ADVANCED FLAW MANUFACTURING AND CRACK GROWTH CONTROL

M. Kemppainen[1], J. Pitkänen[2], I. Virkkunen[1] and H. Hänninen[3]

[1]Trueflaw Ltd., Tekniikantie 21, P.O.Box 540, FIN-02151, Espoo, Finland
[2]VTT, Kemistintie 3, Espoo, Finland
[3]Helsinki University of Technology, FIN-02015, Espoo, Finland

ABSTRACT. Advanced artificial flaw manufacturing method has become available. The method produces true fatigue cracks, which are representative of most service-induced cracks. These cracks can be used to simulate behaviour of realistic cracks under service conditions. This paper introduces studies of the effects of different thermal loading cycles to crack opening and residual stress state as seen at the surface of the sample and in the ultrasonic signal. In-situ measurements were performed under dynamic thermal fatigue loading of a 20 mm long artificial crack.

INTRODUCTION

An advanced flaw manufacturing method has been developed for crack production to NDT qualification and training purposes. The method is based on thermal fatigue damage mechanism and produces realistic cracks. Single and separate cracks are produced without machining or welding to any shape and size in ready-made components without unwanted changes of the material. Cracks can be produced in the base material or welded areas with accurate control of location, orientation and size. Thermal fatigue damage mechanism allows control of crack characteristics such as surface roughness, opening and residual stresses. [1,2,3]

The challenges in detection and sizing of natural cracks during in-service inspections are related to the differences in the crack characteristics [4,5,6,7]. Opening condition and residual stresses affect the obtained ultrasonic response from corner, specular reflection, and tip diffraction. In service conditions the crack opening and residual stresses are affected by the loading history and can be remarkably changed between successive inspections. This may result even in decreased amplitude height of an actually larger crack [5].

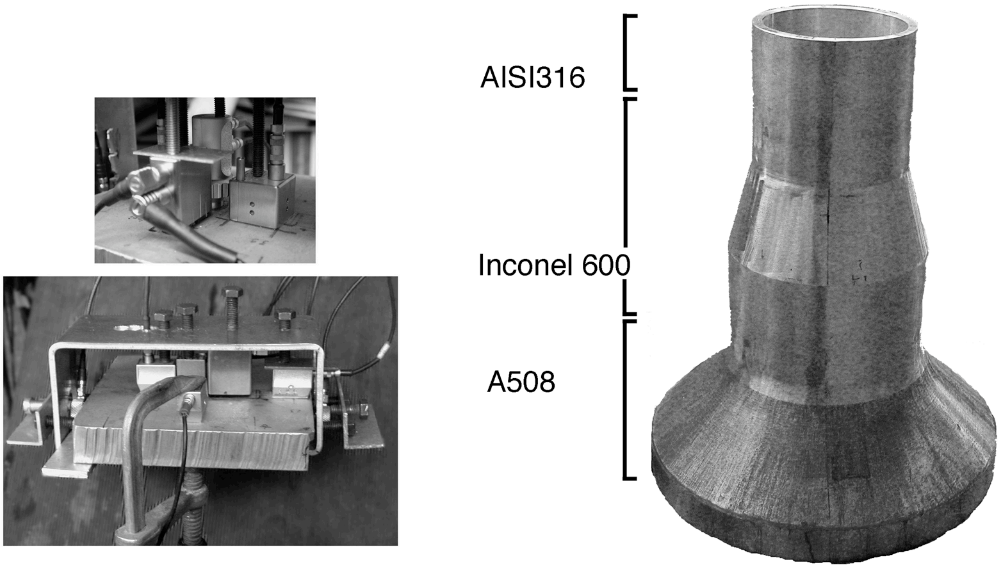
Relationship between the different crack openings, stresses and ultrasonic responses has been studied in this work with realistic thermal fatigue cracks and realistic thermal fatigue loading. Loading was applied by surface temperature cycling of the specimens with different heating and cooling rates and powers.

MATERIALS AND METHODS

Experiments were performed with special thermal fatigue test equipment [8] utilizing high frequency induction heating and water or air spray cooling. Tests were performed with two different specimens: a plate-like sample and a real component (core spray nozzle, safe-end, BWR-type plant). The plate specimen (size 150 x 150 mm, thickness 20 mm) was made of AISI 304 type austenitic stainless steel while the core spray nozzle consisted of three different materials: A508 carbon steel, Inconel 600 and AISI 316 type austenitic stainless steel. There was buttering and 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 steel pipe. Both welds were made with Inconel 182 filler material with Inconel 82 root pass.

Specimens and NDT-setup

The plate sample is visible on the left in Figure 1 and the core-spray nozzle specimen on the right in the same figure. Together 16 probes with two different data collection modes were used with three different fixtures in order to gather the ultrasonic response from the crack under dynamic loading. Figure 1 a) shows two different probe fixtures used in the testing. The selection of the NDT setup is described in more detail in a separate paper of this conference [9].



a) b)

FIGURE 1. Studies were performed with a) a plate sample and b) a core spray nozzle safe-end specimen of a BWR-type nuclear power plant.

A natural thermal fatigue crack was produced in both specimens. The crack in the plate was 20 mm x 7.5 mm (length x depth) (Figure 2) and in the core spray nozzle 15 mm x 5 mm (Figure 3). Crack in the plate was in the base material and the crack in the nozzle was in the heat affected zone of AISI 316 steel pipe. Crack behaviour under thermal fatigue loading was monitored in both specimens ultrasonically and additionally by a digital video camera in the plate specimen. The videotape was used for analyzing the crack opening behaviour during each cycle.

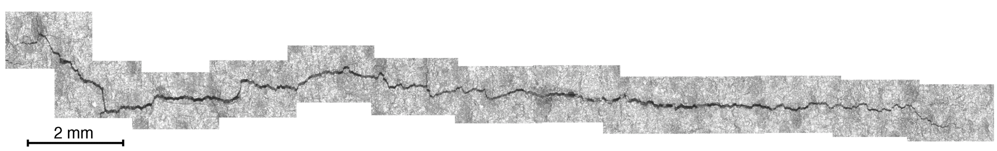


FIGURE 2. The initial condition of the realistic thermal fatigue crack in AISI 304 plate specimen. Crack length is 20 mm and depth 7.5 mm.

FIGURE 3. Dye penetrant indication of the initial condition of the thermal fatigue crack in the HAZ of AISI 316 steel pipe. Crack length is 15 mm and depth 5 mm.

Applied thermal fatigue loading cycles included loading cycles from light to severe. The aim was to produce different temperature gradients in different depths of the material and to study their effect on the crack behaviour. Two loading cycles and NDT response of one ultrasonic probe for both specimens are analysed in this paper. Cycles used for the plate specimen are a fast water-cooled cycle (heating 5 s, cooling 10 s) and a slow air-cooled cycle (heating 5 s, cooling 30 s). The heating power and time were identical for both cycles and the difference was caused by the cooling media and time. Two water-cooled cycles were analysed for the core spray nozzle, a fast cycle (heating 2 s, cooling 4 s) and a slow cycle (heating 5 s, cooling 6.5 s). The heating power and time and cooling time were different for these cycles, but the cooling media was the same. Loading of the crack in the plate sample was monitored with a 45° shear wave probe (4 MHz) and in the nozzle specimen with a 55° shear wave probe (1.5 MHz). Performed studies included also finite-element modelling of the cycle. Some of the obtained modelling results are presented in a separate paper of this conference [10].

RESULTS

Ultrasonic results of plate specimen

The results obtained with the plate specimen show concurrent changes in the ultrasonic response and crack opening behaviour. Figure 4 shows the results for the water-cooled (0.07 Hz) cycle and Figure 5 for the air-cooled (0.03 Hz) cycle. Corner and tip amplitude curves are shown as amplitude variation so, that the maximum amplitude value is set to zero and the others are the real decibel values below that. Thus, the actual amplitude values from the corner and crack tip cannot be directly compared. Corner and tip amplitudes can be compared between two different cycles, because the same reference value was used for both cycles.

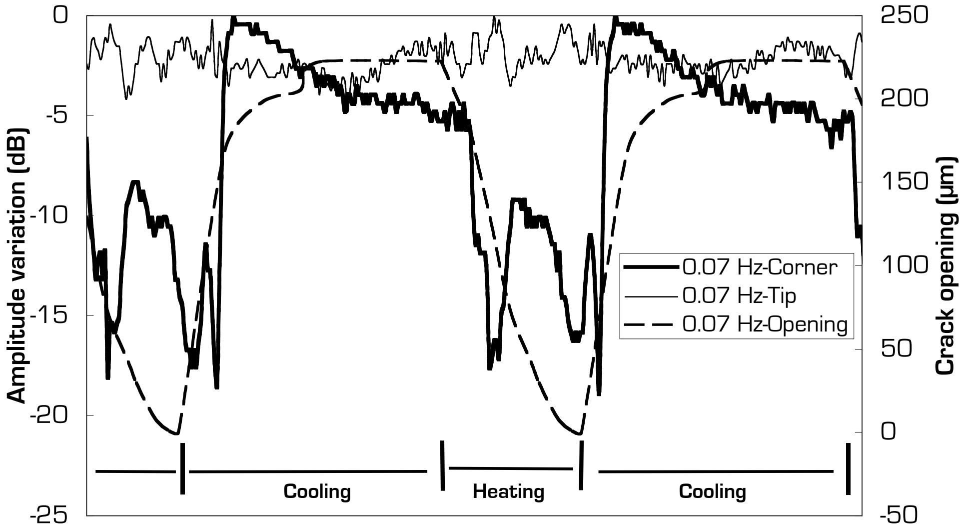


FIGURE 4. Relationship between ultrasonic amplitudes (from corner and tip) and crack opening during the water-cooled thermal fatigue cycle.

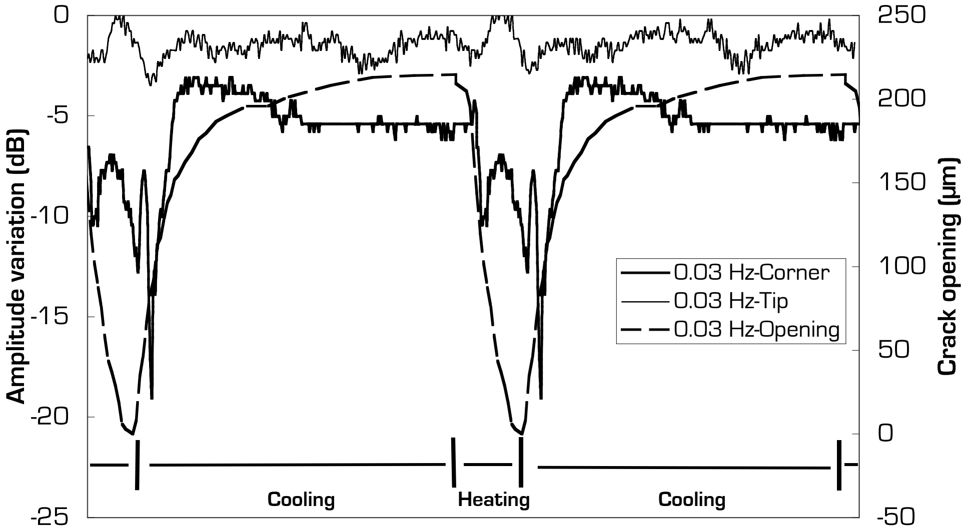


FIGURE 5. Relationship between ultrasonic amplitudes (from corner and tip) and crack opening during the air-cooled thermal fatigue cycle.

Results show, that the minimum corner amplitude of the water- and air-cooled cycles was the same, but there was a 3.1 dB difference in the maximum amplitudes. Both cycles closed the crack totally on the surface during heating and opened it to the maximum width at the end of the cooling.

The faster water-cooled cycle (0.07 Hz) closes the crack at the surface effectively, but at the same time it opens the crack tip (Figure 4). The applied water cooling opens the mouth of the crack very fast and as continued the opening stops to a value of about 223 μm. At the same time when the opening reaches the steady value, the corner amplitude was decreased about 5 dB. Towards the end of cooling the crack tip amplitude begins to increase, indicating an increasing opening of the crack tip. The maximum corner amplitude difference was 18.9 dB with this cycle.

Correspondingly, the slower cycle (0.03 Hz) closes the crack during the heating and the corner amplitude decreases (Figure 5). When compared to the faster cycle, the amplitude decrease is slower indicating difficulties in the closing of the crack. During air cooling the crack opens slowly and finally reaches the maximum opening of about 215 μm. The corner amplitude first increases and then starts to decrease during cooling. Corner amplitude reaches a steady value of about 2.5 dB below its maximum value. The crack tip amplitude has a clear peak during the heating indicating the opening of the tip. The maximum corner amplitude difference was 15.8 dB with this cycle.

Different thermal fatigue cycles left the crack in different conditions. This can be seen in the residual corner amplitudes and the residual crack opening. The residual level of the corner amplitude after specific cycles was compared to the initial, in-advance measured level of the corner amplitude. The residual corner amplitude was –5 dB for the water-cooled cycle and –7.1 dB for the air-cooled cycle. The residual surface opening of the crack was 221 μm for the water-cooled cycle and 249 μm for the air-cooled cycle.

Ultrasonic results of nozzle specimen

The results obtained with the core spray nozzle specimen show concurrent changes in the ultrasonic response and the temperature cycle. Figure 6 shows the results for the faster (0.17 Hz) loading cycle and Figure 7 for the slower (0.09 Hz) loading cycle. These figures show the corner and tip amplitude curves as arbitrary amplitudes and both have different amplification. Thus, corner and tip amplitudes of a specific cycle cannot be compared. However, corner and tip amplitudes can be compared between two different thermal cycles.

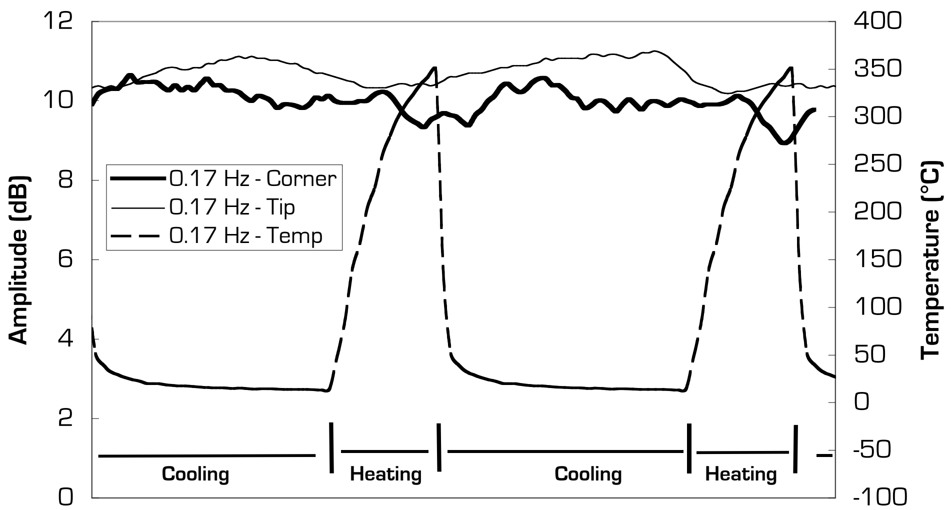


FIGURE 6. Relationship between ultrasonic amplitudes (from corner and tip) and applied 0.17 Hz thermal fatigue loading cycle of the nozzle specimen.

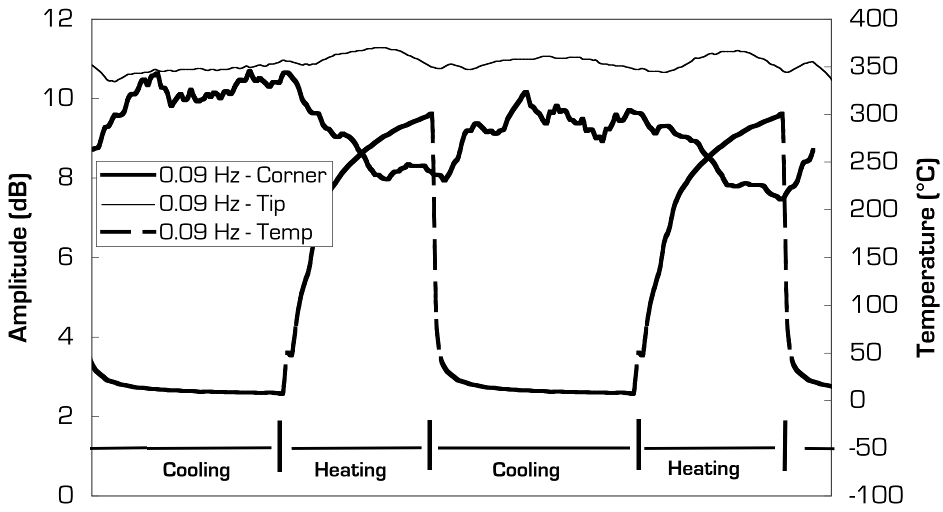


FIGURE 7. Relationship between ultrasonic amplitudes (from corner and tip) and applied 0.09 Hz thermal fatigue loading cycle of the nozzle specimen.

During the faster cycle (0.17 Hz), the corner amplitude has its maximum value in the beginning of the cooling and minimum in the end of heating. The difference between them is about 1.5 dB. The increase of the tip amplitude indicates that the highest temperature is effective at the crack tip 2-3 seconds later than at the surface. With the slower cycle the corner amplitude difference is about 2.5 dB. With the slower cycle, the crack tip amplitude increases during the heating, indicating the opening of the crack tip. The maximum difference of tip amplitude is 1.1 dB for the faster cycle and 0.9 dB for the slower cycle.

<u>Destructive results after TF vs. UT measurements</u>

The plate sample was destructively tested after the tests, while the crack in the nozzle was not opened. The non-destructive measurements of the crack in the plate sample resulted in 8.0 mm depth with RMS-value of 0.6 mm. The true size of the crack was 7.7 mm. The crack was cut in two pieces about 0.5 mm away from the deepest location. The semi-elliptical shape of the fracture surface and the cross-section of the crack are shown in Figure 8 a) and b), respectively.

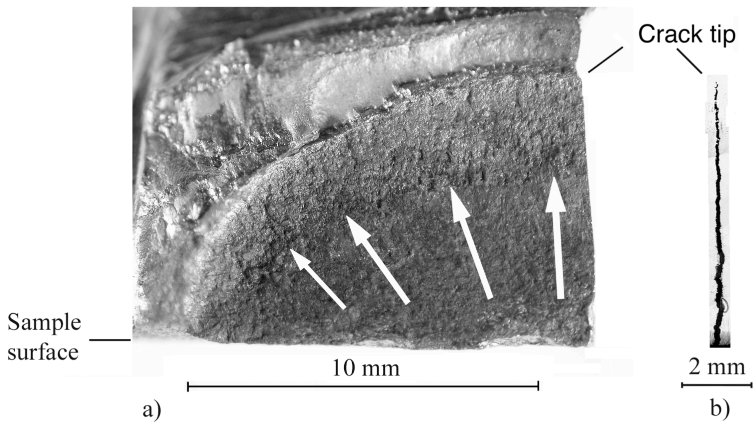


FIGURE 8. Results of destructive testing: a) semi-elliptical fracture surface of the crack and b) cross-section of the crack.

DISCUSSION

During thermal fatigue loading the heating closes the crack and cooling opens it. This is seen in the obtained corner amplitude as decrease during closing and increase during opening of the crack. Different loading cycles have different effect on the crack opening and on the ultrasonic response obtained from the surface and subsurface parts of the crack.

The faster cooling opens the crack mouth more than the slower cooling. The corner amplitude decrease during heating is slower with the slower cycle even though the heating parameters were similar. Amplitude minimum is reached only during the first 1-2 seconds of the air cooling. In a dynamical situation, the slower cycle show higher values of crack tip amplitudes. These indicate, that loading with the slower, air-cooled cycle opens the crack more in the subsurface parts and near the tip than with the faster, water-cooled cycle. The obtained residual amplitudes show, that when the sample is cooled to the ambient temperature, the corner amplitude is lower after the slower air-cooled cycle. However, the measured residual opening shows contrary results, the air-cooled cycle leaving the crack mouth more open. This results in a conclusion, that the dynamical thermal fatigue loading stores heat in the sample, which closes the crack, but when the sample is totally cooled down, the crack is opened due to thermal contraction. As unloaded the thermal fatigue crack opening is small and ultrasonic amplitudes are low. Thus, the crack is sensitive to changes of stress and already minor loadings may change its ultrasonic response. Other authors [5] have also shown a similar tendency of the thermal fatigue cracks.

From the results it can be seen that the corner amplitude has its minimum until the cooling has started. This indicates that during the heating the surface layer is under compression and the crack is closed. When the cooling is started the crack opens at the surface and this allows crack closure in the subsurface parts of the crack. This effect is pronounced with the less effective air cooling, where the subsurface material is not cooled down as fast and it stays longer under compressive stress. The corner amplitude height is a reflection of a bigger area where the outer surface layer plays minor role. This explains the hump of the amplitude curve during the heating phase as during the heating the compressed surface layer opens the subsurface part of the crack, giving raise to the corner amplitude.

Results show, additionally, that during the cooling the crack first opens fast and wide and the corner amplitude reaches its maximum. At the same time, the deeper parts of the crack are still heated up and experiencing compressive stresses. With continued cooling the crack tip region is also cooled down and experiencing tensile stresses, which allow closure of the surface part of the crack. This is seen as a decreased value of the corner amplitude. Certain cycles show a clear steady plateau value of the corner amplitude indicating stabilisation of the opening at the surface and near surface parts of the crack.

The amplitude differences during the loading are related to the stress variations. These are different with the cracks in the plate and nozzle samples. The smaller crack in the nozzle sample shows smaller amplitude differences than the bigger crack in the plate. This is related to the different loadings and crack sizes as mentioned in the literature [6].

CONCLUSIONS

The results of performed studies show, that during dynamic loading different parts of the crack experience different opening and closing conditions. Depending on the loading, the surface layer, crack mouth, and subsurface parts of the crack may simultaneously be in the opposite phases. That is, the crack maybe closed at the surface but at the same time has its maximum opening at the tip. Similar thermal fatigue loading history can appear in service conditions affecting the residual state of the crack opening and stresses. If the crack is closed at the surface, the detection performance is decreased. Respectively, if the crack tip is tightly closed, the sizing performance is decreased. The used novel flaw production method provides a possibility to use realistic cracks in the NDT qualification and to control the ultrasonic response of the produced flaw. As shown, the method can be used to study interaction between loading and ultrasonic response of realistic cracks with simple samples and full-scale mock-ups.

ACKNOWLEDGEMENTS

This work has been performed under a research project funded by Trueflaw Ltd., National Technology Agent Finland, Pacific Northwest National Laboratories (USA), Fortum Nuclear Services Ltd, and Teollisuuden Voima Oy.

REFERENCES

1. Kemppainen, M., Virkkunen, I, Pitkänen, J., Paussu, R. and Hänninen, H., "Realistic Cracks for In-Service Inspection Qualification Mock-ups," in *Proceedings of the 8th European Conference on Non-destructive Testing*, Barcelona, Spain, 2002.
2. Kemppainen, M., Virkkunen, I, Pitkänen, J., Paussu, R. and Hänninen, H., "Comparison of Realistic Artificial Cracks and In-service Cracks," in *Proceedings of the 8th European Conference on Non-destructive Testing*, Barcelona, Spain, 2002.
3. Kemppainen, M., Virkkunen, I, Pitkänen, J., Paussu, R. and Hänninen, H., *J. of Nuclear Eng. and Des.* **224**, 105-117 (2003).
4. Wirdelius, H. and Österberg, E., *SKI Report 00:42*, Sweden, 2000, 50 p.
5. Becker, F.L., Doctor, S.R., Heasler, P.G., Morris, C.J., Pitman, S.G., Selby, G.P. and Simonen, F.A., *NUREG/CR-1696 PNL-3469* **1**, 1981, 170 p.
6. Ibrahim, S.I. and Whittaker, V.N., *British J. of NDT*, 233-240 (1981).
7. Gauthier, V., "Thermal Fatigue Cracking of Safety Injection System Pipes Non Destructive Testing Inspections Feedback," *Proc. of NEA/CSNI Specialists' Meeting on: Experiences with Thermal Fatigue in LWR Piping Caused by Mixing and Stratification*, Paris, 1998, pp. 436-453.
8. Kemppainen, M., *Design and Implementation of Thermal Fatigue Testing Facility, Report MTR 1/97,* Helsinki University of Technology, Espoo, 121 p.
9. Pitkänen, J., Kemppainen, M. and Virkkunen, I, "Ultrasonic Study of Crack under Dynamic Thermal Load," in *Proc. of Review of Progress in Quantitative Nondestructive Evaluation,* Melville, New York, 2003. To be published.
10. Virkkunen, I., Kemppainen, M., Pitkänen, J. and Hänninen, H., "Effect of Thermal Stresses along Crack Surface on Ultrasonic Response," in *Proc. of Review of Progress in Quantitative Nondestructive Evaluation,* Melville, New York, 2003. To be published.