Grown cracks for NDT development and qualification

I Virkkunen, M Kempainen, H Ostermeyer, R Paussu and T Dunhill

Defects are needed to develop new NDT methods and to assess the performance and reliability of used methods and procedures. It is crucial to have representative defects in order to have an accurate and realistic assessment of the performance of NDT. Representativeness should be to the actual service-induced defects that the NDT method is used to evaluate. While various techniques have been used to create such defects, all conventional techniques seem to have some shortcomings that limit true assessment of the NDT performance. This paper describes recent developments of defect manufacturing technology based on controlled thermal fatigue. It is shown that most of the traditional limitations can be overcome using the currently available technology. Finally, three real-world application cases are presented showing the use of such cracks.

1. Introduction

The real performance and reliability of used NDT techniques and procedures should be known in order to effectively use them. Without this knowledge, it is difficult to select the correct methods and inspection targets, let alone determine correct inspection intervals. Also, dependable performance information that highlights potential targets for further improvement is necessary for the development of better NDT techniques. To provide this crucial information, various performance demonstration and qualification procedures have been established and are under development(1,2).

One of the key challenges in assessing NDT performance is the production of relevant test blocks with which the performance can be tested. These test blocks should contain defects identical to those expected in real inspection, but with known and predetermined location, size and other properties. Producing such controlled natural defects has been, and still is, quite a difficult task. Consequently, a number of defect simulation techniques have been developed, each with their virtues and limitations. As proposed in an ENIQ working document(2), there is essentially four classes of defects currently available (numbering and highlights added):

1. Implanted defects where a pre-existing defect is attached to the testpiece. The attachment usually takes the form of a weld in a machined recess. The technique has the benefits that there is flexibility in the type of defect that can be included and that the insert can be carefully accessed prior to insertion. The main disadvantages are that the insertion process may produce artefacts which either give away the implant's position or make the inspection response unrealistic in some way. An example of this latter affect is implants into an austenitic weld where the implant material will not form a continuous part of the weld and the attachment welds **may significantly influence the performance of the inspection being qualified in an unknown manner**.
2. Weld doping or weld modification where for instance crack prone material is added to the weld to promote localised weld cracking. Other examples include introduction of porosity or slag. The main advantage over the previous process is that there are no insert attachment welds. The main disadvantages are that the final size of the defects and their character would need to be confirmed by supplementary inspection. This means that there is a **risk of comparing one inspection method with another rather than comparing one inspection against known flaw parameters**. Another disadvantage is that the doping process can **influence the material properties of the weld in the immediate vicinity of the defect, potentially affecting the inspection in an unpredictable manner**.
3. Machined defects where a defect can consist of a cut or machined void. Electro discharge machining (EDM) is perhaps the most relied upon technology in this area where a shaped electrode is used to erode the testpiece. The process is most suitable for production of surface defects, although it is possible to use in combination with welding to produce buried defects. The main advantages of this method are that it tends to be relatively inexpensive, the resulting defect parameters are known to fairly tight tolerances at fabrication and the parent material is left largely unmodified apart from the presence of the machined slot. Disadvantages are that **it is difficult or impossible to produce any of the characteristic roughness expected from plant defects** and that using standard implantation techniques, **the tip radius is likely to be large compared to many crack species**.
4. Grown defects where cracking is initiated and propagated into testpieces in much the same way as would occur in plant, simply accelerated to make fabrication times practical. The main processes used for this class of defect are fatigue, thermal fatigue and stress corrosion cracking. **There are limitations associated with each growth method, but this option has the advantages of realism and avoidance of attachment welds. The main disadvantage aside from restrictions in the implant process is likely to be reliance upon a supplementary inspection to confirm critical flaw parameters**. In the schemes already discussed, this limitation can be minimised by using the defects in parametric specimens and then destructively examining some or all of the specimens once the qualification process is complete.

Conventionally, methods 1-3 are applied for performance demonstration and qualification. Most qualifications in effect currently rely on defects produced with these three defect types.

As is evident from the above quote, finding suitable defects for performance demonstration is a rather demanding task. Obviously, the problems in using defects that 'affect the inspection in an unpredictable manner' make it difficult if not impossible to infer real-world performance from the performance demonstration data acquired using unsuitable defects. This effectively undermines the practical value of the whole exercise. As stated by the ENIQ

Iikka Virkkunen and Mika Kempainen are with Trueflaw Ltd, Espoo, FI-02330, Finland. Tel: +35 8456 354415; Email: iikka.virkkunen@trueflaw.com

Henner Ostermeyer is with EON Kernkraft GmbH, Germany.

Raimo Paussu is with Fortum Nuclear Services, Finland.

Tony Dunhill is with Rolls-Royce plc, UK.

working document(2):

> Some plant defects when inspected with techniques generally used in plant present a very significant challenge to testpiece design and testpiece defect fabrication. Examples are the qualification of ultrasonic inspections of austenitic or Inconel weld metal and inspections for intergranular stress corrosion cracking in or near stainless steel welds. In both cases, the conventionally applied testpiece defect manufacturing processes have been shown to introduce unrealistic defects with significant manufacturing artefacts.

For more reliable performance demonstration and qualification, further development is needed to get realistic test defects that allow true observation of real world performance. In particular, the development of type 4 defect manufacturing(2) which gives realistic defects and avoids any attachment welds would be needed to overcome their traditional disadvantages – namely restrictions in growth procedure and reliance upon a supplementary inspection to confirm critical flaw parameters.

Trueflaw produces type 4 grown cracks using thermal fatigue cracking mechanism. The purpose of this paper is to present the current status of the crack manufacturing technology and how some of the limitations mentioned above have been overcome. Furthermore, the paper presents some application examples of how this technology has been used to solve real-world problems in different fields.

2. Trueflaw crack manufacturing technology

Trueflaw produces defects using natural thermal fatigue damage process. The defects are grown in much the same way as could occur during in-service condition. However, the growth is accelerated to make production times practical and controlled to enable predetermined flaw parameters. Flaw production is done *in-situ* to ready-made samples. Cyclic thermal fatigue loading is induced locally by alternating heating and water spray cooling, as described by Kemppainen(3). The loading is based on pure thermal loading and there is no welding, machining, or mechanical treatment applied. No artificial initiators of any kind are used and the material microstructure is not disturbed in the process. More detailed information on the properties and use of produced cracks has been presented earlier(4,5,6).

2.1 Restrictions in growth procedure

Manufacturing of grown defects has traditionally been restricted to simple component shapes and small components. The reason has been that crack growth, in general, requires stress to provide a driving force. Providing the required stress mechanically becomes impractical when material thickness increases or geometry becomes more complicated. Huge mechanical loading equipment would be needed to generate sufficient stress to most components of any practical interest. Even if such equipment was available, accurate control of induced stress in complex shapes during crack growth would be very difficult and it would not be possible to limit the stress only to areas where defects are needed.

In contrast, thermal loading can be applied to local areas in heavy components. Since only a limited volume is stressed at any given time, the needed equipment is relatively light. Furthermore, the ability to locate and control the stressed volume enables accurate control over flaw growth location and essential flaw parameters.

Consequently, thermal fatigue cracks can be grown in components of any size or shape.

2.2 Confirming critical flaw parameters without supplementary inspections

In order to use test defects to assess NDT performance, the true parameters of the defects must be known. Otherwise, the error in NDT results cannot be accurately determined and the true reliability of the NDT remains unclear.

Some of the parameters of test defects can be readily measured, for example, surface length. However, most important defect parameters, defect depth in particular, are not directly observable. It may be argued that reliable defect depth information is the most important challenge on many defect manufacturing techniques.

Defect manufacturing techniques in general and grown cracks in particular conventionally rely on 'supplementary inspection' to give defect depth information(2). Consequently, reliability is assessed by comparing one inspection method with another rather than comparing inspection to-be-qualified against accurately known flaw parameters. This is unacceptable. The alternate route, suggested by the ENIQ working document(2), is to destructively examine the defects once the qualification is complete. While this has been successfully done in some special cases(7), it is not generally considered a feasible option. Test blocks with realistic geometry are far too expensive to manufacture to allow this kind of qualification. Furthermore, any additional qualification, re-qualification and method development would require a new set of test blocks.

To overcome this very significant shortcoming, Trueflaw has developed an alternative way to verify critical flaw parameters, and in particular the flaw depth. This approach retains the credibility of destructive examination and avoids the expensive and problematic destruction of valuable test blocks. The key feature of this approach is the development of a highly repeatable crack growth procedure. Because of the repeatability, not all the cracks need to be destructively examined. In simple terms, the procedure is as follows: first, the desired crack depth is produced in a representative validation sample. This sample needs to have similar material and similar local geometry, but can be simplified and smaller compared to the actual test block. This validation crack is destructively examined to reveal the true crack depth and other desired parameters (crack opening, surface roughness and so on can be measured at this stage). Then, using the same procedure, a similar crack is produced in the actual test block. Due to very good repeatability, this crack has the same depth and other essential parameters as the destructively examined validation crack. Finally, all the destructive validation cracks are analysed to give an estimate on the process variability and a tolerance is determined to given crack depth values.

2.3 Crack growth repeatability

The repeatability of the crack production is most important as this is reflected in the crack growth tolerance that can be given for the crack depth. Thus, significant effort has been made to assess and analyse process repeatability. Throughout its history, Trueflaw has manufactured and destructively examined altogether 215 validation cracks to date. The work is ongoing and new data is added continuously. The data spans a wide variety of materials, component geometries and crack sizes.

As an example, Figure 1 presents the current validation data for austenitic stainless steel base material. The data includes a wide variety of different austenitic stainless steel base material samples and crack sizes. The maximum error in this data set is ±0.4 mm. The standard crack depth tolerance given for produced cracks is ±1.0 mm, due to practical client requirements. It is seen that the process variability is well within the given tolerance.

2.4 Limitations of thermal fatigue crack growth

The nature of the described thermal fatigue crack growth technology allows only surface-breaking cracks to be manufactured. Furthermore, the location where the crack is to be manufactured must be attainable (*ie*, the loading tool must fit to the location). This prevents crack production to, for example, inner diameter (ID) of very small tubes. Currently, the smallest tube ID where cracks have been produced is about 16 mm.

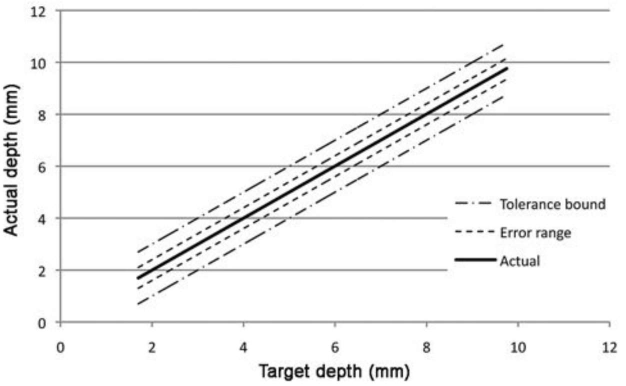

Figure 1. Example of validation data for austenitic stainless steel

While the technique is applicable to a wide variety of materials, there is also some materials that present a challenge. Currently cracks can not be manufactured, for example, to copper and aluminium.

3. Case examples on application of Trueflaw technology

Three cases using Trueflaw cracks are presented in the following to give an overview on the application possibilities. The three cases were selected to give a diverse selection of non-trivial applications. The cases span different materials, component geometries and crack sizes.

3.1 E.ON reactor pressure vessel head nozzles

The non-destructive inspection of dissimilar welds is an important part of the inspection programme in refuelling outages in nuclear power plants. The inspection of the inner weld surface in the reactor pressure vessel head nozzles of German PWR plants is complicated by geometrical constriction. This dissimilar weld is accessible only through a 1 mm-thick gap, through which the eddy current probe must pass. For this inspection, a new eddy current technique had to be developed. Due to the geometrical limitations, the probe design had to ensure an extremely flat probe. The qualification of the inspection technique was performed with a test specimen made of a real nozzle using EDM notches as simulation of cracks according to applicable rules.

During the inspection in 2007 an indication was found close to the austenitic side of the dissimilar weld in one nozzle. The signal was not within the phase range of defects found in the qualification and the signature was totally different from the signal of notches. So, the indication was not classified as a defect signal. Nevertheless, it was decided to make further investigation to find out the reason for the signal.

One of the points to study in this investigation was to find out the difference between notch signals and the signals of real cracks. The next aim was to develop a visual technique able to inspect the inner weld surface through the 1 mm gap. A new test specimen was made using again an original nozzle. Trueflaw was ordered to manufacture cracks in this new specimen and as well to make different EDM notches and notch fields as a reference.

E.ON supplied an original nozzle to Trueflaw to be used as a test block. Part of the test block was marked to be used for validation. Trueflaw produced validation cracks of desired size in this area. Figure 2 shows an example image from a validation crack with measured crack opening on the surface. The area containing the validation cracks was then cut out from the tube using electric discharge machining (EDM) and the cracks destructively examined to reveal the true crack depth. During the production, E.ON and consultant expert of the authority (TÜV) visited Trueflaw to follow the progress. Subsequent to the accepted validation result, the final cracks were manufactured and the sample supplied to E.ON.

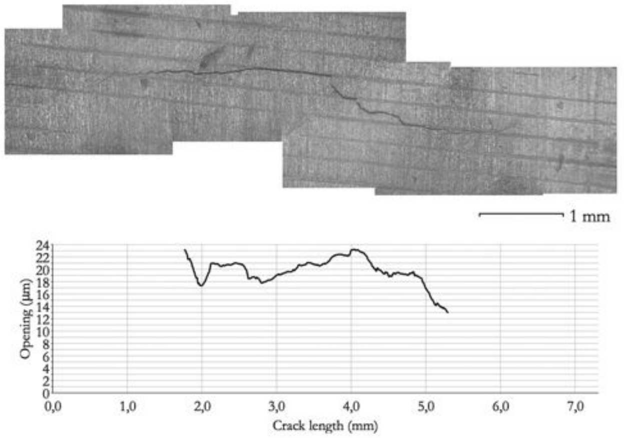

Figure 2. Example validation crack in E.ON nozzle. The crack was imaged using a camera microscope and is shown with respective crack opening measured from the image

With the manufactured cracks, the eddy current system qualification was repeated, and the phase range for defects could be basically verified but reduced at the edges. It could be proved that, due to a crack with secondary crack close to it, no phase shift occurs when more then one crack is in the area of influence of the probe. The new developed visual inspection technique (using special optical components and CCD chip together with an optical fibre lighting) was as well qualified with the natural cracks from Trueflaw.

In the 2008 outage, a second inspection with the optimised qualification and the visual inspection was made. It could be shown that the reason for the indication was of geometrical nature. A crack in the component could be excluded.

3.2 Fortum steam generator primary collector

Fortum Ltd, Loviisa Powerplant (Finland) conducted an ultrasonic qualification for a VVER steam generator primary collector during the 2008 summer outage. A schematic illustration of the steam generator is presented in Figure 3.

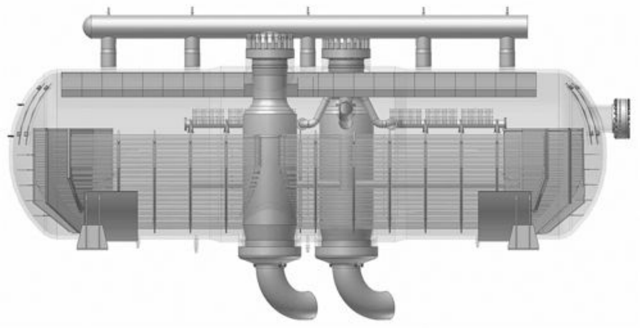

Figure 3. Loviisa powerplant horizontal steam generator

The area of interest is cracking in M48x5 threaded holes of the primary collector flange. The inspection is done using phased array UT with scanning from top and inner diameter (ID) surface of the primary collector. It was decided to use a component removed from a similar powerplant, that never went to operation, as a test block for the qualification. Figure 4 shows the qualification test block. The flaw types to be detected are shown in Figure 5.

Fortum provided Trueflaw with the target flaw sizes and locations for this very challenging geometry. The flange is a forged ring fabricated from Ti-stabilised austenitic stainless steel. Since the material and geometric conditions are unique, new validation for each crack size was required for reliable flaw production. A material sample was cut out from the test block for validation purposes. A simplified validation sample was machined that replicated the local

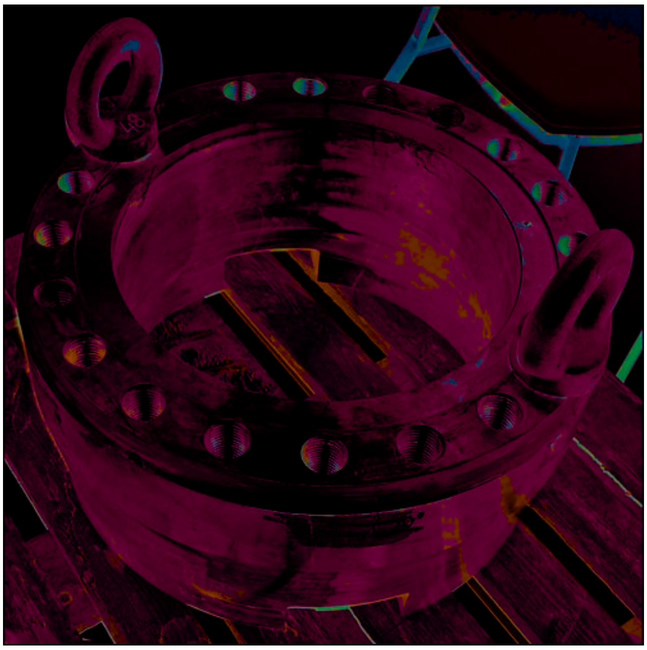

Figure 4. Loviisa test block from vintage material

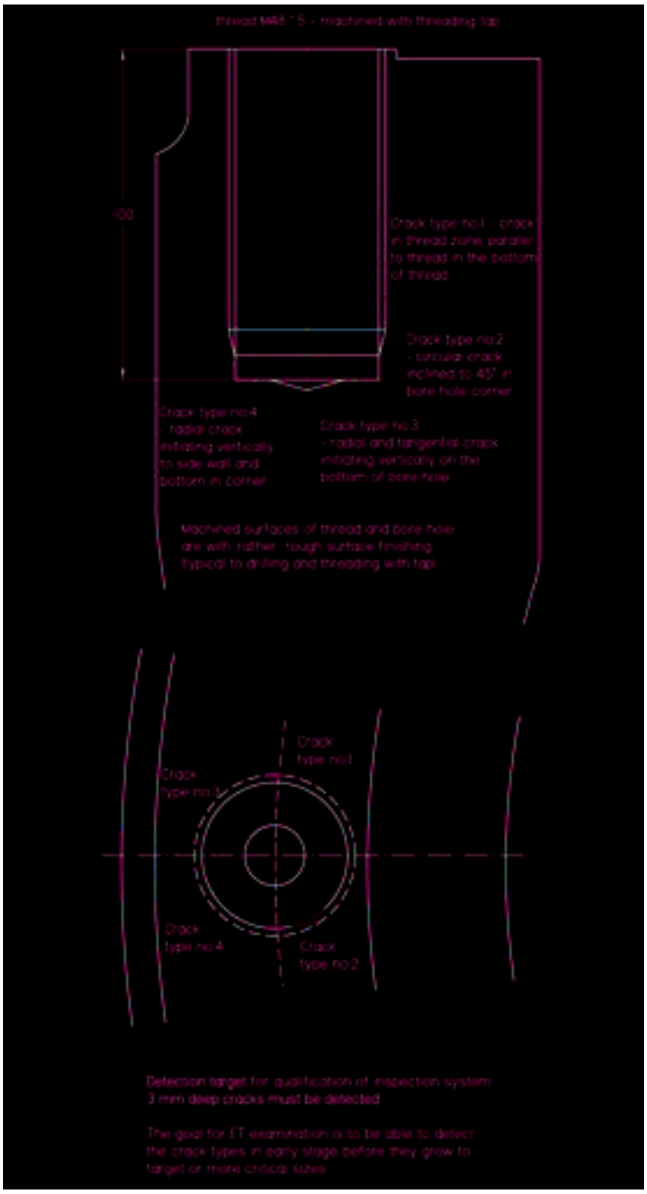

Figure 5. Flaw types to be detected in Loviisa primary collector qualification

geometry conditions of the threaded hole bottom cup.

Trueflaw produced validation cracks for all the desired flaw sizes and locations and supplied a destructive evaluation report to Fortum. After accepted validation, the production of the actual qualification defects was done and test block supplied to Fortum. Figure 6 shows an example of a fracture surface from this validation. Thermal fatigue cracks were supplemented with a selection of EDM notches in different locations.

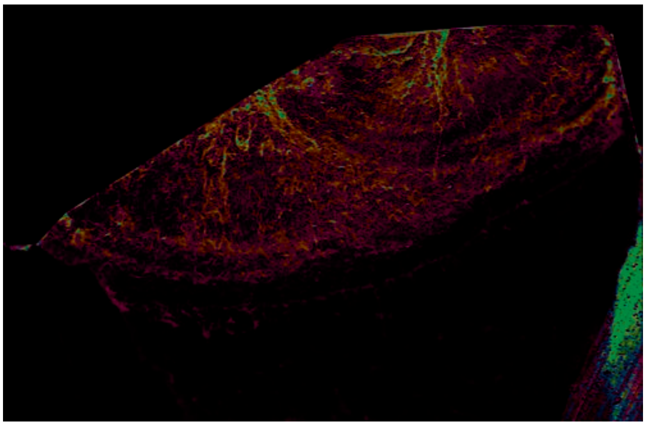

Figure 6. Fracture surface from a destructively examined validation crack corresponding to crack type 3 in Figure 3

The open trials on the test block were performed during the 2008 summer outage. All the defects were successfully detected in open trials with UT examination (even the small sizes). Loviisa now has a reliable inspection procedure that is tested with real cracks.

3.3 Rolls-Royce seal fin sample

Rolls-Royce wished to study the effectiveness of novel NDT methods in detecting cracks under conductive coatings and needed a sample with a known crack population. The component chosen for this work was the seal fin region of a turbine disc. In use this component is covered with a wear coating (TBT406). The task was to create a realistic testpiece containing cracks under the coating and by using the Trueflaw method the cracks could be placed in the required position at the tips of the fin. Figure 7 shows a schematic illustration of the seal fin sample.

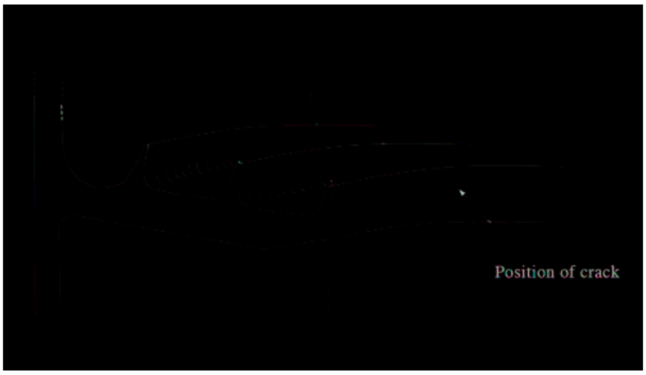

Figure 7. Schematic image of the seal fin sample

The fin sample was provided by Rolls-Royce. The material and geometry were both new to Trueflaw. Consequently, part of the fin sample was dedicated to production test and validation. In this case, all the critical flaw parameters were directly observable and depth validation was not necessary. It was expected that the crack opening would affect the NDT methods to be studied. Consequently, several production trials were completed to allow production of a variety of crack openings. Furthermore, while doing the production tests it became evident that different fin locations in the sample had different responses to fatigue loading.

Numerous cracks were produced at different locations on the seal fin sample to allow determination of inspection capabilities in all interesting locations. A sample red dye penetrant test (PT) image from a crack produced in the fin sample is shown in Figure 8.

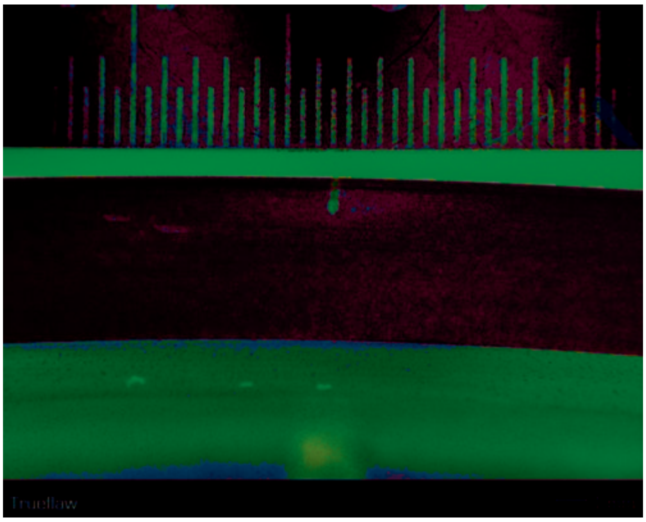

Figure 8. PT indication of seal fin crack

Characterisation was done by using penetrant testing with magnified digital imaging to measure the crack size and the crack opening. Some NDT (thermosonics) was carried out prior to the coating being applied. Following verification of the cracks using fluorescent penetrant the part was coated and a sample crack cut out. X-ray computer tomography was used to visualise the crack under the coating to verify the coating material had not entered the crack. This can be seen in Figure 9(a), showing the coated fin. Figure 9(b) shows the X-ray image with the tip of the fin removed making the crack beneath clearly visible. This sample is now being used in a series of trials to establish if an inspection method is possible.

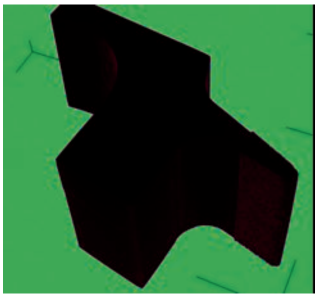

Figure 9(a). X-ray image of seal fin showing coating is uncracked

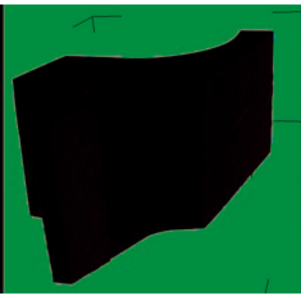

Figure 9(b). Seal fin tip removed from X-ray image showing subsurface crack

3. Conclusions

The most significant disadvantages traditionally associated with realistic grown defects have been overcome by developments in the thermal fatigue crack growth process as shown in this paper. The developed validation procedure has solved the traditional problem of reliance upon a supplementary inspection to confirm critical flaw parameters for grown cracks. A similar validation approach could be used with any repeatable crack growth process.

Thermal fatigue cracks have been successfully used in numerous practical applications ranging from qualification to development and testing of novel NDT methods. This is shown by the various real-world application cases presented in this paper. The technology is reliable and mature.

Acknowledgements

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