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Use of Digital Image Correlation (DIC) for detection of defects and monitoring of structural integrity in the nuclear industry

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ABSTRACT

Optical techniques are becoming the measurement devices of choice across much of the manufacturing and monitoring industries. As an example of this, a senior measurement specialist at Rolls Royce commented that 'if the price was right, we would use camera measurement systems for as much as possible'. The key reasons for this are usually cited as being able to take non-contact measurements, ease of use and flexibility.

This paper looks at potential applications for camera based measurement technology. A system based on Digital Image Correlation techniques supplied by Imetrum was used for the assessment process, both because of the company's interest in the nuclear field and their system resolution being higher than competitors. To find those that were most likely to find a suitable market niche, a range of applications was elicited from relevant industry technical leaders worldwide. With over 30 potential areas identified, the research team decided to progress by assessing the technical enablers that would demonstrate the feasibility of applying Imetrum's technology to each of these. Three key requirements were identified: 1) Take measurements on metals with no applied pattern; 2) Measurements not adversely affected by oxidation of surface and 3) Detect sub-surface defects.

The results presented here demonstrated that: 1) For cold worked stainless steel ground with 600 & 1200 emery paper, the software managed to track movement of the surface accurately; 2) Oxidised surfaces could also be accurately measured and 3) There was evidence to suggest that a sub-surface linear defect was discovered. The software also suggested that point defects in the ferritic sample may be visible.

INTRODUCTION

The Since the development of Digital Image Correlation (DIC) technique[1], optical techniques are becoming the measurement devices of choice across much of the manufacturing and monitoring industries.[2-4] The key reasons for this are usually cited as being able to take non-contact measurements, ease of use and flexibility.[4] DIC is an image identification method for measuring object deformation whereby digital images are captured before and after the deformation using an optic instrument are subject to correlation analysis. A key advantage of this technique is that sub-pixel resolution can be achieved.[3, 5, 6]

This paper looks at potential applications for camera based measurement technology. To find those that were most likely to find a suitable market niche, a range of applications was elicited from relevant industry technical leaders worldwide. Application areas identified included creep testing; stain gauge replacement; hot inspection beneath clad surfaces; inspection of in-reactor pipes; residual stress investigation; vibration assessment in service; assessment of pipe supports; waste drum fingerprinting; fuel clad inspection for kiss bonds; remote video detection of fine flaws; cable inspection in service; detect stress relaxation of internal bolting; loading of jet pump beams; structural assessment; validating FEA & CFD models; crack-growth monitoring; shrinkage in large welds; monitoring during hydro tests. All of these application areas are in some way dependent on three enabling factors:[7, 8]

1. Can a DIC system take measurements on metals with no applied pattern?
2. To what extent are measurements adversely affected by oxidation of surface?
3. Can a DIC system detect sub-surface defects from surface strains?

A common requirement for the use of DIC for nuclear manufacturing inspection, structural integrity assessment and monitoring the components in service is the presence of a surface quality required for the software to measure displacements to the required precision.[9] However it is important to know whether an engineering surface (e.g. as milled), as opposed to an artificially enhanced (e.g. by applying a random pattern to the materials surface) can be accurately used to detect surface displacement. Therefore some test trials were carried out in order to understand the implication of surface quality for the software to measure displacements to the required precision. As polished cold worked stainless steel was used to examine the surface quality effect due to its high yield strength which allows for the application of large strains.

Another requirement for the employability of DIC for the monitoring of the components in service is the ability to predict the strain evolution in a sample that is ageing with time whether mechanically, environmentally or both. Potential applications include the detection of in service creep, environmental assisted cracking and crack extension. Therefore some specific tests were carried out to assess the feasibility of using a “fingerprint” reference picture taken before the sample aged by oxidation and deformation.

Since it is highly desirable to be able to detect subsurface or surface breaking defects that are present due to manufacturing process, the use of DIC technology in the detection of sub-surface defects in the components was also investigated. Although DIC is a surface technique and surface-breaking cracks should not be detected[10], it might still be able to identify the evolution of strain localization to the surface of a component which is associated with the presence of a subsurface defect. Clad bond fuel-plate zirconium alloy, produced by hot-rolling, and a ferritic steel plate with weld overlay containing manufacturing flaws were chosen to study the subsurface defects.

Preliminary experimental work using an Imetrum system (based on DIC principles) has been undertaken. The trial was divided into two types; the first studied the effect of different surface quality finishes on measurement precision. The second assessed whether the displacements that can be measured will reveal the presence of surface breaking or sub-surface defects arising from the welding overlay process. Three different alloys of stainless steel, a zirconium alloy and composite alloy of ferritic steel with weld overlays were used. The dog-bone type tensile test samples were strained in a vibration-reduced assembly in the elastic state. The tensile samples for studying the effect of surface finish and oxidation were tested without applied patterns or markings. Video files were collected using both large and small fields of lenses. The processed data confirmed that the software can accurately measure the strain in different engineering surface finishes and degraded surfaces due to the high temperature oxidation. Furthermore preliminary data showed that it was possible to predict the strain evolution in a sample from a "fingerprint" reference picture taken before the sample was further oxidized and strained. The positive results of this study are encouraging for the exploitation of this technique in the nuclear industry for remote detection of ageing components. The use of this technology in the detection of sub-surface defects in the components will also be discussed.

EXPERIMENTAL DETAILS

Three different alloys were used as shown in Figure 1. To study the effect of surface quality, stainless steel 304 was selected. Prior to machine the dogbone tensile test samples the stainless steel sheet was cold rolled 20% to increase the yield strength and increase the range of measurable elastic strain. The samples were ground with 600 and 1200 grit silicon carbide paper to study the effect of surface on the strain precision achieved. In order to do so, the DIC measured strain was compared to the strain measured with a clip gauge and a strain gauge positioned nearby the imaged area.

The same samples used for the investigation of the surface quality were subsequently "finger printed" by taking some reference images. The samples were then subsequently oxidized in air at 650°C for period of 18 hours in order to simulate an ageing process (e.g. in service oxidation) subsequently strained. The rationale behind this procedure was to establish whether the fingerprinted image could be used to accurately detect the strain present on a degraded sample (this situation would represent detection of in service creep, for instance). The strain was calculated by the DIC software from the comparison of the image of the sample oxidized and strained using the fingerprinted as a reference image. The strain obtained in this way was then compared with the strain measured by a clip-on extensometer.

The material used to investigate the ability of sub-surface or surface breaking defects detection via DIC were Zircalloy plates joined by hot rolling and a ferritic plate weld cladded with austenitic stainless steel via arc welding. From the Zircalloy materials a total of five samples were manufactured. In order to simulate a subsurface defect, a hole with diameter of 0.3 mm or 0.4 mm was drilled from the side in the centre of gauge length as shown in Figure 1. The weld cladded ferritic plate was non destructively inspected (e.g. ultrasound, dye penetrant…) and the identified location of defects was marked with a felt tip pen. Two dogbone tensile samples were cut so that the gauge length of the sample was populated with a know defect. Afterwards both types of the tensile samples (Zircalloy and ferritic) were stressed whilst DIC inspection was carried out on the surface. The zircalloy and ferritic steel samples were spray painted in order to provide a good pattern for the software to track the strain and eliminate the surface finish effect on the data.

MTS Alliance RT/100 100KN tensile test machine was used for all the samples. Tests were conducted using a home-made vibration reduced assembly as shown in Figure 2. The test was carried out in the elastic region with the maximum applied load of 10 kN for stainless steel, 2 kN for ziraclloy and 77 kN for ferritic steel samples with the rate of 0.25 mm/minute. An extensometer with a 25 mm gauge length was used.

The video files were collected using the Imetrum software. Two sets of video files were collected for each sample. Two lenses with large field of view (LFOV), 26 mm × 19 mm, and small field of view

(SFOV) (0.9 mm × 0.7 mm) was used. In processing of the data for study of the subsurface defects 8 or 10 targets (i.e 4 or 5 extensometers) were selected.

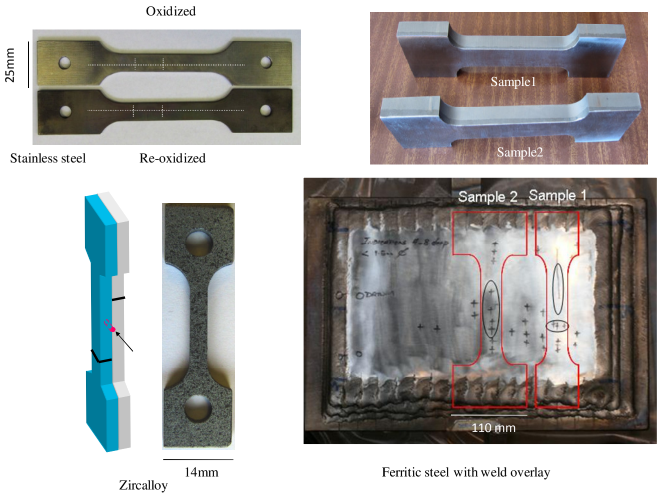


Figure 1 Samples used in this study: Dogbone samples used to investigate the effect of surface preparation and the ability to "finger print" a sample (Top left), zircalloy tensile sample containing a subsurface defect introduced as slit or hole (bottom left), the weld cladded ferritic plate with the markings of the defects detected via conventional non destructive inspection (bottom right) and tensile sample cut out from the cladded plate (top right).

RESULTS AND DISCUSSION:

1. *Stainless steel samples to study the Surface quality and the oxidation*

The test conducted for the stainless steel samples (1200 grit marking in both oxidised and non-oxidised state and 600 grit marking) showed that the software can accurately track the surface movement. The comparison of strain measured by strain gauge and large and small field of view is shown in **Error! Reference source not found.** where strain measured in three different ways is plotted as a function of time.

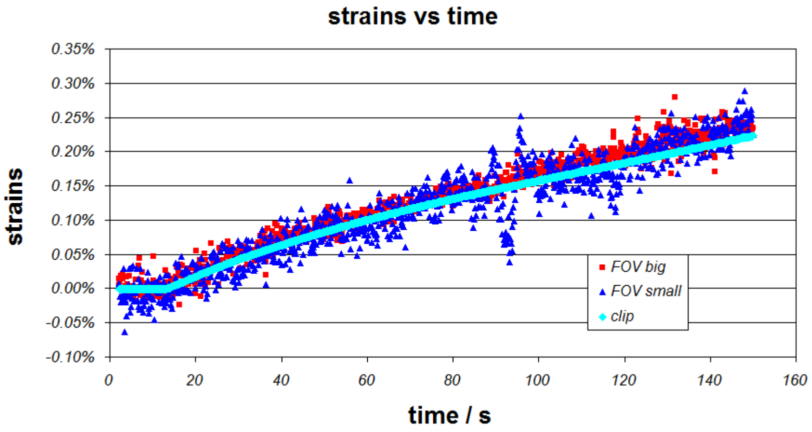


Figure 2 Strain against time measured with a clip gauge, a large and a small field of view optics.

A more accurate comparison is obtained by plotting the strain measured optically with the reference strain measured via conventional methods (clip gauge) so that it is possible to obtain more quantitative data. The strain measured by LFOV (Figure 3) lens correlates quite well with the reference strain measured via a clip gauge and the R^2 of the best fit line is 0.97. However the SFOV correlates less well with the strain measured by the extensometer and the R^2 of the best fit line is 0.907 (Figure 4).

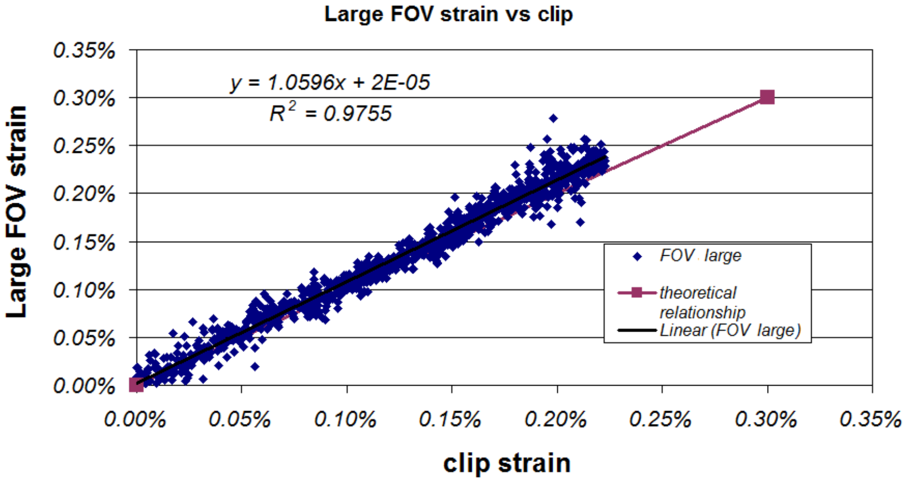


Figure 3 Strain measured with a LFOV plotted as a function of the strain measured using a clip gauge.

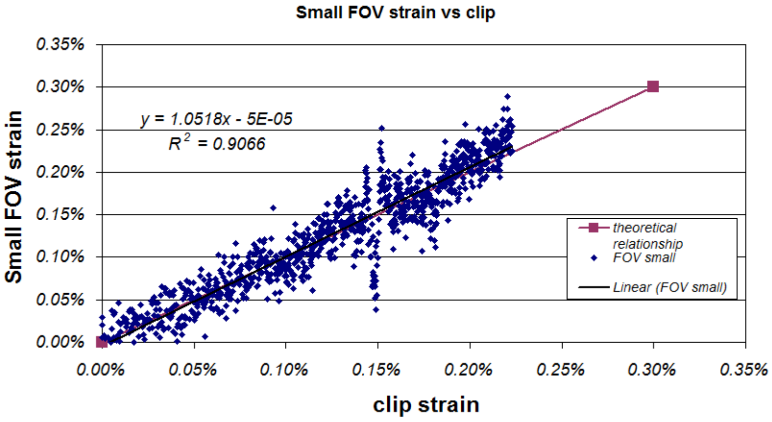


Figure 4 Strain measured with a SFOV plotted as a function of the strain measured using a clip gauge.

2. *Stainless steel samples to study the ability to fingerprint a sample*

The samples used for the above tests were also used to evaluate the possibility of measuring the strain after re-oxidation and by using the reference image collected before the re-oxidation and correlate it with the strain measured by the extensometer. Furthermore, with this test it was also possible to extract some information regarding issues of the repositioning of the camera and evolution of the surface (i.e. decorrelation).

The strain predicted using a reference image collected before the re-oxidation (finger print) and the measured strain on an aged sample using DIC is shown in Figure 5. These results suggest that it is possible to use a fingerprint image for the determination of strain on a component that is aged by oxidation and deformation. Potential applications include the detection of in service creep, environmental assisted cracking and crack extension.

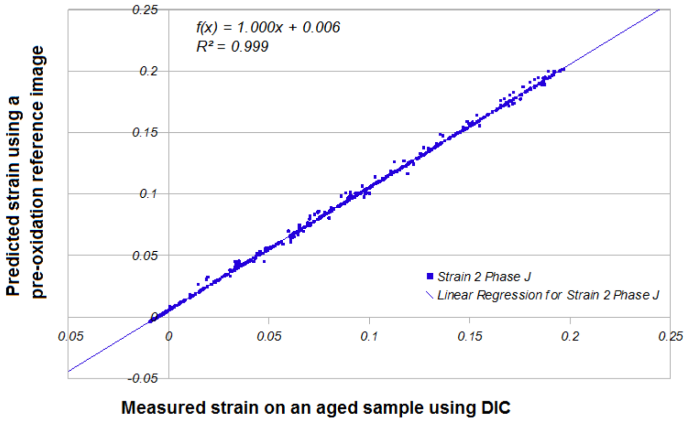
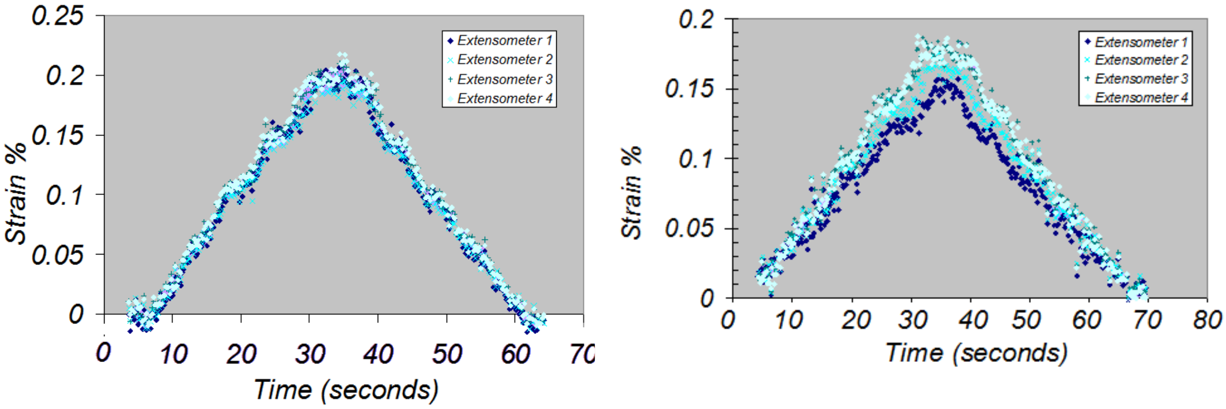


Figure 5 Strain predicted using a reference image collected before the re-oxidation (finger print) and the measured strain on an aged sample using DIC.

3. *Zircalloy samples to study the detection of sub-surface defect*

Figure 6 (a) shows the strain against time for samples with no defect and no slot. As expected, the amount of the strain is similar for the extensometers selected along the defect. By introducing the defect in one side the sample, it was expected that the amount of strain would increase from extensometers far from the defect to the extensometers close to the defect (Figure 6 (b)). This trend was observed for all the samples. As it can be seen in the graphs of extensometers against time is a qualitative observation and because the small changes in the strain, it is difficult to appreciate the differences between strain gauges. Therefore it was decided to plot strain from the extensometer that does not lie on the defect along with the rest of the extensometers. This is presented in Figure 7 and Figure 8. For the sample without a hole or slot, the m and R^2 values are close to the ideal value of 1. This clearly indicates that the amount of strain is the same from one side of the sample to the other side. Slight deviation is due to scattering in the data as it can be seen in the related graphs of extensometers against time.

Figure 8 shows the data for the sample with 0.3mm hole and slot, the *m* values are significantly greater that 1and increases as the extensometer moves to the other side of the sample where the defect has been introduced. This deviation from linearity means that the extensometer 1 is probably in elastics region whereas the rest of the gauges are in plastic region thus indicates the presence of a defect.



(a) (b)

Figure 6 strain against time for samples with no defect and no slot (a) and strain against time for samples with 0.3mm in diameter hole (b).

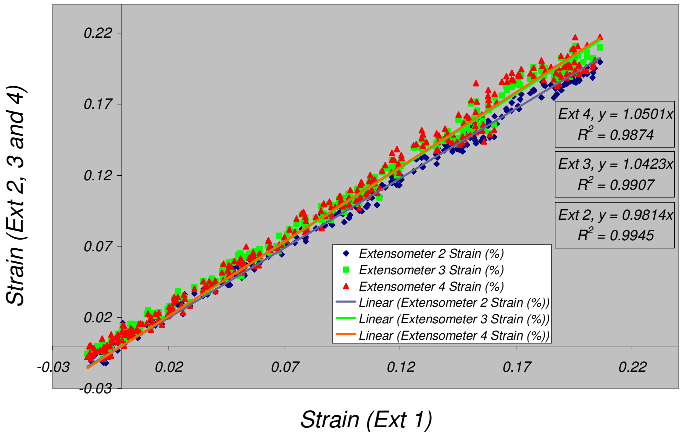


Figure 7 Strain for extensometer 1 against the rest in the sample without hole and without slot.

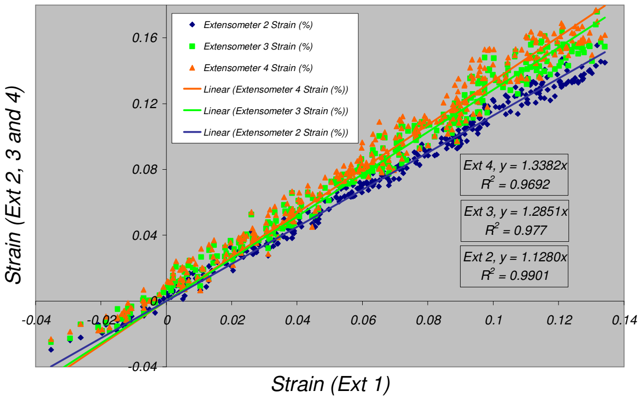


Figure 8 Strain for extensometer 1 against the rest in the sample with 0.3mm hole and with slot.

4. Ferritic steel with weld overlay samples to study the detection of sub-surface defects

Similar approach for the processing of video files that was used to analyze the data for Zircalloy samples was used to analysis the video files for the ferritic steel samples. It was expected that in the area without defect the amount of strain to be the same from one side to another side of the sample as the height of the optical extensometers were the same however it was found that the amount of strain increased from left side of the sample to the right side of the sample. This trend of having different amount of strain in either side of the sample was observed for all the processed data regardless of the position of the optical extensometer in the stain gauge, sample grip size, location of the sample in the ferritic plate and type of tensile test machine that was used. This trend was not observed in all data for stainless steel and Zircalloy samples. Based on these observations it can be suggested that the source of this behaviour in the ferritic steel samples is the nature of sample - it is a composite of the parent steel with various layers of weld overlaid (Figure 9). This material composition does induce small localised strains, and so can mask any impacts of sub-surface defects. c. The full field software was used to measure an area with a linear defect (detected by ultrasound). The full field software seemed to suggest that there were local features near the line depicted by the ultrasound marking. The features from the defects shown in the strain map are complex but irregularities seem to be reasonably clear. The full field strain maps for the linear defect in ferritic steel is presented in Figure 10 (a,b). Considering that linear subsurface defect was aligned in the loading direction (vertical), it is not surprising that the full field map of the strain in the vertical direction (ε_{yy}) does not show any particular discontinuity (Figure 10 a). However, the full field map of the strain in the horizontal direction (ε_{xx}) seems to capture a discontinuity in the Poisson contraction which is associated with the local defect (Figure 10 b). The fact that the discontinuity is slightly translated from the position of the marked defect suggests an inaccuracy in the marking of the defect, which in fact was done for indicative purposes only, and not to precisely indicate the defect location.

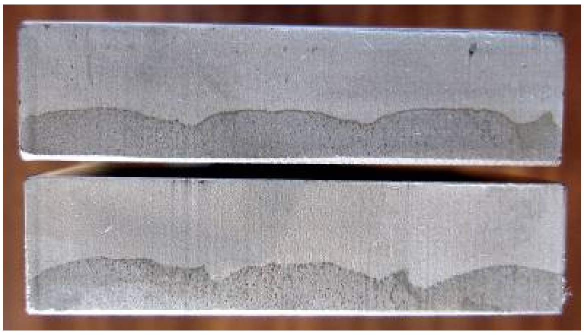


Figure 9 The substrate/clad interface of the actual tensile test specimens

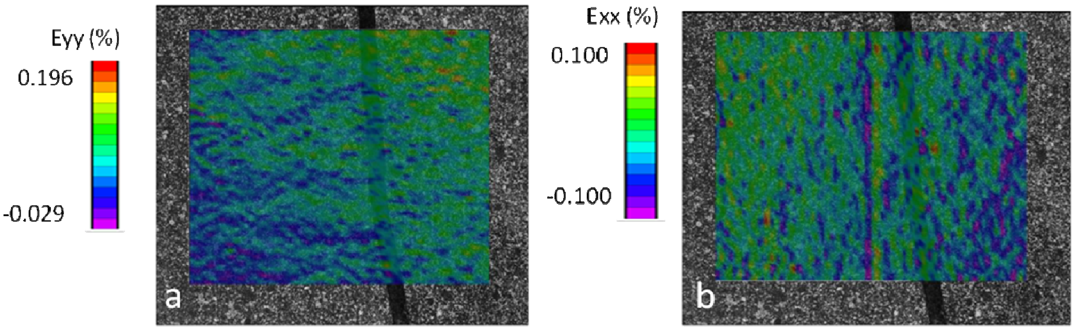


Figure 10 Linear defect Eyy strain map overlaid on sample with ultrasound marking (a) and linear defect Exx strain map overlaid on sample with ultrasound marking (b).

CONCLUSIONS:

The results of the tests that were conducted to examine the engineering surface effect demonstrated that although the surface was unmarked the software managed to track the surface accurately and DIC lenses with different fields of view showed good correlation to the strain gauge and each other. The measurements taken from the non-oxidised and oxidised samples showed good correlation with one another.

The use of a fingerprint image can be exploited for the determination of strain on a component that is aged by oxidation and deformation. Potential applications include the detection of in service creep, environmental assisted cracking and crack extension.

The detection of the sub-surface defects proved to be a more difficult task. However employing a refined test procedure it has been demonstrated that the Imetrum's software consistently showed the localized variation of strain in the point-to-point and full field measurements. Therefore, sub-surface detection and related applications seem to be possible. Further experiments are needed to fully prove the initial investigations.

The positive results of this study are encouraging for the exploitation of camera based measurement techniques in the nuclear industry, both for component manufacture and inspection of installed elements. Having demonstrated capability in the three enabling technological challenges, the next step is to start to develop systems for the specific application areas identified at the start of this investigation.

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