PRODUCTION OF REALISTIC ARTIFICIAL FLAW IN INCONEL 600 SAFE-END

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The importance of NDT qualification has received significant attention during the recent years. Recent findings of cracks in Inconel 600 in different NPP components have also increased interest in the reliability of in-service inspections of this material. This, in turn, sets challenge for manufacturing of representative qualification specimens and flaws. A new, advanced flaw production technique has become available. The technique enables production of realistic cracks to ready-made mock-ups without implanting or welding.

This paper describes the advanced crack production technique and its application to Inconel 600. A realistic, controlled crack was produced to a core spray nozzle safe-end mock-up. The technique produces true fatigue cracks, which are representative of most real, service-induced cracks. The technique is applicable to any shape or size of component and results only in an intended crack without unwanted disturbances. The technique allows production of a single or separate cracks as well as different combinations of them.

In addition to the controlled crack production, the paper introduces studies of the effects of different thermal fatigue loading cycles on the ultrasonic response obtained from the crack in Inconel 600. Results of the study show the effect of different thermal fatigue loading cycles on the obtained ultrasonic response during dynamic loading of the artificially produced crack. Control of crack growth and relationship between loading parameters and ultrasonic response are discussed.

Introduction

The last decade has brought new challenges for the nondestructive testing in the nuclear power field. Several through-the-wall leakages in components and structures that have not been covered by in-service inspection programs have gathered attention of the whole nuclear community. One of current concerns is the primary water stress corrosion cracking of Inconel 600 alloy and its weld metals in the pressure vessel head and bottom penetration nozzles. This type of degradation and crack growth was not originally considered in components in question.

The NDE qualification procedures are still under development all over the world. This includes development of better flaw production techniques producing representative flaws. There are certain factors that have to be taken into account when a flaw is used as a reflector for ultrasonic inspection. The ultrasonic response is affected by different crack characteristics, among others, location, orientation and size of a crack[1], the opening of a crack and crack tip[2,3,4], the remaining residual stresses in the material[5,6], fracture surface roughness[7,4], crack tip plastic zone[8] and filling of the crack with water[9]. These characteristics of cracks affect propagation, reflection, diffraction, transmission, attenuation and diffusion of ultrasonic energy[9,10].

Wüstenberg et al.[11] mentioned, that if the main interaction of a flaw used in qualification is based on the crack tip diffraction, the only possibility would be use of service-induced flaws as cut outs from real components and weld implant them to qualification mock-ups. This was based on the fact that there was no flaw production technique capable of producing realistic cracks or flaws which represent sufficient weak crack tip diffraction. Hence, there is a need to develop a flaw manufacturing technique that is capable of producing realistic flaws representative from all typical characteristics point of view.

A novel artificial flaw production technique and its applicability for Inconel 600 is introduced in this paper. The technique is used to produce a realistic crack in a core spray nozzle mock-up component of a BWR-type nuclear power plant. Furthermore, the ultrasonic response of the crack under dynamical thermal loading was studied in order to understand the relationship between ultrasonic response and different crack opening conditions.

Materials and Methods

The flaw production technique is based on thermal fatigue loading. Loading is applied by high frequency induction heating and water or air spray cooling. Produced flaws are representative of real, service-induced fatigue flaws in metallographic sense and hence they are supposed to be representative also in terms of NDE response. The technique allows production of realistic flaws with controlled location, orientation and size. Characteristics of flaws produced with the technique are introduced in more detail in references [12,13,14]. The technique is applicable to different materials and virtually any shape or size of a sample. The only requirement for the crack production is that the intended location must be accessible.

Sample

This paper introduces flaw production to a full-size core spray nozzle, safe-end mock-up (BWR-type nuclear power plant). Figure 1 shows the nozzle consisting of three different materials: A508 carbon steel, Inconel 600 and AISI 316 type austenitic stainless steel. There is a buttering and a joint weld between the carbon steel (with cladding on the inner surface) and Inconel 600 safe-end, and a butt weld between Inconel 600 safe-end and AISI 316 austenitic stainless steel pipe. Both welds were made with Inconel 182 filler material with Inconel 82 root pass. After welding the working allowances were machined away. The finishing machining removed the root pass so, that the welds of the ready-made mock-up are Inconel 182.

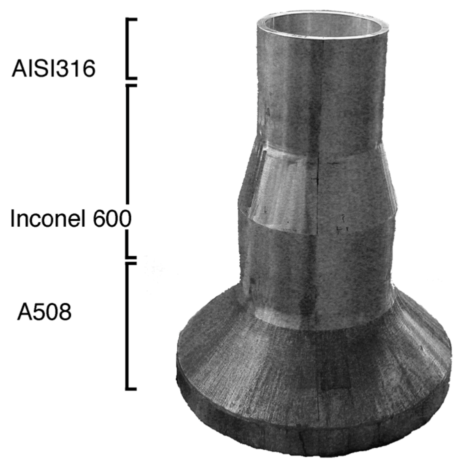

Figure 1 Core spray nozzle mock-up with Inconel 600 safe-end.

Figure 2 shows the drawing of the nozzle mock-up and the intended location of the flaw production. The intended location is in Inconel 600 in the HAZ of the buttering weld. The wall thickness of the Inconel 600 safe-end in the intended location is 23 mm. Nozzle was received as ready-made and no machining or welding was allowed. Flaw was to be produced to the inner surface in as-received condition of the nozzle. The specimen was nondestructively tested after flaw production and no destructive tests were performed.

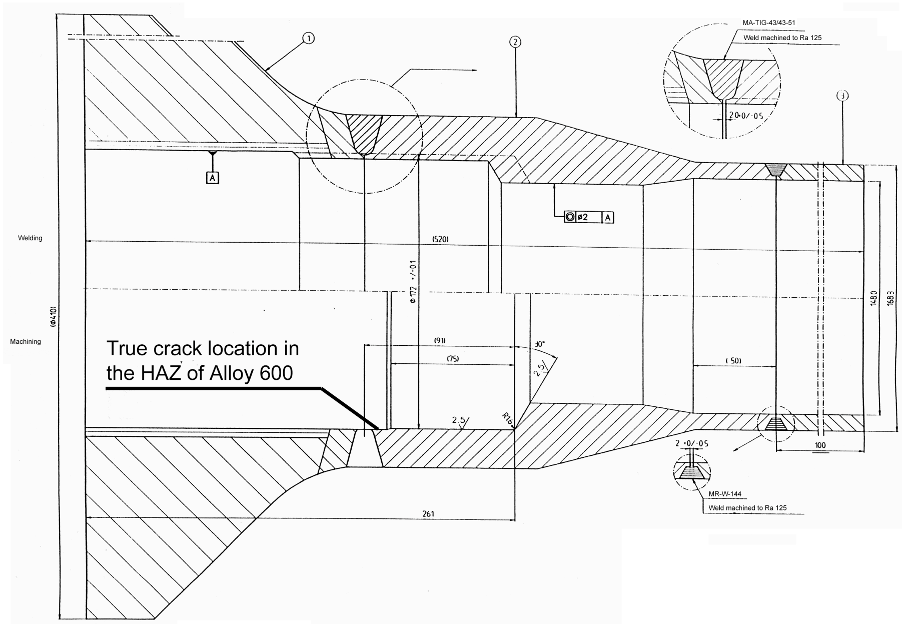

Figure 2 Drawing of the core spray nozzle and location of the produced crack in Inconel 600 safe-end in the heat affected zone of the buttering weld.

NDT set-up

A pulse-echo shear wave probe (41°, 1.5 MHz) was used when performing the inspection of the nozzle after crack production. The same probe was used during the studies of the relationship between ultrasonic response and crack loading. These studies were performed with a ready-made crack. The probe was attached on the outside surface of the mock-up and the surface breaking crack in the inner surface was monitored through the wall, in front of the weld. Ultrasonic signals were gathered in-situ during continued thermal fatigue cycling of the crack. Details about the NDT measurement system are given in reference[15].

Applied loads

In order to study the effect of different loadings, two different thermal fatigue loading cycles were applied. Temperature curves of applied cycles are shown in Figure 3 as measured from the sample surface. The first cycle (B1) had high heating rate and short cooling time with heating and cooling times of 10 and 15 s, respectively. The second cycle (B2) had lower heating rate and longer cooling time with heating and cooling times 20 and 25 s, respectively. Water spray cooling was applied for both cycles. The first cycle reached higher temperature than the second cycle. In order to see the effect of the stabilised cycles, B1 loading was applied as 20 and B2 as 16 successive cycles.

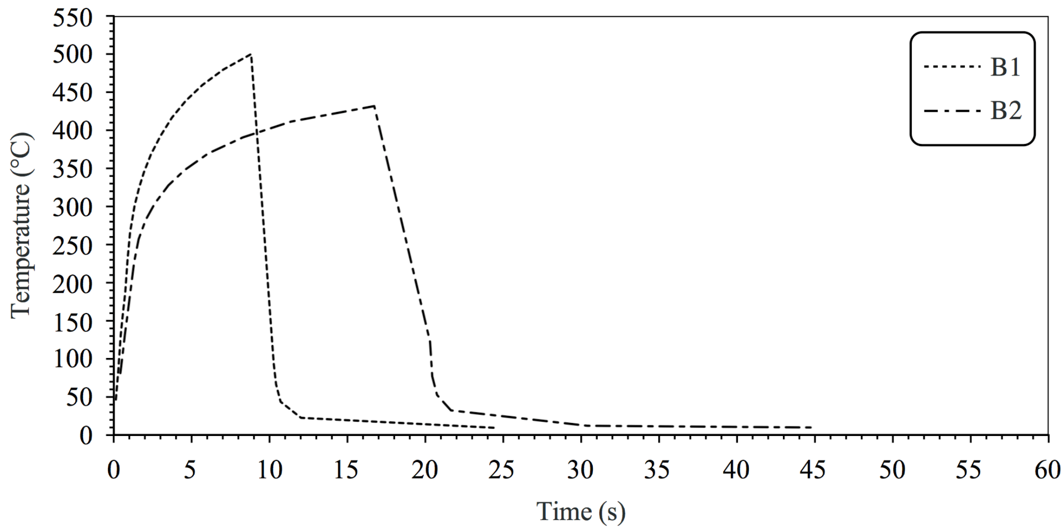

Figure 3 Two different temperature loading cycles used in the studies.

FEM-analysis

Applied cycles were analysed by finite element modeling (FEM) giving results of temperature and strain distributions through the material thickness during dynamical loading. Used finite element model is presented in more detail in reference[16].

Results

A realistic crack was produced in the inner surface of the nozzle. Figure 4 shows the dye penetrant indication of the produced single crack in Inconel 600 safe-end in the heat affected zone of the buttering weld. The weld is located in the upper part and Inconel 600 base material in the lower part of the figure. The length of the crack is 14.2 mm and the depth is 5 mm, thus being about 22% through the wall. The maximum surface opening of the crack varies locally between 30 – 45 µm. In the figure, there is also a very small (less than 1 mm deep) secondary indication in the corner of the shoulder visible in the lower part of the figure. The initiation of the secondary crack was caused by the stress rising effect of the shoulder. Without vicinity ofsuch a stress riser, there would have been no secondary cracking. The secondary indication does not affect the performance of ultrasonic testing as it is located about 7 mm away from the actual crack.

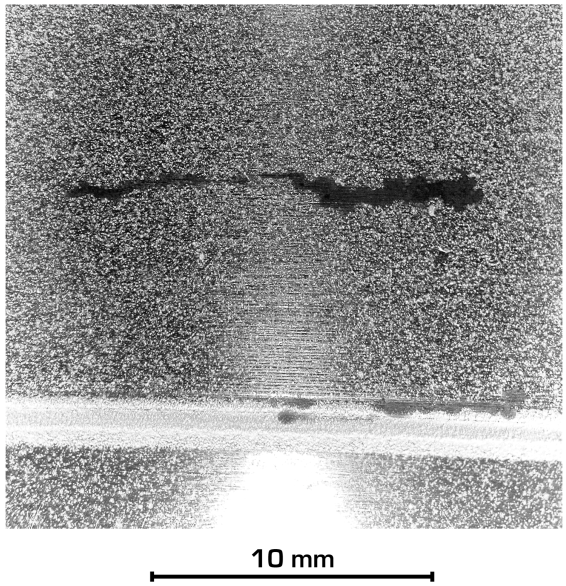

Figure 4 Dye penetrant indication of the produced realistic crack in Inconel 600 safe-end in the heat affected zone of the buttering weld.

The size of the crack was controlled by process control during the production and confirmed by ultrasonic testing. The obtained signal from the crack at room temperature is shown in Figure 5. The reflections from crack opening corner and subsurface parts of the crack are visible in the figure. The ultrasonic inspection sized the crack to be 18 mm long and 6 mm deep. The measured length by ultrasonic testing is clearly bigger than the actual value as seen from Figure 4. Also the measured depth differs from the given process value, but it lies inside the production tolerances (±1 mm).

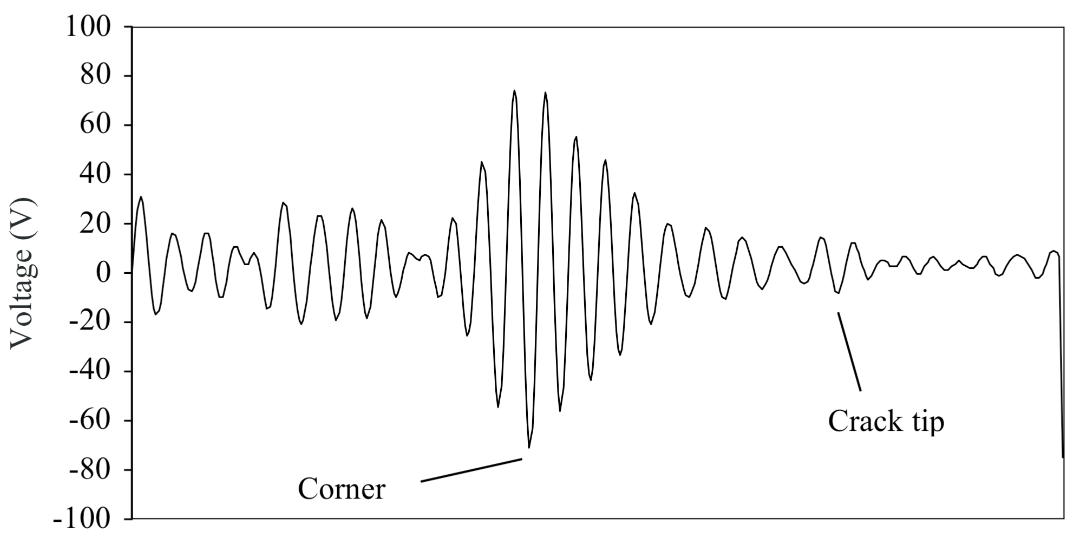

Figure 5 A-scan obtained from the crack at room temperature (41°, 1.5 MHz, shear wave probe).

The studies of ultrasonic response versus dynamical thermal loading resulted in a large amount of ultrasonic data. Figure 6 shows the ultrasonic signal obtained from the crack in the end of cooling and heating phases of cycle B2. The figure clearly shows the differences between different crack opening states. Results shown in the figure have been obtained in the turning points of surface temperature cycles.

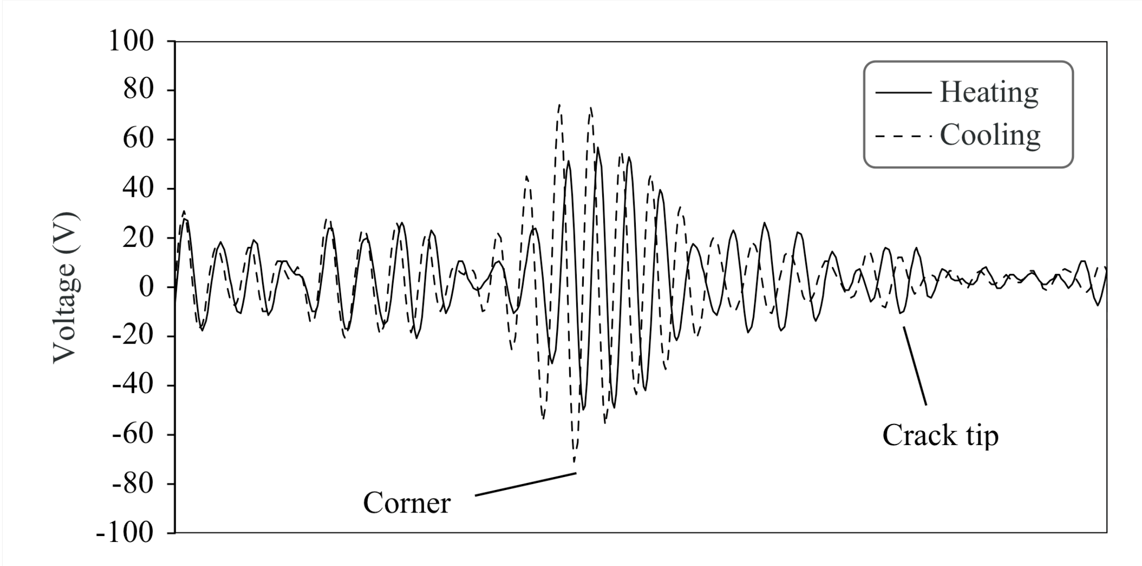

Figure 6 A-scans from the crack in the end of cooling and in the end of heating of thermal fatigue loading cycle. Differences in ultrasonic response are related to the crack opening and closing behaviour.

Results of finite element modeling gave temperature and strain distributions through the wall thickness. Figures 7 and 8 show solved strain distributions for analysed cycles B1 and B2, respectively. Nozzle ID is in the left side and OD on the right side of both figures. The results clearly show the difference between the faster and slower loading rates.

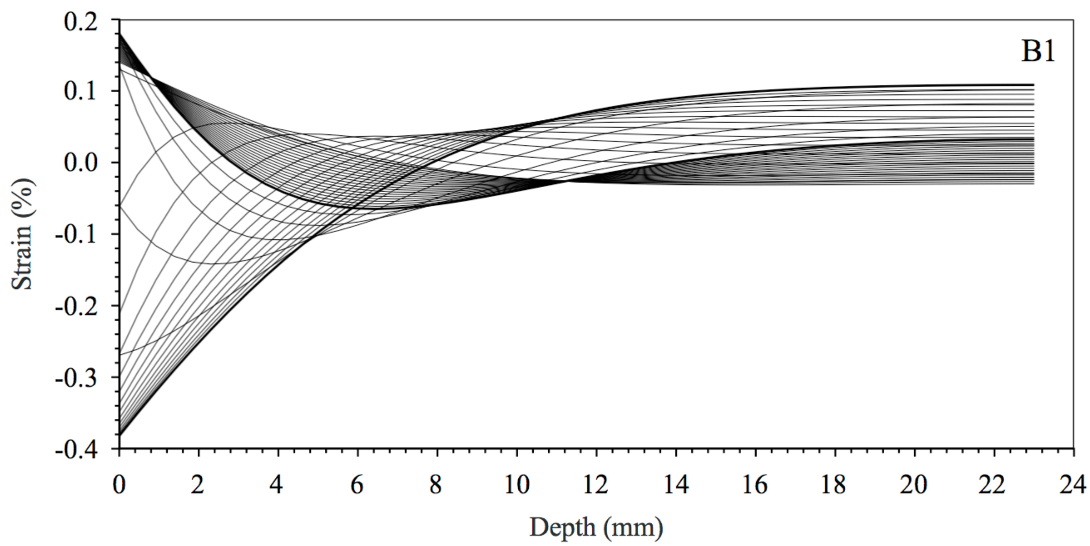

Figure 7 Strain distribution for loading cycle B1. Nozzle ID on the left and OD on the right side of the figure.

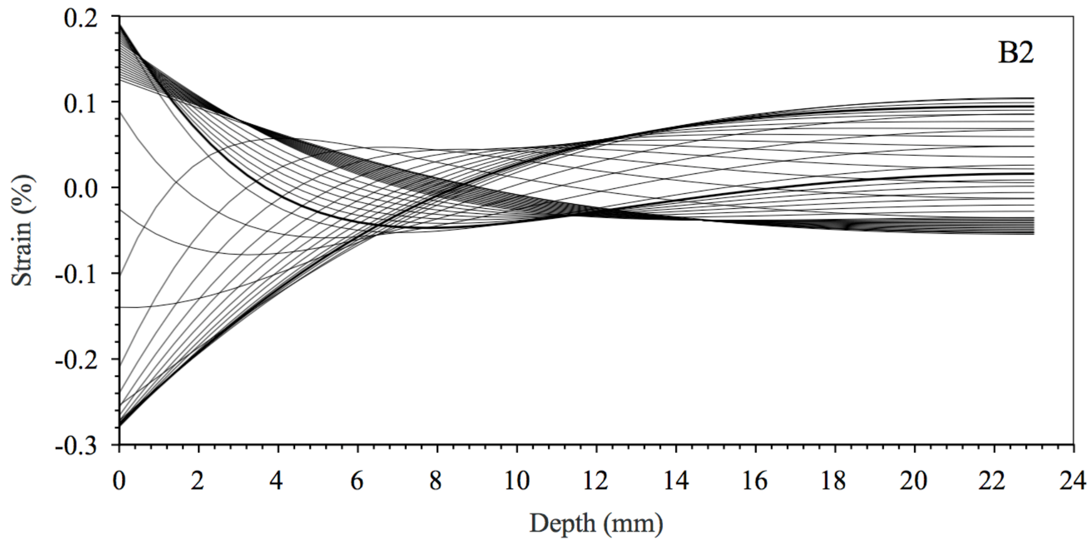

Figure 8 Strain distribution for loading cycle B2. Nozzle ID on the left and OD on the right side of the figure.

The obtained ultrasonic signal amplitudes from corner reflection and crack tip varied during the loading. These variations are related to the opening behaviour of the different parts of the crack. Figures 9 and 10 show the combined results of strain variations from modeling and measured changes of ultrasonic amplitudes from corner reflection and crack tip for cycles B1 and B2, respectively.

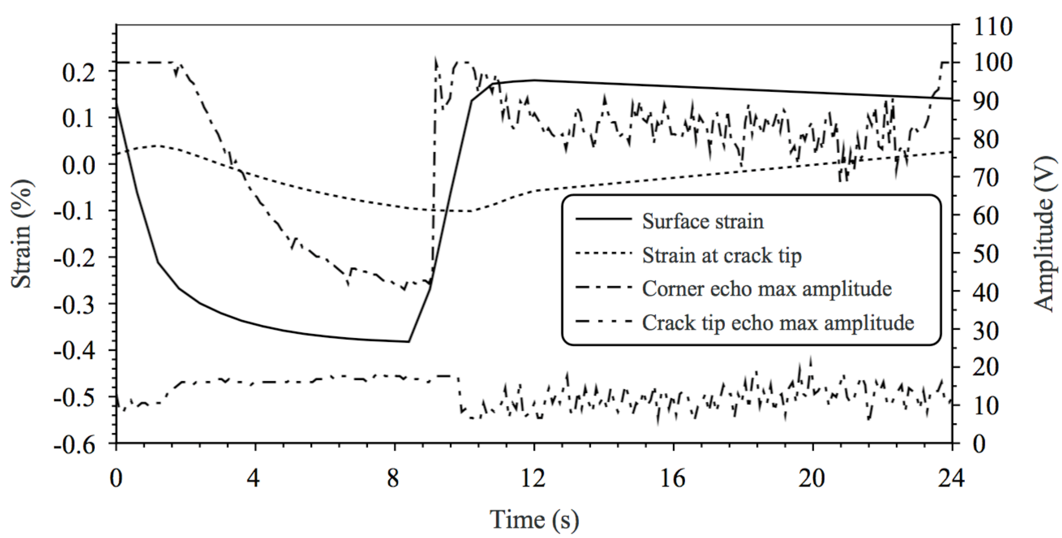

Figure 9 Combined results of strain and ultrasonic amplitude variations from crack corner and tip caused by loading cycle B1.

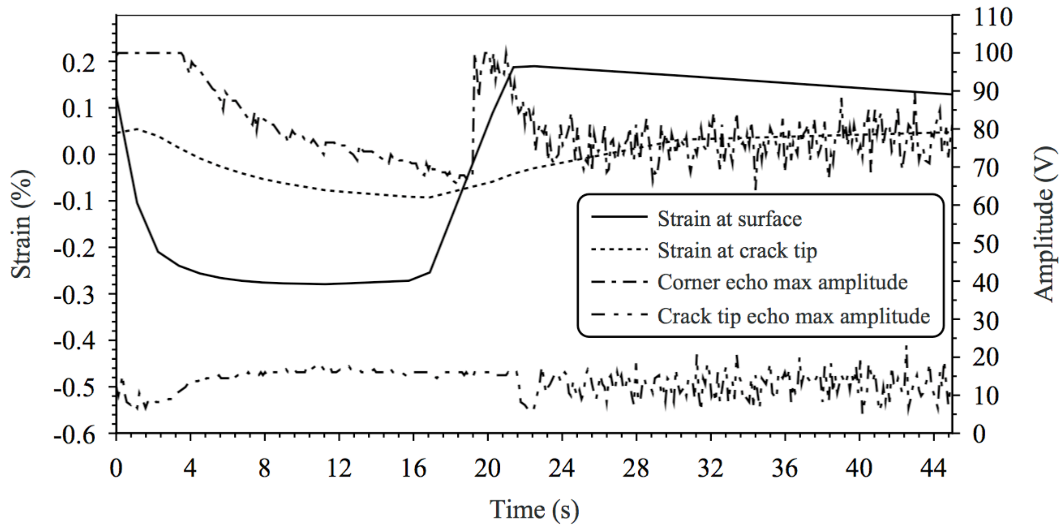

Figure 10 Combined results of strain and ultrasonic amplitude variations from crack corner and tip caused by loading cycle B2.

Discussion

The results show that a realistic crack was produced in the heat affected zone of the buttering weld in Inconel 600 safe-end, as intended. The flaw location and size were accurately controlled. The dye penetrant indication shows a single, tortuous crack, which has a natural propagation in the heat affected zone of the buttering weld. The crack is narrow and its opening varies in different parts of the crack.

The ultrasonic response is determined to be a crack-like indication. Similarly, the amplitudes from corner, face and crack tip are representative and set realistic challenge for the inspection. Ultrasonically the produced crack represents a difficult reflector caused by its realistic characteristics. The realistic crack causes unhomogeneous reflections affecting the detection. The tight crack tip and small crack tip radius make the sizing of the crack challenging.

It was shown that the technique is applicable to ready-made mock-up without causing any alterations to the component. The results show, that the technique fulfills the important factors to be taken into account when performance demonstration is designed and an artificial flaw is used as a reflector. These factors include correspondence of reflector dimensions and dynamic range of echo amplitude, representativeness of position, orientation, fracture surface roughness and reproducibility of the artificial reflector both metallografically and echodynamically[1,11].

The results of ultrasonic response versus thermal fatigue loading show how different parts of the crack are opening and closing at different time moments. For example, the corner amplitude decreased during heating and increased during cooling. While the crack tip amplitude increased during heating and decreased during cooling. That is, crack tip amplitude changes were opposite to the corner amplitude.

Amplitude decrease is caused by crack closure and increase by opening of the crack. It is known that the surface breaking part of the crack is closed during heating and opened during cooling as described, e.g., in reference[17]. However, the ultrasonic results of the crack tip amplitude show, that the tip is openend during heating and closed during cooling. This is caused by temperature cycling inducing stress gradients in the specimen. During heating the surface layer of the material is heated up and experiencing increased compressive stresses. At the same time, subsurface parts of the crack are at lower temperature and may be under tensile stress. The increase of crack tip amplitude during heating clearly indicate that the crack tip is opened, i.e. under tensile stress.

The finite element modeling, however, shows different results for the strain variations in the depth of the crack. For both analysed cycles the model shows decreasing strains during heating and increasing strains during cooling at the crack tip. This is explained by the fact that the model was made for solid material and does not take into account the flaw in the material.

Conclusions

The novel artificial flaw production technique is available for different materials including Inconel 600. The technique is applicable to full size mock-ups with challenging multi-material structures. Flaw production does not cause any unwanted alterations and is applied to ready-made, finished surfaces. The produced flaws are realistic thermal fatigue cracks. Cracks are tortuous, tight, narrow and have a small crack tip radius. Hence, the reflection properties of produced cracks are realistic.

Flaws produced with the new technique can be used in NDE training and qualification purposes. The accurate positioning, control of crack size and reproducibility offer an opportunity to have realistic reflectors in testing, training or qualification specimens. The production process does not set any requirements for the specimen and, hence, also specimens with existing flaws can be used.

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