REALISTIC CRACKS FOR IN-SERVICE INSPECTION QUALIFICATION MOCK-UPS

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Abstract

One of the essential requirements for in-service inspection qualification is the representativeness of the defects used. The best representativeness is achieved with realistic defects. However, present techniques for artificial defect production in NDT test mock-ups are not able to produce defects truly representative of real flaws. Defects manufactured, for example, by weld implantation or by creating weld solidification defect always result in one or more extra weld interfaces in the test piece. These interfaces can be easily detected by NDT. In order to avoid this problem there is a need for development of better defect manufacturing techniques.

A new method for producing realistic artificial flaws is presented. The method is based on thermal fatigue and enables production of real cracks directly in the mock-ups used for NDT in-service inspection qualification without welding or machining. Single crack or network of cracks can be induced in the base material, welded areas, threaded areas, T-joints and so on without artificial crack initiators. The location, orientation and size of produced cracks can be accurately adjusted. The produced cracks can be used to simulate different types of in-service induced cracks such as thermal and mechanical fatigue cracks.

Introduction

Thermal fatigue, i.e. material degradation due to successive temperature changes, is one of the life-limiting mechanisms in nuclear power plant conditions. A typical component, where thermal fatigue cracking occurs, is a T-joint where hot and cold fluids meet and mix. The turbulent mixing of fluids with different temperatures induces rapid temperature changes to the pipe wall. The resulting uneven temperature distribution prevents thermal expansion and gives rise to thermal stresses. The successive thermal transients cause varying, cyclic thermal stresses. These cyclic thermal stresses cause fatigue crack initiation and growth similar to cyclic mechanical stresses. (1)

The thermal stresses are typically equi-biaxial and they are strongest at the loaded surface. The loading is strain controlled and very high local stresses can arise. If the stresses locally exceed the yield stress of the material, thermal residual stresses arise (2). Due to the high surface stresses, the thermal fatigue cracks often form a mosaic-like crack pattern of shallow cracks, sometimes called elephant skin fracture. Some of the shallow cracks extend deeper into the material and can grow through the wall (3). Besides these distinct features caused by the typical thermal fatigue load pattern, the thermal fatigue cracks are quite similar to the mechanical fatigue cracks.

Experimental

In order to verify the controlled thermal fatigue crack production method different test samples were produced. Samples were studied both non-destructively and destructively. Thermal fatigue loading was applied with high frequency induction heating and water or air cooling in order to achieve high heating and cooling rates. Initiation and growth of cracks were followed by replica assisted light optical microscopy. Ultrasonic examinations were performed to determine the non-destructive response of produced cracks. Destructive testing and scanning electron microscopy were carried out to study the microstructural propagation and fracture surface morphology.

The used process does not need any crack starter or artificial initiator and it can be applied to the actual surface of a component. As a result of that, the process does not leave any unwanted alterations in the material, which could be detected in ultrasonic or eddy current examination.

Microscopy

In an austenitic stainless steel the thermal fatigue cracks initiate at slip bands, which form microcracks. From these microcracks one single crack grows larger by controlled thermal cycling. In Figure 1, there is an example of a ready-made surface breaking macrocrack. The crack follows the crystallographic crack path through the microstructure. The crack path is tortuous, but the macroscopic surface crack growth follows the predetermined direction. Crack propagation through the microstructure is tortuous, as well. In Figure 2 a cross-section is shown, where the transgranular crack propagation can be seen.

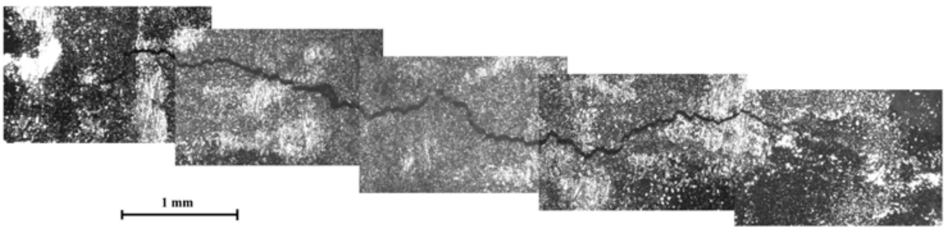


Figure 1. Surface breaking thermal fatigue crack (surface length ca. 6,5 mm) in an austenitic stainless steel plate.

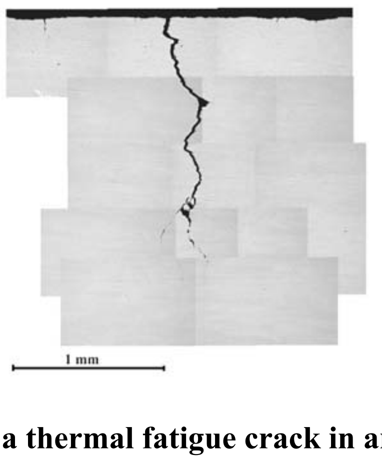


Figure 2. Cross-section of a thermal fatigue crack in an austenitic stainless steel.

The controllability of the produced crack includes also the control of the depth of the crack. The crack contour of the produced crack follows a semielliptical shape approaching the semicircular shape. Artificially produced cracks have rough fracture surfaces where crack extension can be followed by fatigue striations. An example of typical striations is shown in Figure 3. The average value R_z of surface roughness is between 35 and 125 μm.

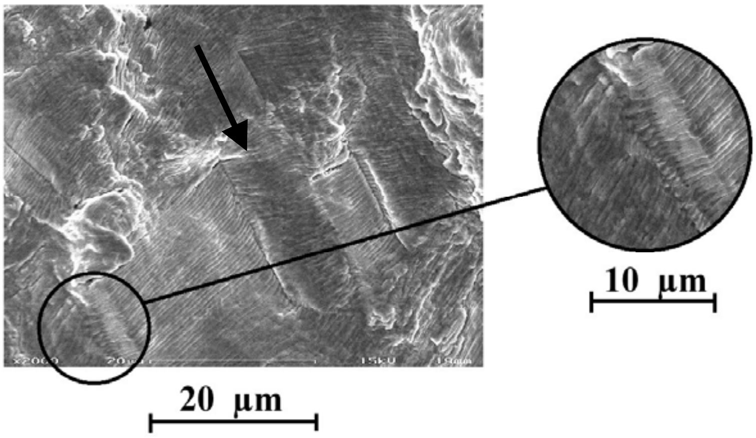


Figure 3. Striations on the fracture surface of an artificially produced thermal fatigue crack in an austenitic stainless steel plate. The arrow shows the crack growth direction.

Non-destructive testing

Artificially produced thermal fatigue cracks in austenitic stainless steel pipe and cladding were characterised by EC and UT measurements. In the austenitic pipe two cracks were introduced (in axial and circumferential directions). Cracks were characterised with longitudinal, transverse and secondary creeping waves. Two techniques with longitudinal waves, 0°L single element probe and ADEPT60°L 2 element special probe, were used. With both probes the crack tip was detected. With 0°L no proper echo from the crack face was detected (accurate mechanised inspection was not carried out). Echo from the crack tip was detected both with 45°T (S/N ca. 15 dB) and 70°T (S/N ca. 10 dB) 2 MHz probes (Figs 4 and 5). With mode conversion probe (Fig. 6) the received secondary creeping wave echo disappeared locally. The reason is most likely a compressive residual stress, which presses crack faces together enabling the ultrasonic energy to go through the crack.

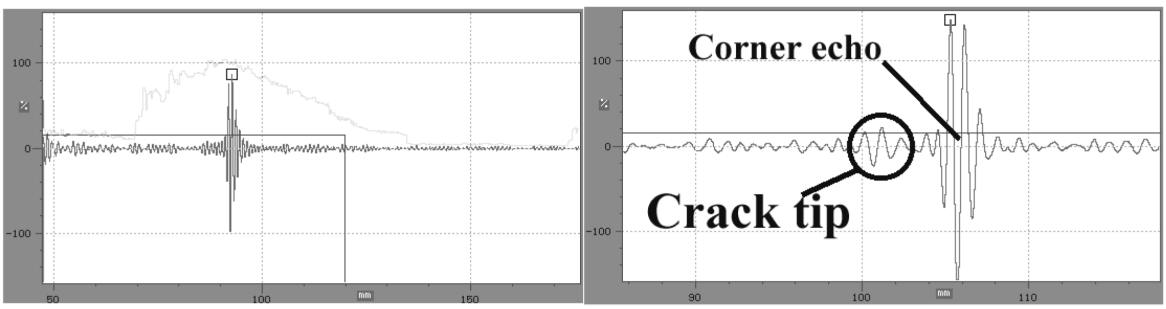


Figure 4. Ultrasonic A-images from an artificially produced thermal fatigue crack with 70°T probe (MWK 70-2E).

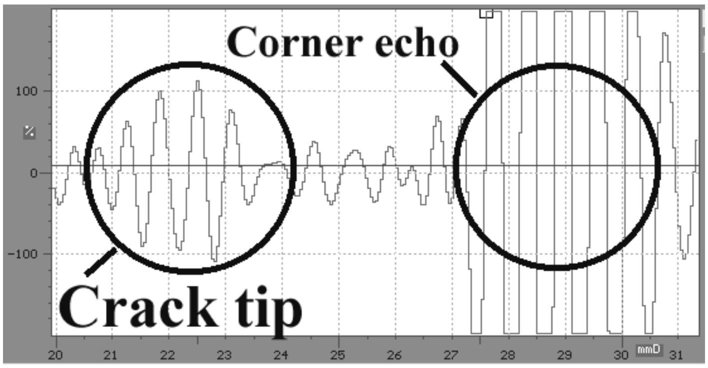


Figure 5. Ultrasonic A-image from an artificially produced thermal fatigue crack with 45°T probe (MWK 45-2).

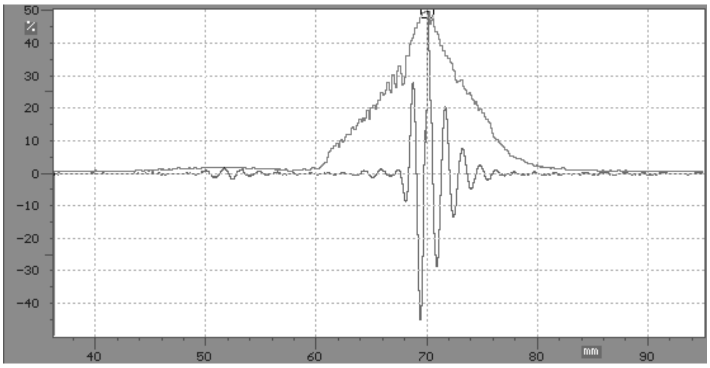


Figure 6. Ultrasonic A-image from an artificially produced thermal fatigue crack with secondary creeping wave probe (WSY 70-2).

Artificially produced thermal fatigue crack in the austenitic stainless steel cladding was detected with eddy current inspection. The impedance level varied in the cladding depending on the δ-ferrite content and the location of the strip welded cladding (middle of strip, HAZ, fusion line). According to eddy current calibration the artificially produced thermal fatigue crack was estimated to be about 3-4 mm deep (Fig. 7).

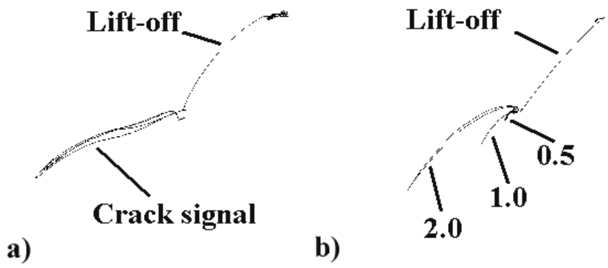
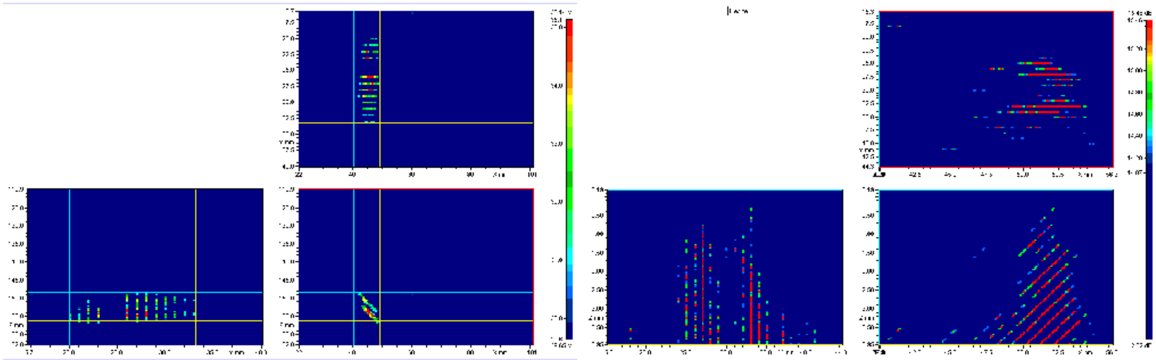


Figure 7. Eddy current signal from a) an artificially produced thermal fatigue crack and b) three EDM-notches (depth 2,0/1,0/0,5 mm) in austenitic stainless steel strip welded cladding.

The crack was detected by ultrasonic 70°TRL probe on the crack-opening surface. The crack was detected also very clearly with long sound path from outside of the test block with 41°T 1MHz probe. With both cases no crack tip echo was detected (Fig. 8). It may be caused by a high compressive stress affecting the crack tip.



a) b)

Figure 8. Ultrasonic testing results of an artificially produced thermal fatigue crack in austenitic stainless steel cladding with a) 41°T (1MHz) and b) 70°TRL (2MHz) wave probes.

Residual stress

Residual stress can easily be measured on the surface of the sample. Measurements through the thickness of the sample near the crack are not as easy. Figure 9 shows an example of cumulative change of surface residual stress caused by continued thermal fatigue cycling. Residual stress measurements through the thickness of the sample were not performed in this study.

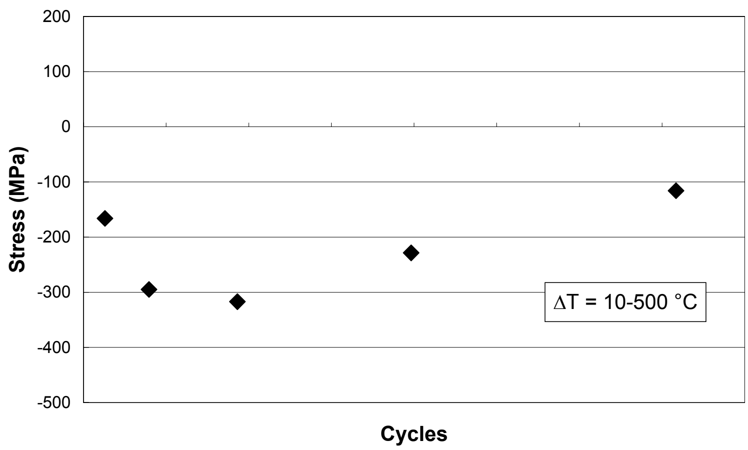


Figure 9. Change of surface residual stress as a function of continued thermal fatigue cycling (ΔT=10-500 °C) in an austenitic stainless steel plate.

The change of surface residual stress in the example shown above demonstrates that the applied thermal fatigue cycle has a strong effect on the final residual stress distribution. By using a different number of thermal cycles the residual stress can be adjusted to the wanted level.

Real components

The developed defect production method works well when the result is studied from the metallographical and non-destructive response point of view. A further interest is to verify the applicability of the method to real components. Verification has been done with different types of components: pipe section, butt-welded pipe, T-joint of two pipes and a collector head threaded screw hole. Materials were different types of austenitic stainless steels. Results of these tests are shortly presented in the following paragraphs.

Pipes

Three different sizes of pipes were examined during the experiments. Cracks were produced on the inner surface of the pipes. In Figure 10 is an example of a pipe (dia. ca. 450 mm, wall thickness ca. 30 mm) on the inner surface of which one circumferential and one axial thermal fatigue crack were produced. The cracks were produced to the base material with lengths of about 20 mm. Cracks have been produced also in the inner surface of a 159 x 8,5 (diameter (mm) x wall thickness (mm)) pipe. The crack almost penetrated the wall thickness being 6,8 mm deep. Additionally cracks have been produced to the heat affected zones of butt-welded pipes.

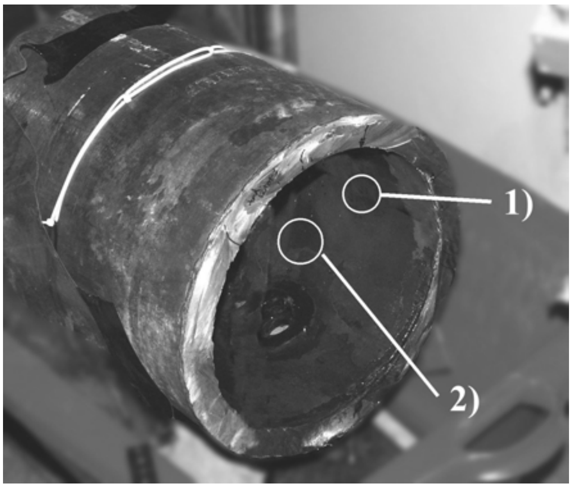


Figure 10. Austenitic stainless steel pipe: 1) circumferential and 2) axial thermal fatigue crack (pipe diameter 450 mm, wall thickness 30 mm).

T-joint of two pipes

Artificially produced thermal fatigue cracks were produced in the corner of T-joint of two pipes of different sizes (110*20 mm and 570*35 mm). Neither surface nor any other pre-treatment was performed for the area in question. Two individual cracks were produced in the wanted locations with location accuracy of ±1° and size accuracy of ± 0.3 mm (surface length).

Collector head

Method was applied to a piece of a collector head taken out from an operating power plant. The piece included three threaded holes (dia. 48 mm) with a bottom cup in the end of the holes. Artificial cracks were produced to the threaded area and to the bottom cup area. Cracks produced to the threaded area were used as initiating flaws for afterwards produced transgranular stress corrosion cracks. A general picture of the collector head mock-up is shown in Figure 11 and Figure 12 shows an example of a crack produced at the bottom of a thread.

Figure 11. Production of cracks inside of an austenitic stainless steel collector head threaded screw hole.

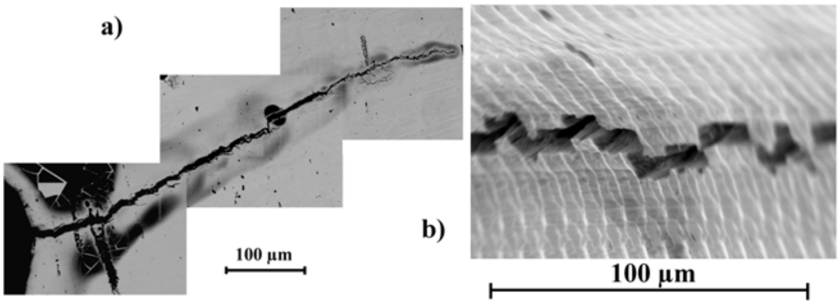


Figure 12. Artificial crack at the bottom of a thread: a) cross-section and b) crack opening on the surface of the thread bottom.

Discussion

The crack path of the artificially produced thermal fatigue crack is tortuous. Tortuous shape is a result of the transgranular crack initiation and growth mechanism. The produced crack has rough surfaces exhibiting clear striation formation and crack has a semielliptical shape.

Characteristically thermal fatigue causes residual stresses in the material. The applied thermal loading and the number of cycles determine magnitude of the residual stress. Thus, the residual stress near the cracks can be controlled. Residual stress can be adjusted qualitatively in compression or tension. Residual stresses present in the vicinity of the produced flaw can have a strong effect on the ultrasonic response of the crack. Changes in the residual stresses along the crack path (at the crack tip, in the middle of the crack and near the sample surface) affect the penetration of ultrasonic energy in different locations.

These changes increase the uncertainty of the signal analysis and affect the difficulty of flaw sizing.

Conclusions

A new artificial flaw production method for NDT-qualification defect production purposes has been developed. The method is based on thermal fatigue damage mechanism. The flaw production can be controlled so that location, orientation and size of cracks can be accurately adjusted. Individual cracks can be grown without causing any additional alterations (e.g., notch or other artificial crack starter or weld seam) in the material. Cracks can be produced to the base material or the welded areas, to simple plate samples or full scale mock-ups.

The morphology of the produced cracks is similar to the real, in-service induced thermal fatigue cracks. The cracks propagate transgranularly, have rough fracture surface, the crack tip radius is small and cracks are tight. Artificially produced thermal fatigue cracks do not have oxide layer on the fracture surfaces, as is the case with in-service induced cracks. However, oxide layer can be grown by subsequent heat treatment.

By ultrasonic testing the crack tips were detected. Artificially produced thermal fatigue cracks showed similar ultrasonic properties as the real ones (corner echo, crack tip, crack face) and cracks were reliably characterised. Crack in the austenitic cladding was detected easily, but no crack tip echo was detected which makes the sizing of the crack difficult. Welded cladding caused also some uncertainties in eddy current inspection.

It was shown that artificial, representative cracks can be produced to samples and mock-ups of different size and shape. The experiments performed proved that artificial surface breaking thermal fatigue cracks can be induced to practically any kind of components with practically no limitations in location, orientation or size.

Acknowledgements

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