High Sensitivity Ultrasonic NDE Method for Early Detection of Creep Damage in Alloy Steel Steam Systems in Power Plants

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ABSTRACT

Creep is the time-dependent, thermally assisted deformation of a component operating under stress. Metal pressure components such as boiler tubing, headers, and steam piping in power plants might operate at thermal conditions conducive to causing creep damage over the operating life of the component. To ensure safe and reliable operation of such components in service, utilities periodically use non-destructive evaluation (NDE) techniques to inspect these components for damage. These inspections are largely targeted at detecting late stage creep damage in which cracking is active in the component and provides qualitative rather than quantitative data. Recent advances in NDE technology have provided enhanced capabilities for incipient creep failure detection. In this work we seek to develop a high sensitivity NDE system that will apply time reversal focusing (TRF) and full matrix capture (FMC) ultrasound testing techniques that have already shown a capability to identify early stage creep damage, and to produce a library of defects with the aim of providing inspection limits and the probability of detection for the technique and thus enable accurate life cycle prediction for components under inspection. For this purpose, an analysis of specimens with a range of creep induced damage has been performed with the aim to generate a specimen set with representing Type IV creep damage in an early stage of damage. Modelling and experimental validations were performed that determine the amplitudes of the ultrasound signals reflected by small diameter reflectors with dimensions down to 5μm. The experiments have shown that small cracks with dimensions close to several micrometres, caused by creep damage, should be detectable using ultrasonic focusing transducers with frequencies 25-50MHz. Future signal analysis work (including FMC and TRF) and mechanical scanning prototype system design for in-situ testing are envisaged and presented.

1 INTRODUCTION

This paper presents results from an ongoing development project that aims to develop a new ultrasonic phased NDE testing technique for the detection of Type IV creep cracking, to determine the sensitivity of defect detection and the limits of technique/system/ultrasonic
array performance, to produce a field prototype NDE ultrasonic array system, signal processing and software for the examination of power plant steam pipe welds for creep damage, to quantify results to assess the extent of creep detection and categorise into (i) cavitation formation (ii) cavitation coalescence (iii) formation of micro-cracking and (iv) macro-cracking, to demonstrate the NDE system performance on in-service, in-situ steam pipe welds and to validate the technique results against representative samples containing realistic creep defects. The present results will be shown systematically through the definition of defect parameters, theoretical assessment and modelling of UT phased array with full matrix capture, time reversal focusing technique discussion, scanner and ultrasonic instrumentation design, and phased array transducer assembly.

2 CREEP DEFECT NATURE AND TEST SAMPLES MATERIALS

Creep is a phenomenon which many materials experience at elevated temperatures. Many metals have high melting points and at ambient room temperatures their strain is effectively a function of stress only, independent of time. As the temperature increases to near the melting point of the material, the strain of the material becomes a function of the stress, its temperature and time. Hence creep is a time dependent effect which can lead to significant permanent deformation of materials and the structures they are used to construct at stress levels less than the yield stress of the material. The initial elastic strain and primary creep take place within a short period; the material then remains in the secondary steady state period for a long time and finally moves into an exponential accumulation of strain in the tertiary leading to final fracture. In high strength alloys such as the types used in thermal power plants, at the start of the tertiary stage, the damage appears in a phenomenon where very small voids (also termed pores or cavities) form at the grain boundaries of the metal. Figure 1 illustrates the position of these voids and their effect on the creep curve.

![Figure 1. The nature of creep damage starting as small voids at the grain boundaries and their effect on the strain rate of the material leading rapidly to fracture.](image)

As the voids increase in number and grow in size, the section of the material available to bear the load decreases and so the stress in the material increases; as the rate of strain in the steady-state regime is proportional to the stress through a power law, the creep rate increases exponentially into the tertiary regime. With time, the voids begin to coalesce first into micro-cracks and then into macro-cracks, leading to fracture. Therefore, in order to use these high strength alloys for elevated temperature operation, it is critical to know accurately the time to failure for a particular material so that the design is safe.
Hence, creep affects a component globally when put under specific conditions (a long period of time at elevated stresses and elevated temperatures) but the introduction of a welded joint leads to a particular set of problems, the most serious of which termed Type IV cracking is the focus of this project. The type of the damage refers to the position on a welded joint where the cracking occurs as illustrated in Figure 2. Type IV position is defined as the fine grained region on the outside edge of the HAZ next to the parent.

![Figure 2. Definition of creep cracking types in a welded joint [1].](image)

Creep strength enhanced ferritic (CSEF) steels are a class specifically designed for the high temperature environment of thermal power plants. From their early introduction in coal-fired power stations they are now being considered for application in oil and gas processing plants and the next generation of nuclear power plants [2,3]. The CSEF steels cover a range of alloy compositions but the high strength martensitic-ferritic 9-12% Cr steels are of particular interest and concern to industry. Grade 91 – 9Cr1MoNbV – is an attractive alloy from a creep-resistant view point and was adopted quite widely around world for construction of high temperature power plant components. However, the subsequent discovery of its susceptibility to Type IV damage has dampened enthusiasms, leading to a search for modified alloys - for instance the use of boron in the composition [4]. Nevertheless P91 presently remains a widely used material in power plants necessitating the development of advanced inspection techniques for Type IV. Thus, the P91 material is well suited for ultrasonic inspections for this project, affording a good environment to attempt the detection of the very small voids which is the main goal of the project.

### 3 THEORETICAL ASSESSMENT & MODELLING – UT PHASED ARRAY WITH FULL MATRIX CAPTURE

The use of ultrasonic phased array systems for non-destructive testing (NDT) has increased dramatically in recent years [5-7]. The main advantage of using arrays in NDT over conventional single element transducers is the ability to perform multiple inspections without the need for reconfiguration and also the potential for improved sensitivity and coverage.

Full matrix capture (FMC) technology for phased arrays is becoming increasingly attractive to industry. The development of FMC based inspection techniques is an active area of research, offering benefits in terms of defect detection and sizing and increased flexibility. FMC is a data acquisition process which collects time domain signals for every possible transmitter-
receiver combination in an array transducer. Initially the first element in an array is excited, while all elements are used as receivers. This method of transmitting on one element and receiving on all is then repeated until every element with in an array has been excited.

The main advantage of this technique, over more conventional parallel transmission methods, is that a fully focused image can be achieved where every pixel acts as a focal point. However, the sequential nature of FMC requires a more computationally intensive post-processing approach than traditional inspection techniques. The advantages of this approach are increased sensitivity to small defects and greater inspection coverage.

In order to numerically assess the FMC technique two routes of investigation have been followed: (i) working on MatLab environment, a code was developed implementing FMC acquisition resulting to the interpretation of results in terms of Total Focused Images (TFI) and (ii) CIVA simulation software package has been used for the validation of the simulated results. Implementing the array detailed in Table 1, B-scans were generated (Figure 3).

<table>
<thead>
<tr>
<th>Array Parameters</th>
<th>Probe</th>
<th>5L64-I1</th>
<th>10L64-I1</th>
<th>5L128-I3</th>
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<tbody>
<tr>
<td>Number of elements</td>
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<td>64</td>
<td>128</td>
<td></td>
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<tr>
<td>Element width</td>
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<td>0.35</td>
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<tr>
<td>Element pitch</td>
<td>0.6</td>
<td>0.5</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Assumptions on non-available array dimensions.

In order to confirm the stability of the proposed algorithms, the B-scans generation were repeated for all different defect positions. The usage of the FMC for all transmit–receive combinations allows emulation of any beam-forming scheme through offline post-processing.

![B-scans generated from CIVA and Matlab data matrices.](image)

**Figure 3.** Typical generated B-Scans from CIVA and Matlab data matrices.

### 4 TIME REVERSAL FOCUSING TECHNIQUE

The time reversal focusing technique is another potential method to enhance the detection of creep induced damage. The ‘time reversal’ concept has been applied in several different fields including medical imaging [8], sonar applications [9] and communications [10]. The technique essentially reverses the record of the mechanical wave in the time domain and the
reciprocity of wave field interactions with the source of a reflected wave leads to an enhancement of the subsequent re-reflected amplitude.

A single element transducer based time-reversal method was investigated using the finite element method. The finite element meshing conditions were appropriately set based on 20 elements per wavelength to achieve sufficient precision to model the wave propagation. These virtual inspection simulations will be verified using the project prototype system on the library of specimens containing voiding damage in these sizes. It should then be possible to make a final assessment of the time-reversal concept.

Figure 4. The single channel time reversal concept based on four stages (left). The model concept for the time-reversal study and the expression inside PZ Flex (right).

The simulation model setup is described in this section by an illustration of the single channel concept (See Figure 4). The three main components for the present study are (1) the transducer, (2) the metal and (3) voids/side-drilled hole (SDH) flaws. Figure 4 illustrates as well the model setup diagrammatically and shows the expression of this model in PZ Flex.

The model was fully three-dimensional (3D) and variable meshing was used around the voids simulating early stage creep damage; the size of voids modelled was 50, 100 and 500μm in diameter. The frequency of the transducer was set at 25 and 50MHz and the metal was assumed to support longitudinal waves at a velocity of 5900m/s. The flaws were placed at a distance of 10mm from the surface in order to generate results which could be verified against experimental data once the prototype is generated because the attenuation of frequency components at 50MHz is expected to be severe. The transmission of the excitation signal wavelet into the medium is illustrated in Figure 5 on left.

Figure 5. The basic model containing the propagating initial wave and the 3mm SDH target at the position 20mm ahead of the probe where the void like targets is introduced (left). The reflected waveform from a 3mm SDH at a position just ahead of the transducer (right).
Figure 5 on right shows the reflected waveform from the 3mm SDH target at a position just ahead of the radiating transducer at a frequency of 50MHz. The correct signal is captured by accurate timing gate (shown in dotted-red) and the amplitude is based on an absolute value. Figure 6 on left shows the waveform received from the 500μm voids isolated and time reversed – which is the primary concept behind the method. Figure 6 on right shows the result of sending a waveform to interact with the 500μm voids at the same range as the 3mm SDH.

Figure 6 The time-reversed waveform captured in PZFlex within the time-window of the 3mm SDH (left). The reflected waveform from the 500μm voids at the same range as the 3mm SDH when the input waveform was the time-reversed waveform (right).

5 SCANNER AND ULTRASONIC INSTRUMENTATION

The scanner was designed to implement a single probe pulse-echo system and a two probe pitch-catch system. The scanning area was set to the area size prepared for the metallurgical replication – 40mm x 150mm and the scanning resolution was aimed to be better than 0.1mm. The system was designed with 4-axes of motion – i.e. 4 motors – to ensure that both probes are fully independent. The system was designed to be operated by a stable commercial motor controller (Galil 4153) which can independently operate a maximum of 5 motors. The control application programming interface (API) was built using C++ for interfacing with the main prototype software designed and implemented in the LabView environment. The pulser-receiver instrumentation was designed for the specific requirements of the scanning prototype (the signal generator, signal digitiser, amplifiers and switching for pulse-echo operation).

Figure 7. The prototype scanner on a test bed half-pipe of identical outside diameter and wall thickness to the components that the system was designed to inspect.

6 PHASED ARRAY TRANSDUCER ASSEMBLY

In order to evaluate the possibility to use the linear phased array probes for creep damage defect detection experimental investigations were carried out. The object under investigation was selected to be the slice sample extracted from the offcuts of the branch. Measurements were performed using linear 18.5MHz frequency, 128 elements (pitch 0.25mm) phased array...
probe and OmniScan MX PA system. The experiments have been carried out using linear scanning with aperture of 16 elements. The object under investigation with denoted positions in which measurements were performed is presented in Figure 8. Results obtained using 18.5MHz linear array probe are presented in Figure 9. As it can be seen, that presented B-scan type images does not give very high spatial resolution. The observed indications (the defects or structural non-uniformities to be inspected) possess linear dimension in the range of several millimetres. Small dots in the image corresponding to single position of the linear scanning is the not the indications but the numerical noise of phased array system. It is necessary to underline that the gain of the system was set close to the maximal available value (65dB). On the other hand it is known that the single creep damages cracks are rather small with dimensions in the ranges of 5-100µm or even smaller. So, it can be assumed that indications are more related only to the large non-uniformities giving strong reflections. It can be seen also that the level of the background noise related to the material or performance of phased array is quite high. Further work and analysis is needed here and it will be performed before the end of the project.

![Image](image)

Figure 8. Slice sample extracted from the offcut of the branch with denoted measurement positions

![Image](image)

Figure 9. B-scan images obtained on the slice sample by using 18.5MHz frequency linear array probe left) position 5, right) position 6.

## 7 CONCLUSIONS

The general object of the project partly presented in this work is the development of a novel inspection technique enabling detection of creep damage defect in early stages of their growth. Solution of such task requires detection of very small defects with dimensions starting with several micrometres up to several tens of micrometres. The task is partially simplified by the fact that not a single crack, but some cloud or line of them should be
detected. Preliminary analysis of the different inspection methods has shown that only several of them in principle enable detection of so small reflectors. The current state analysis have demonstrated that the most promising technique detection of creep damage is measurement of the back scattered signals using high frequency focused transducer, while the effective power and usefulness of the FMC and TRF algorithms are still under investigation. However in order to estimate possibilities of this technique, further theoretical and experimental investigations should be carried out and parameter of ultrasonic system which meets the requirements of the project should be determined and optimized.

ACKNOWLEDGMENTS

This work is a part of the EC FP7 R4SME project “Development of a high sensitivity ultrasonic phased array non-destructive testing (NDT) method for early detection of creep damage (Type IV cracking) in alloy steels used in high temperature, high pressure steam systems of electricity generating thermal power stations (CREEPTEST)”, grant agreement no. 312610.

REFERENCES