ABSTRACT

The life of steam pipes in power stations varies considerably and a significant factor is failure by creep strain accumulation. Access to these pipes of many different shapes is difficult, as they need to be closely packed together and heavily lagged. Monitoring of the pipes is therefore mostly done when the plant is closed down for periodic maintenance. Needed are devices of a very rugged design that can be permanently installed on pipes to provide for monitoring their remnant life when the plant has been shut down and the pipes cooled to the same temperature for each measurement. Currently in use are E.ON UK Power Technology gauges arranged to reveal creep movements in two directions. This is along the length of the pipe and about its circumference. The creep revealed by the gauges is obtained by use of a special-to-purpose optical measuring system. These measurements provide for planning the replacement of pipes as they approach their end of creep life and this is part of achieving reliable operation of plant when in service and also overall cost effective management of power stations. The ARCMAC gauge system for measuring strain has been developed in the light of experience of its use to achieve high confidence ratings in the data obtained. This creep strain monitoring system provides data that can be used to underwrite life extension of power stations, many of which are now in operation beyond 225,000 hours.

In co-operation with the Mechanical Engineering Department of Imperial College London, further developments of the ARCMAC system are in progress. This paper presents the development of the combination of two monitoring methods, namely Digital Image Correlation (DIC) and Auto Reference Creep Management and Control (ARCMAC), which are currently being used to monitor strain in high temperature steam pipes. Both methods operate on the principle of capturing a series of digital images of a ‘sensor’ at different points in time, subsequent analysis of which results in an estimate of creep strain rate, which is used in remnant life assessments.

Introduction

A requirement for plant monitoring and refurbishment programmes is to achieve reliable plant operation between programmed plant shutdowns. This requires particular attention to high-risk areas and key components the failure of which can cause costly and lengthy unscheduled shut down of the power generation plant. For monitoring steam pipes, Power Technology has developed a passive strain sensor and measurement system (ARCMAC) that is being further developed with support from Imperial College London. This includes provision for employing Digital Image Correlation (DIC) measurements for detailed strain mapping. The ARCMAC measurement system, developed by Power Technology, uses precision optics to capture and record successive strain images that with digital image processing provide creep strain data for each plant operation period [1].

There is also the point that main steam pipes operate at a pressure of 180 bar and a temperature of 568°C. The dimensions of these steam pipes are typically of bore 240 mm and outside diameter 360 mm. The threat to the integrity of the main steam pipe parent material is mainly due to creep life exhaustion. Typically CMV steel, the main steam pipe parent material, has steady creep rates of the order 1-3 x 10^{-8} hour^{-1}. This is equal to predicted creep strain accumulations ranging from 200-600 micro-strain based on 20,000 hours of operation. The ARCMAC system can satisfactorily measure to 160 micro-strain within required limits. Hence, the ARCMAC data provides a good basis for assessing the creep strain rate.
Nomenclature

\( \varepsilon_y \) - strain in the y-direction (vertical)
\( \varepsilon_x \) - strain in the x-direction (horizontal)
\( G_L \) - installed gauge length (mm) between the weld pins
\( A \) - manufactured reference distance (3mm)

ARCMAC

This is a creep management system developed by E.ON UK, Power Technology. The system has been evaluated against metrology standards [1] and can measure strains as low as 160 micro-strain with better than 12% accuracy. This is the accuracy required for component specific secondary creep rates. An initial gauge image is captured using a precision camera system on installation of the gauge and this image capture is repeated after about 2 year's operation. Images are compared and the creep strain accumulated determined to give the creep strain rate.

Used in conjunction with the MPC Omega methodology [1], which requires a multi-axial material damage parameter ‘Omega’ derived from creep tests, the ARCMAC system enables improved predictions of component remnant life, based on a uniaxial measurement of creep strain rate. The ARCMAC system [1] consists of:

1. A portable hand held camera unit and an image capture logger.
2. Inconel gauges, which are used to carry the measurement targets (SiNi spheres) and in addition there is an installation tool and protective covers.
3. Dedicated measuring and recording software.

The camera unit is designed with a telecentric lens, beam splitter and diffuse light source. These are arranged so as to provide illumination along the axis of the camera (Figure 1). Important is that the SiNi target spheres are appropriately illuminated so as to provide for the needed good measurement. The three target spheres provide images in the form of three circular points of light. Two of these points of light come from the two spheres on one Inconel gauge and these provide a reference dimension. Image analysis software calculates the distance between the centers of each light spot.

![Figure 1. ARCMAC Camera Unit](image)

![Figure 2. Measurements from Image Processing](image)

The strain is obtained from the relationship [1]:

\[ \varepsilon = \frac{Ratio - Ratio_0}{G_L} \]  \(1\)

where \( Ratio \) is defined in Figure 2, \( G_L \) is the installed gauge length (mm) between the weld pins and \( A \) is the reference distance between the two targets on the gauge half. Using the micro-strain data from previous measurements, accumulated strain and strain rate can be determined. An additional requirement has been to extend the capability of the system to measure circumferential and axial creep strain rates on different parts of the pipe. To achieve this, the gauge attachment holder needed to be modified to accommodate two pairs of ARCMAC gauges to provide a biaxial configuration [2].

![Figure 3. Biaxial Gauge Attached to a Pipe](image)

Figure 3 shows a biaxial gauge attached to a pipe. The pipe surface is initially prepared by lightly grinding the surface to clean metal, thereby removing surface scale and oxide. Each gauge half is secured to the pipe by stud welding, with the gauge length being the distance between the two stud weld pins. One of the gauge parts carries two spherical silicon nitride targets, whilst one spherical target is secured in the other gauge part. The Silicon Nitride targets are brazed into a recessed location hole in the gauge body during manufacture.

A gauge installation tool has been developed and manufactured using an ABS polymer and rapid prototyping technology. This allows the operator to quickly transfer gauges onto the component for welding. Figure 4 shows a typical gauge installation tool, in this case one that has been designed to install both uniaxial and biaxial gauges. The gauges are loaded into slots on the
underside of the installation tool shown in Figure 4, secured in position by the retention clip. The gauge holder also allows the operator to position up to 8 pins to provide a location for a gauge protection cover. The gauge installation tool has 4 access holes to allow spot welding of a biaxial gauge array, in addition to positioning slots to allow the attachment of the camera location pin.

![Figure 3. Biaxial ARCMAC Gauge Installed](image)

![Figure 4. Gauge Installation Tool](image)

Digital Image Correlation

DIC is a non-contact optical three-dimensional measuring system. It is a versatile and robust system, which is suitable for measuring deformations under static and dynamic loads. The DIC system supplied by GOM [3] operates with a software package called ARAMIS. ARAMIS provides an extensive range of post-processing functions, such as the ability to resolve strains in any direction and vary the resolution of the strain field without recapturing images. A very significant feature of DIC is the ability to work over small (mm²) and large areas (m²) in various environments. It is possible to measure strains from 0.05% to greater than 100%. In order to measure strain a random or regular speckle pattern with good contrast is applied to the surface of the test object. The deformation of this pattern is recorded by the CCD camera and evaluated using the digital image processing. ARAMIS splits the viewed object into a set of correlation areas known as facets and allocates coordinates to the image pixels within the facets. Variations in the facet size and shape are tracked in successive images and used to calculate the displacements and strains. The first set of coordinates is gathered in the reference condition from which all subsequent deformations are referenced. In the following research, the DIC method was used together with ARCMAC camera system to relate the two sets of strain information.

Compact Tension Specimen

DIC and ARCMAC were used to study the strains generated in the x- and y-directions for a notched Compact Tension (CT) specimen. In Figure 5 an image of the CT specimen is shown during loading with the loading points labelled. Two pairs of ARCMAC gauges (AM1 & AM2) were arranged at different points along the ligament of the CT specimen (see Figure 5). Figure 6 shows the DIC strain in the x- and y-directions for 4.5 kN on the CT specimen. The strain in the y-direction ($\varepsilon_y$) shows a region of strain concentration almost centred at the notch tip and this strain reduces away from the notch tip.

![Figure 5. CT Specimen analysed using DIC and ARCMAC](image)
Table 1 summarises the ARCMAC and DIC measurements at the two gauge locations (AM1 and AM2) for 4.5 kN. Both ARCMAC gauges measure strain over a gauge length of ca. 35 mm whilst the DIC measures the strain concentration local to the centre line (x-axis), thus it can be expected that the results do not match exactly. As expected, the ARCMAC measurement over a greater gauge length gives a lower overall strain value due to averaging effects.

<table>
<thead>
<tr>
<th></th>
<th>ARCMAC $\epsilon$</th>
<th>DIC – along x-axis $\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm – AM1</td>
<td>0.5 %</td>
<td>1.1%</td>
</tr>
<tr>
<td>29 mm – AM2</td>
<td>0.1 %</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

**TABLE 1. ARCMAC and DIC for CT specimen at 4.5 KN**

**Comparison of DIC Software**

In order to evaluate the effectiveness of the ARAMIS software, it is necessary to compare the results obtained with other strain analysis systems, as well as the ARCMAC gauges. Here tests have been performed on mild steel material and the images analysed using ARAMIS from GOM [3] and StrainMaster from LaVision [4]. Both software systems operate on the same principle where the initial non-deformed speckle pattern is compared to the subsequently deformed images. The tests conducted were with tensile dog-bone specimens, the dimensions of which are given below (see Figure 7). The speckle paint pattern is applied to the front surface, with a hidden back surface defect. The purpose of such an inclusion is to simulate internal defects within a welded joint along the pipe work, which if detected by DIC would substantiate the use of the equipment for non-destructive testing.

Figure 7. Diagram of Dog-Bone Specimen geometry employed showing back surface defect
The results of the comparison are given above in Figure 8. Both plots are of the tensile (vertical) strain, $\varepsilon_y$, and both are at maximum load, 20kN. As a result of the geometry of the defect, the specimen suffers shear yielding at the corners of the defect, highlighted here by the high levels of strain at 45°. There is additionally a circular region of high tensile strain in the centre of the strain maps, which is caused by the reduced material cross section in that region, effectively making the defect visible. Thus it is clear that the DIC process can be used to detect sub-surface defects within weld like structures.

In regards to the differences between the two strain plots we can see that the general features are present in both, namely the shear yield lines and the circular region of high tensile strain. Table 2 below shows that the agreement between the two is high at the points of interest. Further research will be conducted to obtain the accuracy levels of ARAMIS and StrainMaster software for different speckle patterns employed.

<table>
<thead>
<tr>
<th>Location</th>
<th>ARAMIS $\varepsilon_y$ Strain</th>
<th>StrainMaster $\varepsilon_y$ Strain</th>
</tr>
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<tbody>
<tr>
<td>Centre of defect</td>
<td>&gt;10%</td>
<td>&gt;10%</td>
</tr>
<tr>
<td>Shear stress line, just outside defect</td>
<td>~5%</td>
<td>~5%</td>
</tr>
<tr>
<td>Remote from defect</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>

**TABLE 2: Comparison of localised $\varepsilon_y$ strain values obtained using ARAMIS and StrainMaster**

**Tensile Dog-Bone Specimen Testing on Pipe Material**

In addition to performing experiments to compare software packages, tensile tests were performed to evaluate the potential results obtained from steam pipe material. The typical pipe material used is CMV steel, whose major alloying elements consist of Chromium (0.5%), Molybdenum (0.5%) and Vanadium (0.25%). Upon hardening the material strengthens to achieve a maximum tensile strength of 610 MPa [5]. In addition the alloys synergistically increase the high temperature creep rupture strength by reducing the coarsening mechanism of spheroidisation, which would occur in plain carbon steel at elevated temperatures [6]. In addition, the geometry used for these specimens was slightly different in that the defect was 3mm deep, while the specimen thickness was 6mm. The specimen itself was machined from a section of used pipe and thus had an element of ageing associated with it.

The strain maps produced from the loading are presented below in Figure 9, with $\varepsilon_x$ on the left and $\varepsilon_y$ on the right. It is clear that the defect is visible, even though for this specimen it is 3mm away from the surface. A difference between these sets of results is that the circle of tensile strain is not as clearly visible as it was for the previous tests in the $\varepsilon_y$ picture as the materials and the loading conditions are different for each case. It was shown that the use of the DIC method on CMV material can be used for non-destructive testing purposes.
In previous calibration experiments, satisfactory results were obtained for six different camera positions. The position of the camera relative to the test specimen was varied in order to investigate the performance of the system for possible misalignments. The six different positions were at 0mm, 1mm, 2mm, 3mm, 4mm and 5mm away from the specimen. It was seen that the percentage error calculated were below 10% for most tests. However, a limit to our measurements was seen to exist at the 5μm displacement corresponding to 160 micro-strain. It was decided that this was mainly due to two factors. The illumination provided by the light source used and the analysis of the camera. To address the light source issue, a new light engine light source was designed by E.ON UK Power Technology.

The new light engine incorporated a series of Light Emitting Diodes (LEDs). LEDs have a number of advantages over normal incandescent bulbs and other light sources. They are significantly more energy-efficient than an incandescent bulb, which is very useful in battery-powered devices. LEDs can be built inside solid cases that protect them making them extremely durable. LEDs have an extremely long life span: typically ten years, twice as long as the best fluorescent bulbs and twenty times longer than the best incandescent bulbs. Finally, LEDs dissipate much less heat than incandescent light bulbs with similar light output. A number of 3mm diameter LEDs using 4volts and providing 1270 mcd illumination at 50μA with a viewing angle of 60° were used in building the new light engine. The LEDs were connected in series. This prolongs battery life by lighting several LEDs with the same current as just one LED. The only consideration is that the power supply must have sufficient voltage to provide about 4V for each LED plus at least another 2V for the resistor. Figure 10 shows the results in the intensity of the new light source by comparing two images of the ARCMAC gauges obtained with the two different light sources. The image taken with the new light source is much more illuminated and as a result the target spheres can be viewed better.

![Figure 10. (a) ARCMAC gauges using LED light source (b) ARCMAC gauges using electro-luminescent strip light source](image)

Discussion of Calibration Test Results

The ARCMAC system has been calibrated in the laboratory, at room temperature, using an Extensometer Calibration Rig (ECR) supplied by the National Physical Laboratory (NPL) (see Figure 11). The ECR has been calibrated in compliance with the BS EN 10002-4:1995 and ASTM E83-96 standards. The maximum error over a nominal extension of the ECR of 0 - 2.5mm was 0.1 μm. Figure 11 shows the ARCMAC camera unit positioned on the ECR. The two parts of the gauge body are attached to the moving and fixed test bars on the ECR and positioned with a nominal gauge length. Three datum images are captured and then the gap between the two parts of the gauge is increased in steps of 5 micrometers, at the end of each step three images are captured. Once the maximum calibration extension has been reached the same process is repeated, this time decreasing the gap until datum position is reached.
The cameras shutter speed and gain settings are altered to give the reflected light spot the optimum characteristics for subsequent image processing. At this stage of the systems development these optimum conditions are evaluated by reference to a ‘map’ of an ideal light intensity variation, which is known to produce acceptable calibration results. Further research is in progress to evaluate the sensitivity of the cameras control settings on the measurement results.

The image data is processed using ImageJ, resulting in a value for the ‘ratio’ defined in Figure 2. Site installation experience has shown that the camera unit will not always be positioned precisely normal to the target gauge. This is one of the reasons for the choice of a telecentric lens in the camera unit; it is tolerant of angular misalignments to a reasonable degree. However the downside is that the ‘working distance’, which is the optimum distance between the lens and the target, is at around 92mm +/- 3mm, so that the lens must be located inside the camera unit with reasonable precision. In addition the working distance of the lens coupled with its physical length means that the camera unit is approximately 450mm long. This means that some plant locations are inaccessible with this arrangement. Hence several calibration runs have been undertaken with the camera re-positioned to represent conditions on site. The following room temperature calibration tests are reported:

- Axial positioning: Camera unit normal to the gauge, with the axial position varied from nominal to +4mm; bounding experiences from site installations.
- Angular misalignment: Camera unit positioned at the nominal position, with angular misalignments up to 10°; bounding experiences from site installations.

*Light Source Comparison for Nominal Position (0mm)*: The camera unit is normal to the gauge and the distance of the camera and the gauge is 0mm (nominal position). Results obtained using the High Intensity Source are improved in comparison with the electro-luminescent strip light source especially for lower strains (Figure 12).
Light Source Comparison for 2mm Offset: For the next set of results, the camera unit is normal to the gauge and the distance of the camera and the gauge is 2mm. Results obtained using the High Intensity Source are improved for medium and higher strains (Figure 13). Using the High Intensity Light Source it was possible to measure strain down to c.a. 64 micro-Strain or 2 micrometers extension.

Figure 13. Comparison of light source error for 2mm Offset

Light Source Comparison for 5° Angular Misalignment: For the next set of results, the camera unit is at the nominal position with angular misalignment of 5° (Figure 14). Results obtained using the High Intensity Source are improved for most measured values of strain.

Figure 14. Comparison of light source error for 5° Angular Misalignment.

Light Source Comparison for 10° Angular Misalignment: For the next set of results, the camera unit is at the nominal position with angular misalignment of 10° (Figure 15). Results obtained using the High Intensity Source are improved for most measured values of strain.

Figure 15. Comparison of light source error for 10° Angular Misalignment.
Conclusions

There are occasions when in addition to the ARCMAC data, it would be very helpful to be able to search for the presence of sub-surface cracks, other defects and areas of localised creep strain accumulation in pressurized pipes and joints of power stations as reported on here for the laboratory specimens. The use of x-ray and other techniques cannot always be employed in the limited access and confines of a power station. Also, it would be helpful to be able to monitor the steam pipes when they are stressed at 568°C as well as when they are not in use. One problem is that the pipes need to be heavily lagged and the joints and other points of interest can be difficult to gain access to with this equipment and there are also personal safety considerations due to the high operating temperatures.

The research findings show the useful complementary data that can be obtained when combining DIC with ARCMAC methods to study a tensile specimen that has a defect introduced at its centre. Also, it has been demonstrated there was similar good correlation between the two methods for a notched Compact Tension (CT) specimen. Additionally, the use of LED as a light source has significantly improved the readings of the ARCMAC system. This has led to an improved strain resolution which is c.a. three times better than the system using a light strip source which if further validated will greatly reduce the time interval between successive inspections.

At this time, there is a challenge in using DIC coatings as they can be damaged when the power station is in operation. This is by high temperature and related oxidation and other coating contamination processes (e.g. scaling and encrustation) on the pipe surface. The continuing research is to try to resolve these issues. This is to find ways of generating speckled pipe surfaces that will withstand the harsh conditions of hot steam pipes. Also, this is to research ways of achieving the additional methods for monitoring of steam pipes to obtain their remaining life data. At this time, the advantage of the rugged ARCMAC gauges is that they survive well the contamination conditions of steam pipes in service.

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References