the First World War, when some of the first low Molybdenum (Mo) and Chromium (Cr) steels were developed. The beneficial effects of Vanadium (V) on the creep rupture properties were appreciated later. Power station tubes and pipes of the 0.5%Mo-0.2%V alloy steel were first installed in 1940. CMV pipe material is manufactured according to British Standard BS 3604:1 [2] Type 660 material specifications. The major alloying elements are Cr (0.5wt%), Mo (0.5wt%), and V (0.25wt%). This material is manufactured to produce a uniformly fine dispersion and distribution of the precipitates that serve to improve the creep strength of the material. Purmensity [3] found that the particular precipitate that rules the strengthening is V_4C_3 . This strengthening is achieved through the restriction of the grain interior deformation by these intra-granular carbides. Grain boundary precipitates provide a site for the nucleation of cavities.

CMV material has been used extensively for at least 30 years in the construction of high temperature steam pipe-work for power generation facilities. Environmental considerations require existing and future power plants to produce fewer emissions, such as carbon dioxide, sulphur dioxide, and nitrous oxides. Reductions in carbon dioxide emissions can be met by improving the thermal efficiency of the plants and this can be achieved with higher plant operating temperatures and pressures. When economics permit, Ferritic steels SA-335 [4] P22, P91, P92, P122 and E911 (European alloy similar in composition to P92 grade with similar capabilities) are often considered to be the upgrade material for the existing and next generation of power plants that run at these higher temperatures and pressures. However, the accumulation of creep damage in CMV material during service will also occur in higher alloy Ferritic steels, although

the evolution and progression are different. This is discussed further in the *Replica Metallography* section.

Creep Deformation in Low Alloy Steels

The mechanisms that contribute to deformation and eventual rupture include primary creep hardening, carbide precipitate coarsening, intergranular and transgranular creep cavity formation and cracking. Figure 2 is a Scanning Electron Microscope (SEM) image, provided by E.ON UK, showing predominantly intergranular creep cavities in a service-aged main steam CMV pipe bend.

In primary creep, a dislocation substructure forms resulting from initial strain hardening. For low alloy Ferritic material, the initially fine carbide dispersion coarsens as a function of time and temperature in the range 500-700°C. Liaw *et al.* [5] found that this coarsening leads to a reduction in the creep strength and that the agglomeration of carbides promotes cavity formation. Figure 3 illustrates this in a CMV main steam pipe gland steam connection where there are creep cavities and cracking through a region of agglomerated grain boundary carbides. This image was also provided by E.ON UK. Steen *et al.* [6] showed that the cavity formation is especially applicable in a high internal stress region where the dominant mechanism is the Orowan looping around incoherent carbide precipitates. Therefore, the creep properties of service-exposed samples are inferior compared to their newly exposed counterpart. Owing to this, the remaining life predictions made using original material specification properties will not apply for service-exposed materials.

For the purpose of life extension, Dobrzanski [7] has classified the creep evolution of a low alloy Cr-Mo steel as the development of cavities, the growth of these

cavities, the formation of micro-cracks and the formation of macro-cracks that lead to eventual rupture. He also demonstrated that intergranular cavitation cracks were the dominant factor in service damage of power station boiler components operating in the creep regime, although some degree of intergranular crevice cracking was observed.

Creep damage tends to have a localized nature in CMV pipes subjected to relatively high temperatures (540 to 600°C) and plant stresses in the range 40 to 60 MPa. On pipe-work systems creep damage typically occurs in welds at the following locations;

- Pipe to pipe (or bend) butt welds
- Terminal or near terminal welds
- Trunion support attachment welds
- Small bore branch fillet welds
- Miscellaneous attachment welds or repair areas
- Thermocouple pockets and gamma ray bosses
- Drain connection fillet welds
- Maintenance flange welds
- Large/medium bore branch connections

In addition creep damage can evolve in parent material on pipe-work bends and straight sections as well as in large castings and forgings.

The types of piping typically subjected to creep failure include main steam pipes that transport the steam from the outlet headers to the turbines, hot reheat pipes that carry the steam from the boiler to the reheat (intermediate pressure) turbine and other components such as headers (especially superheat) that are essentially distribution systems.

The complex thermo-mechanical nature of Ferritic welds leads to inhomogeneous material properties around and within the welded metal. Four crack

types (I-IV) can be categorized as shown in Figure 4, depending on the location in or around the weld. Within the Heat Affected Zone (HAZ), the microstructure varies from fine to coarse grains. The deformation and rupture of circumferential weldments occurs especially between the HAZ extremity and the base material and is therefore linked to Type IV cracking.

It was found by Coleman *et al.* [8] that during primary-secondary creep, the location of the maximum axial and hoop stresses shifts from the inner surface to the outer surface in the different weld regions. This was surmised to be due to the redistribution of stress from the creep damaged areas where there is a presence of creep cavities to the undamaged regions of the material. As a result of this, the initiation and evolution of creep damage occurs in the outer third of the weld in the fusion boundary.

However, Fujibayashi [9] found, by using the Θ projection technique on simulated low chrome alloy refined grain HAZ specimens, that the presence of grain boundary cavities in the creep damaged areas does not result in significant increases in the stress of the undamaged regions. Viswanathan [1] has indicated that most girth weld Type IV cracking failures have a leak-before-break phenomenon. Additionally, the damage is found to initiate mostly on the outer surface, or sub-surface, since the stress system causing the bending is generally axial or bending. Brett [10] has surmised that a specific class of Type III cracking, occurring in the fully refined HAZ structure immediately adjacent to the fusion line, will increase in significance as the age of the power plant increases further. The most likely explanation for this is due to carbon diffusion that occurs between the CMV parent material and the 2%Cr steel weld. The carbon mismatch increases over time and produces a greater mismatch in creep strength on either side of the fusion line, with the carbon migrating from the parent to the weld

metal. Increased amounts of $M_{23}C_6$ carbides are formed in the weld metal, compromising the carbon content in the adjacent fully refined HAZ zone.

Hayhurst, Mustata *et al.* [11, 12], have demonstrated the complexity of creep situation to be analysed (see Figure 5). This shows a three-dimensional mesh model of a medium bore branch. Through the combination of the constitutive equations generated for each of the zones shown in Figure 5 and Three-Dimensional (3D) Finite-Element (FE) modelling, close agreement was achieved between the results of metallographic examinations of a tested vessel and predicted damage fields of a medium bore branched CMV pipe under constant pressure. This area of research reinforced the point that the 3D analysis was strongly dependent on knowing the correct thickness of both the coarse grain HAZ and Type IV cracking susceptible zones. The thickness of these zones is highly dependent on the weld geometry (thickness, joint preparation) and weld procedure (welding process, time, and electrode). The resultant high degree of uncertainty can be conclusively removed through metallographic examination of the service-exposed specimens. The analysis assumed constant pressure and temperature conditions but did not account for manufacturing defects that may accompany new pipe material. Bolton *et al.* [13] indicate that these manufacturing defects can play a significant part in the initiation and evolution of creep.

Review of Methods

Several methods or techniques can be applied to estimate the level of accumulated creep damage, and hence remnant life, either from site inspections or service exposed material extracted from plant. Usually decisions to undertake major repairs or replacements are based on the findings from a number of different methods to ensure consistency.

These techniques can be broadly grouped into traditional site based, sample extraction and assessment, and recent developments associated with high temperature strain measurement. The techniques are subsequently described along with their associated strengths and weaknesses.

Site investigations

These techniques are deployed during a planned site overhaul and have been identified as part of a pre-planned inspection schedule. Typically the scope of the inspection schedule reflects site specific issues and also, wherever possible, considers the threat of emerging issues associated with similar plant on other sites. Hardness testing and replication are presently the most applied survey techniques.

Dimensional effects

Maharaj [14] obtained a high degree of correlation between the change in outer diameter of an iron base superalloy tube and the development of creep. Creep was quantified by calculating the percentage creep cavities within the metal matrix. However, there are other problems to be considered for steam pipes made of CMV steel and other materials. Care is needed in taking into account the dimensions of working pipes that have undergone high temperature oxidation.

Traditionally during a site outage, convenient locations are nominated for diametrical measurements using micrometers. These measurements can be taken over installed creep pips or directly over the pipe surface, however the results must be corrected for oxide growth and temperature before being used to estimate the effective

strain rate over the operating period. These measurements are useful if obtained with care, and are still used today to provide estimates of strain rate on ageing plant.

Hardness measurements

Site hardness measurements are a technique that can be applied as a screening tool to identify areas of pipework that are softening over time due to creep, which can prompt additional investigations. A high degree of scatter has been observed with these measurements. However, recent developments in the technique [15] have shown that it can be used in a predictive sense to estimate remnant life.

Replica metallography

Replica metallography is a plant offline NDT technique, applied generally during maintenance. It can quantitatively and qualitatively monitor the growth of cavities in low alloy Ferritic steels subjected to high temperature service. The replica preparation process follows the same initial steps of grinding, polishing, and etching as done with preparation of a laboratory microstructural specimen. The final step involves replicating the microstructural pattern onto a film that is subjected to microstructural evaluation thereafter.

Payten [16] has observed that, for a creep finite element model of a main steam line branch connection, Type IV cracking would not only manifest itself on the external surface of the weld HAZ but would be more widespread through the thickness. A surface technique such as replication would need to be accurate in its quantitative or qualitative creep life-assessment as the time between damage indications on the surface and full thickness damage is suggested to be very limited.

In light of the difficulties of traditional replication techniques, alternative techniques have been developed to assist in improving the level of detail and resolution required to quantitatively account for the coarsening of precipitates, nucleation, growth and orientation of cavities, micro-cracks and subsequent cracking. Venkataraman *et al.* [17] developed electropolishing units called CEPIN (Controlled ElectroPolisher IN-situ) and APINE (All Position IN-situ Electropolisher) and applied them to Cr-Mo steels. Components to be replicated are mechanically ground and polished. Final electropolishing is accomplished using CEPIN (for flat and slightly inclined positions) or APINE (for the vertical and overhead positions). Nital is used as the etching agent. Transparent cellulose acetate tapes of 0.02 mm and 0.1 mm thickness are applied with acetone as the softener. The replicas are gold sputtered and can be examined in polarised light contrast metallurgical microscopes up to a magnification of x1600. Venkataraman *et al.* [17] obtained consistent high quality microstructures. They used these replicas to estimate creep pores (CP), oriented creep pores (OCP), and creep cracks (CC).

Compared to other site investigative techniques, replica metallography is a time consuming process whose accuracy increases as the number of samples taken increases. The estimation of cavity population in the form of CP, OCP, and CC can supply important information with regards to creep remaining life. However, this is limited to the low alloy Ferritic steels. For higher alloys steels having between 9-11% Cr, Letofsky *et al.* [18] could not clearly prove a correlation between the creep resistance and the size distribution of particular cavity population. This finding has been a catalyst for the development of new techniques for supercritical plant that will use higher alloy steels. Notwithstanding this, replication remains a well tried and tested procedure on site and is still one of the mainstays in any replacement/repair decision.

Ultrasonic testing

Significant advances have been made with respect to the relationship between creep cavities and ultrasonic velocity, attenuation and absorption measurements in CMV and low alloy Cr-Mo steel material. Figure 6A shows results by Perez *et al.* [19] as to the variation in the theoretical and experimental ultrasound attenuation and velocity values as a function of mean radius of cavities in CMV steel. These results revealed good correlation between creep cavity size (which is strongly related to the degree of creep) and ultrasonic data. Ultrasonic velocity measurements were used by Jayakumar *et al.* [20] to assess the creep damage in service exposed CMV material. It was observed that velocity decreases at higher creep strains (Figure 6B). Furthermore, the velocity change is less for transverse waves compared to longitudinal waves.

Kalyanasundaram *et al.* [21] found that ultrasonic absorption increased with increasing creep strain and associated damage in CMV material. The behaviour was attributed to the altered dislocation structure that leads to a larger contribution to the dislocation damping. Additionally, oscillation behaviour of the reverberation signals was observed and it was concluded that a non-contact reverberation method with laser ultrasonics has the potential for assessment of creep damage.

In the attempt to minimize the UT time and thereby increase its applicability to the power station industry, significant research has been conducted into Linear Phased Array (LPA) technology [22]. Sound beams of many angles are generated sequentially by a single probe, increasing the probability of flaw detection. Compared to the traditional single angle shear wave inspections, a sector scan using LPA can be done in milliseconds instead of scanned traditionally in a few seconds.

Bisbee [23] has documented a 3-step methodology for the detection of creep cracks and creep incipient activity (in the form of cavities) in high-temperature header

girth welds. First level screening is done using long-range guided wave UT to identify welds with susceptible creep cracks. The second activity involves the use of either Time Of Flight Diffraction (TOFD) or LPA for verification and identification of the creep activity. The final step employs a Focused Annular Array Transducer System (FATS) to generate focussed array ultrasonic images. This last activity has the required resolution for the detection of incipient subsurface initiated creep cavitation damage and the ability to differentiate this damage from manufacturing/fabrication inhomogenities. As with the development of all inspection techniques a key aspect is validation, which should include correlation against observed service degradation.

Acoustic emission

The Acoustic Emission (AE) technique employs the use of sound and ultrasound wave signals that are emitted during deformation of an object. These signals can be acquired by sensors mounted throughout the length of a pipeline. The signal information can be used for the identification of a flaw location. With proper validation, the flaw type and criticality level can also be categorized.

Companies such as Margan, Inc. [24] have installed AE monitoring systems on plant and the technique has shown past success in revealing and classifying propagating cracks. Ascertaining the evolution and progression of creep cavities are inherently more difficult to determine using AE. The major issues are the high sensitivity required to identify the creep cavity, interpreting the relationship between the cavity response signal and the damage, and factoring out manufacturing/fabrication inhomogenities.

Magnetic testing

Magnetic methods can be used for the characterisation of creep defects in ferromagnetic materials. For a demagnetised material that is subjected to an external varying magnetic field, the relationship between magnetic field strength (H) and magnetic flux density (B) is shown in Figure 7. During magnetization, the magnetic field, H , is increased until B_{sat} is reached. When H is reduced to zero, the ferromagnetic material will exhibit a residual value called the remnant flux density B_r . Upon reversal of the magnetic field, the plotted relationship in Figure 7 will have an associated coercivity, H_c . Any change in the material microscopic parameters such as creep damage, density and arrangement of dislocations, nature of secondary phases, and grain size would be reflected in these micro-magnetic parameters. Studies performed by Govindaraju *et al.* [25], Negley *et al.* [26], and Mitra *et al.* [27] on Cr-Mo steels revealed that a lower B_r is indicative of creep damage. The level of creep damage has also been found to be related to the product of H_c and B_r . Raj [28] has surmised that these magnetic techniques surpass UT techniques with respect to identifying progressive creep damage. It is anticipated that this technique will become commercially viable as more research work continues with respect to correlation to in-service degradation.

Sample Extraction and Assessment Techniques

Metallographic destructive testing

The most conclusive method of accurately acquiring data for remaining life assessments of any metallic component is through the use of destructive testing. In particular, this activity involves continuous metallographic examination of service exposed samples that have been extracted. In addition to conclusively determining the sole cause of the

damage mechanism being due to creep as found by Maharaj *et al.* [29], sufficient information can be acquired to determine the stage of the creep evolution. Investigation of the carbide precipitate coarsening and cavity formation over time can provide accurate information of the degree of creep and furthermore how close the component may be to rupture failure.

The major obstacle to overcome is trying to obtain meaningful samples, which often requires removal and replacement of piping sections. Multiple samples should be obtained so that there is reliable representation of the entire creep vulnerable pipe-work set. A sufficient plant maintenance window is therefore required.

Sample mechanical testing

The standard uni-axial or multi-axial creep tests can yield valuable amounts of high temperature mechanical property data. This information can assist in the determination of the remaining life of an extracted sample. However, Bolton *et al.* [13] emphasises that any creep remaining life laboratory test, especially with regards to low alloy Ferritic steels, must account for the coarsening of the carbide precipitates that occurs during service. Also, damage mechanisms can be stress state sensitive so that uniaxial tests may not be applicable to service conditions. Finally, minor differences in furnace heat batches may lead to significant differences in the initiation and evolution of a cavity formation damage mechanism. Therefore, laboratory tests should use the same batch of material as in service. Small punch testing is a candidate that can provide the required mechanical properties through small sample extraction. Testing done by Sujimoto *et al.* [30] on a low alloy steel have shown good correlation between the small punch creep test and standard uni-axial creep test data.

Assessment techniques

Temperature and pressure data captured from plant at suitable intervals have been used to provide another estimate of creep life consumption. However, on many occasions it has indicated life exhaustion when site investigation showed no sign of creep damage.

One reason for this discrepancy is that the design codes (BS 806 [31], BS 5500 [32], BS 1113 [33]) for high-temperature pressurized components are based on uni-axial stress rupture properties of the parent pipe material. BS 806 [31] calculates the allowable working stress σ_w as:

$$\sigma_w = (\text{mean stress to cause rupture in 100,000 hours}) / (\text{safety factor}) \quad (1)$$

The safety factor used is mostly in the range 1.45 to 2.10 depending on the material working conditions. This range would subsequently result in a significant variance in the predicted rupture lives. Additionally, based on long remaining life (approximately 200,000 hrs) found on some service exposed CMV material, Williams [34] deduced that the creep rupture extrapolation rules was at best approximate. Furthermore, Hayhurst and Goodlall [35] observed that the creep failure in weldments occurred earlier than the expected design rupture times owing to non-conservative weld strength reduction factors, different mechanical properties and state of the weld material and the effect of multi-axial stress states.

In light of the issues faced in obtaining accurate remaining life estimations using design codes, predictive techniques have been developed and refined, some having the ability to describe the entire creep curve by a single equation. Popular techniques include the θ projection technique [36, 37], the Materials Properties Council (MPC) Ω method developed by Prager [38], and the R5 procedures that are presently maintained

by British Energy Generation Limited. The successful validation of some of these methods has led to their subsequent inclusion, with minor modifications, in assessment codes such as BS 7910 [39], and American Petroleum Institute (API) 579 [40]. In reality, design code estimates of remnant life have a part to play in assessing potential trends resulting from changes in operational profile driven by commercial needs.

New Developments in Strain Monitoring

Digital Image Correlation (DIC)

DIC uses a series of digital images of a surface under various levels of load, upon which a high density random paint pattern can be applied [41]. Correlation software divides the image into squares of pixels known as facets, from which the inter-facet displacements can be calculated between load levels, as shown in Figure 8 [42]. The ARAMIS software [43] uses an averaging method based on a group of facets. The evaluated displacement matrix can be differentiated to produce a full-field strain map of the surface. This allows for easy visualisation of the strain experienced by the component. In addition to this, the strain variation along a drawn line can be obtained, which allows precise numerical analysis of the observed point-to-point strain. The system requires the use of digital cameras.

To study the effectiveness of DIC, a number of laboratory specimens were prepared with hidden simulated faults. One example used was sub-surface defect in the form of a machined groove with depth 3 mm, length 15 mm and width 3.5 mm on the back surface of a CMV specimen of thickness 6 mm and overall width 37.5 mm along the gauge length. In this experiment, the DIC method is applied to the front surface (opposite side of the defect) of the tensile specimen, which is loaded vertically.

Figure 9A shows the von Mises stress (MPa) distribution on the rear surface with inset view showing the von Mises stress (MPa) on front surface for the specimen at a remote stress of 266 MPa. Strain plots for two different stress conditions are shown in Figure 9B. Localised shear band yielding is fully developed on the front surface directly aligned to the rear surface defect. The lower stress condition signified the onset of the characteristic yielding pattern as obtained with DIC. Also in Figure 9B, the DIC strain plots are compared to the FE model (ABAQUS version 6.6-1) using appropriate modulus of elasticity, yield strength and Poisson's ratio values for the CMV steel (Morris *et al.* [44]). Work hardening values for the plastic range of the material were obtained by conducting a tensile test on a similar CMV sample without a defect. Elements used were of the second order, reduced integration, 3D, 20-node, brick type. Good agreement in both the ε_y and ε_x strain field was demonstrated with the ARAMIS and FE analysis. Similar results were obtained with the other laboratory specimens with rear surface defects.

Other tests were done on welded steel specimens that were joined by Manual Metal Arc (MMA) performed with low carbon electrodes. Tensile dog-bone half specimens were fabricated with single-V or double-V weld geometries as shown in Figure 10. The two halves of the tensile specimen were welded together for each of the two weld geometries. In the DIC analysis of the loaded tensile specimens, it is evident that the HAZ experiences higher strains in the Single-V arrangement whereas the weld region experiences higher strains in the Double-V arrangement. Furthermore, patterns in the strain distribution are identifiable and distinguishable over changes in the loading condition. These successive images reveal that DIC is able to monitor early changes in strain distribution across welds.

It is the intent that a high temperature DIC measurement technique will not only be able to monitor the strain rate but to also attempt to categorize the nature of the defect as close to its infancy as possible. The limit to this early defect pattern detection and recognition is approximately 500 $\mu\epsilon$, which is dictated by the image processing software [42] used. The promising findings have lead to further research in this area that will encompass:

- Categorization of different strain patterns based on different defect geometries e.g. pattern recognition of Type IV defects and defects in the extrados of piping bends in CMV material. This will encompass experimental testing on smaller defect sizes and FE modelling of creep cracks on piping. The ability to detect sub-surface defect information from this surface measurement technique will also be further investigated. (Chris, could you have a think about the bullet point above. From my perspective you are quite right is saying that the aim is to ‘attempt to categorize the nature of the defect as close to its infancy as possible’. I you should add some words that highlight that detection of the accumulation of ‘creep damage’ as early as possible is the driver, which would manifest itself as an increasing strain rate that may be quite local to a HAZ. This would occur prior to void linkage and macro-cracking, which may be more easily detected by replication and conventional NDT. I see the DIC as an invaluable technique for detection of damage accumulation at a very early stage, thereby prompting other site investigations, which may include replication etc). So DIC would primarily be used initially across welds, if ARCMAC is used in tandem then ARCMAC can effectively provide a calibrated reference point-to-point strain value, against which the integrated DIC value from the 2D surface strain can be compared.

- Investigation of image degradation due to high temperature and environmental (weathering and contamination) conditions. Initial tests done at high temperature (600°C) [45] have shown that the image to remain robust after a 3 month test. Longer tests will be carried out to ensure that the image quality remains high for at least one maintenance cycle. At that juncture, the strain map can be recorded and the image can be re-applied for the next maintenance cycle.
- Investigation of the application of 2D images techniques on high curvature piping surfaces and reducing the time it takes to acquire a 3D image on-site.

Auto Referenced Creep Measurement And Control (ARCMAC)

The ARCMAC method, developed by E.ON UK, has been in successful use for some years initially as a uniaxial creep strain measurement device and recently developed into a biaxial strain measurement system [46, 47]. The ARCMAC system consists of a Portable Charge-Coupled Device (CCD) camera unit, ARCMAC strain gauge, gauge installation tool, portable laptop computer and image analysis software. The strain gauges consist of two Inconel gauge plates with fixed Silicon Nitride target spheres. The two strain gauges are stud welded as shown in Figure 11A and the CCD camera unit uses a collimated light source to illuminate the spherical Silicon Nitride target spheres as shown in Figure 11B. Over time, strain values are recorded from the movement of the bright circular points of light from each Silicon Nitride sphere and these are compared for creep life determination. Two Silicon Nitride target spheres provide a reference distance of 3 mm on one of the Inconel gauge halves.

Image analysis software is used to determine the separation of the centres of the circular points of light in each direction provided by the two targets on one of the Inconel gauge halves. The strain is calculated as follows:

$$\varepsilon = \frac{\frac{B(t)}{A} - \frac{B(t=0)}{A}}{\frac{G_L}{A}} \quad (2)$$

$B(t)$ is the separation of the two outer targets as a function of time ($B(t)$ is normalised by A to give a Ratio = B/A - see Figure 11C).

The accuracy of the ARCMAC camera, as assessed by a UK National Physical Laboratory (NPL) calibration extensometer, has been improved. This is by using a different design of light source by employing Light-Emitting Diodes (LED) in place of luminescent Strip lighting. The improvement in resolution limit is from 160 to 64 μm . A typical secondary creep strain rate on main steam CMV pipes is ca. $2 \times 10^{-8} \text{ hour}^{-1}$. Currently, the ARCMAC system can measure with confidence a creep rate as low as $1 \times 10^{-8} \text{ hour}^{-1}$ after 2 years (12,000 hours of operation) as shown in Figure 11D.

The durability and accuracy of the ARCMAC gauge is very dependent on the Silicon Nitride spheres. Future high-temperature experiments will be performed to determine the degradation of image quality over time. In conjunction with this effort, an edge-finding technique (that removes the dependency on the spheres) to measure strain will also be investigated. The results of this work will not only apply to high-temperature pipework but also high temperature turbine components. An example of this is the creep susceptible interface of a turbine blade root and disc.

Further improvements to the mobility of the ARCMAC system are presently being investigated through the use of a Digital Single-Lens Reflex (DSLR) camera system. The DSLR camera satisfies the requirement of a mobile system as the battery is incorporated along with an image viewer. Calibration experiments are currently being performed to determine the best camera settings and lens configuration that would allow accuracies to match those obtained by the original ARCMAC camera.

Combination of DIC and ARCMAC

A synergistic integration is achieved through the use of a combined ARCMAC/DIC system. This is with the ARCMAC system providing accurate point-to-point strain measurement and the DIC showing how the 2D strain is distributed between the ARCMAC monitoring points. The ARCMAC uni-axial strain measurement will provide important feedback on the 2D strain field variation provided by DIC, for example across a parent/HAZ/weld interface.

Future experiments to further integrate the two techniques will involve:

- Investigation of the impact of part of the DIC pattern being obscured by the ARCMAC gauges. Experimentation on different defect geometries will be performed to determine whether the defect pattern can still be resolved and distinguished through interpolation or whether a gauge redesign is required.
- Reducing the time taken to acquire an image through the use of a single camera system that can capture both ARCMAC and DIC data simultaneously.

Discussion

The optimal creep condition monitoring strategy will be dependent on plant size, criticality of operations, skill/training of workforce and cost. This strategy can be a combination of any of the methods reviewed. These methods can be classified into ranges (the length of component that can be assessed per unit measurement probe, sensor or gauge) as shown in Figure 12. Generally, a greater length of assessment capability corresponds to a lower ability to detect earlier stages of creep. Three possible creep condition monitoring strategies (A, B, and C) are presented as an illustration.

Strategy A is an example of a plant whose technical workforce is adept in the use of UT as an en-suite tool to find creep susceptible piping by firstly using long-range guided waves, confirming any anomalies through the use of TOFD or LPA, and finally accurately monitoring and tracking the creep activity using FATS. The critical aspect of this strategy is calibration and validation of the method through testing specimens with known defects and on service-exposed specimens. Also, the technique must be continually updated by researching the work of others in this field.

Strategy B can be the case of an aged plant whose plant failure history documentation is thorough. This documentation is analysed to determine the creep susceptible areas of the plant. Dimensional checks are used to confirm creep growth in these areas. A combination of hardness testing, replica metallography, and an accurate strain method such as ARCMAC are used to track creep degradation.

A plant technical team that is very proficient in modelling techniques may adopt Strategy C. An applicable assessment technique can be used in conjunction with a method such as small punch testing to acquire localised high temperature creep data. A Continuum Damage Mechanics (CDM) FE model is generated to reveal the creep susceptible sections of the piping. In this approach, quantities such as axial and bending loads must be accurately known else the model solution would be approximate.

In reality any combination of the above could be adopted to provide an effective integrity management process. Therein lies the issue; which approach should a Utility adopt? especially when the consequences of a failure of such high energy systems could be very serious in terms of personnel safety and commercial loss. The adoption of an integrity management strategy described within this paper should be undertaken with due regard to the relevant country legislative framework. In addition it is clear that success, in terms of minimising the risk of a failure, will depend on close working

between staff involved in Operations and Maintenance, Production, Technical Support, Management and the regulator. This invariably must be achieved within a competitive market framework for Electricity Generation, which for example exists in the UK. This presents significant challenges for the integrity management of current plant, and also for planned new build fossil fired stations in the UK. This future plant will operate under more severe conditions and will be manufactured from materials that may not be as amenable to inspection and assessment using current proven techniques.

Conclusion

In this paper attention has mostly been given to creep processes in power station low alloy steam pipes and the methods for estimating the onset and progression of these processes. Information is also needed on the approach to the end of reliable life of other power station components and parts. Preventative maintenance and condition monitoring strategies are needed to embrace a wide range of life monitoring and other data to decide on component replacement and repair tasks. The objective is to achieve a timely and cost effective programme to ensure the integrity of the power station plant for the next operational period. The planning task to achieve this objective is demanding as the preventative maintenance programme can be different on each occasion.

Improving the monitoring methods and taking advantage of advanced instrumentation and other related technologies (such as the methods presented in this paper) will assist in obtaining more accurate creep data and of other failure processes. It is envisaged that an optimised combination of any of these methods reviewed can become a benchmarked present and future creep condition monitoring strategy.

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