Effect of Crack Opening on UT Response

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Abstract. Crack opening is one of the key parameters affecting the UT response of the crack. Tight cracks with small opening tend to be more difficult to detect and characterize than cracks that have wider opening. In particular, the opening of crack tip has marked effect on the crack tip diffraction signal often used for crack sizing.

Service-induced cracks found exhibit wide variety of different openings. The opening is affected by the service loads and crack growth mechanism. In general, cracks grown by high loads tend to have wider opening than cracks produced by small loads. Furthermore, residual stresses may alter the opening.

In order to simulate the wide variety of openings of the service-induced cracks, a novel method for producing artificial flaws with controlled opening is presented. A set of similar realistic flaws was produced by controlled thermal fatigue loading. The as-produced "baseline" UT response of these cracks was recorded with phased array technique using shear waves. Some of the flaws were then subjected to different loading sequences to manipulate their opening. The UT response of the modified cracks was then recorded and compared to that of the baseline response. The crack tip signals were measured also with longitudinal waves before cutting the specimen. Finally, the sample was carefully sectioned to reveal the opening of the produced flaws and the effect of crack opening to the UT response is analyzed.

1 Introduction

Trueflaw Ltd. manufactures artificial cracks for NDT training and qualification purposes. The cracks are produced directly (not weld-implanted) to ready-made samples using local thermal fatigue loading. The thermal fatigue loading is applied using successive high frequency induction heating and water-cooling cycles. No artificial initiators are used and no mechanical contact to the loaded sample is required. Consequently, the process does not damage or disturb the surface of the sample and the original surface roughness and features are retained.

The used temperature cycles are chosen for each material to be such, that no microstructural alterations are caused by the process. For example, in case of the Inconel alloys (Inconel 600, 690, 182, 82, 152, 52 and the like), the highest temperature used during loading is 500°C. Also, the time spent around the highest temperature is short, typically below 10% of the total cycling time.

In NDE qualification, the relevance and representativeness of used artificial flaws is very important. The artificial cracks or flaws used in qualification or training must give a relevant NDE-response. This is achieved by using flaws similar to the actual service-induced cracks or postulated cracks. More precisely, the used flaws must be similar in terms of some significant parameters, that control the obtained NDE response. One of those important parameters is the crack opening. Tight cracks with small opening tend to be more difficult to detect and characterize than cracks that have wider opening. In particular, the opening of crack tip has marked effect on the crack tip diffraction signal often used for crack sizing.

Natural cracks found during in-service inspections exhibit wide variety of different openings. The opening is affected by the service loads and crack growth mechanism. In general, cracks grown by high loads tend to have wider opening than cracks produced by small loads. Furthermore, residual stresses, if present during inspection, may alter the effective opening seen by the inspector.

1.1 Typical crack opening values in service

Natural cracks exhibit a wide variety of different opening characteristics. This results from the wide variety of different loading conditions and mechanisms that have induced these cracks, as well as the material properties of the material in question.

Wåle [1] has measured crack mouth and tip openings from numerous service-induced cracks. These values are summarized in Figures 1 and 2, respectively. It should be noted that bigger cracks with wider opening are more likely to be found. Consequently, the data is likely to be biased and the population shows too great opening values.

Crack opening values for different artificial flaw manufacturing techniques are even more difficult to find from the literature than that of natural, service-induced flaws. Crack opening values can be measured from Lemaitre et al. [2]. These cracks represent values from numerous flaw manufactures using weld implanting techinques and solidification cracks. This data is summarized in Figures 1 and 2. When reading this data, it should be noted, that measurement of crack opening values from the images was rather difficult and the accuracy of these numbers is limited.

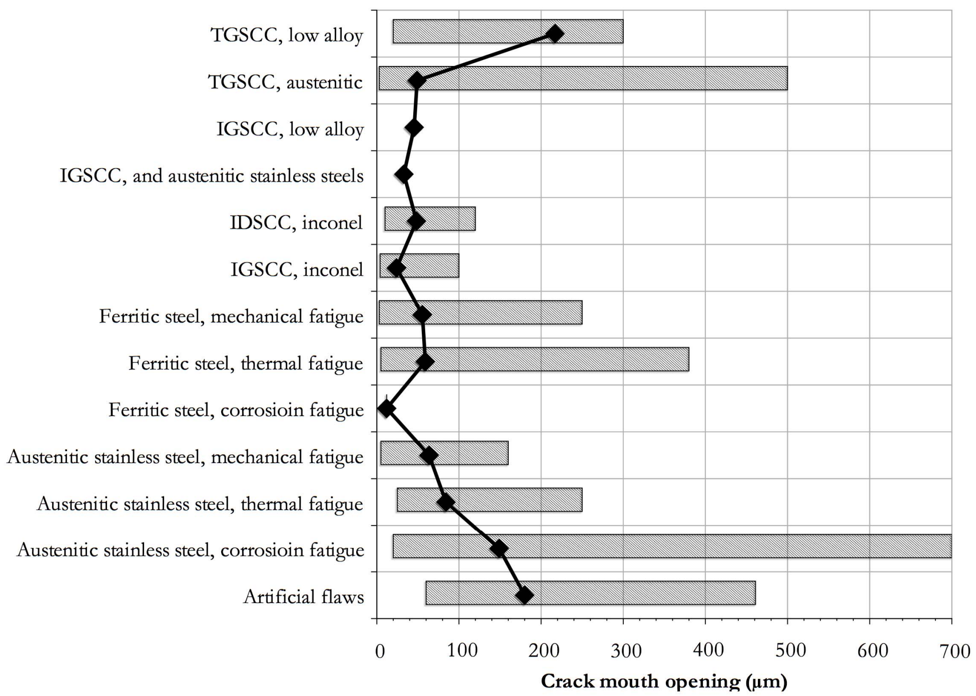

Figure 1. Crack mouth opening (CMO) values of service-induced cracks and artificial cracks, in µm. The bars show the range between minimum and maximum values reported. The dots connected by line show the average value reported. Note, that the average value tends to be closer to minimum than maximum. Values for service-induced flaws were taken from [1]. Values for artificial flaws were measured from [2].

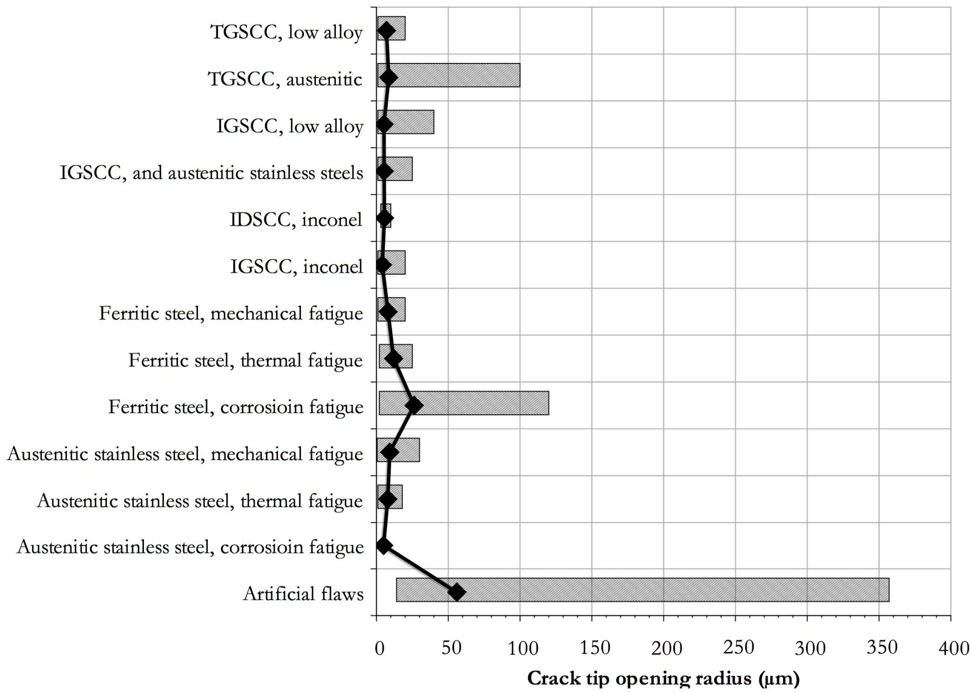

Figure 2. Crack tip opening radius (CTO) values of service-induced cracks and artificial cracks, in µm. The bars show the range between minimum and maximum values reported. The dots connected by line show the average value reported. Note, that the average value tends to be closer to minimum than maximum. Values for service-induced flaws were taken from [1]. Values for artificial flaws were measured from [2].

1.2 Aim of the study

In order to simulate the wide variety of openings of service-induced cracks, a method for producing artificial flaws with controlled opening is desirable. Trueflaw cracks are produced directly to the specimen with applied thermal fatigue loading. Since the crack opening is affected by the loads used to produce the crack, this method also offers the possibility to alter the opening of produced flaws.

The aim of present study was to study the effect of crack opening to ultrasonic inspection to confirm the importance of this parameter to inspection. The possibility of producing cracks with controlled opening was applied and the controllability of the crack opening studied.

2 Materials and methods

To study the effect of crack opening to ultrasonic response and the performance of the Trueflaw crack manufacturing technology in controlling the crack opening, a test sample was manufactured with 5 identical cracks. The sample was prepared from 25 mm thick AISI 304 -type stainless steel and had dimensions of 150 by 150 mm.

After manufacturing, a baseline NDT-responses of the cracks were recorded, as detailed in paragraph 2.1. After first inspection, some of the cracks were subjected to additional loading designed to increase the crack opening. Three different loadings were used to achieve different opening conditions. The loading was not sufficient to alter the size of the cracks; only the opening was altered. In succession, the NDT inspection was repeated in order to reveal the difference in UT-response caused by the changed opening. Finally, the sample was destructively studied, as detailed in paragraph 2.2, to reveal the true crack opening of the cracks. The detailed information on the flaws manufactured are presented in Table 1. Unfortunately, the surface of the chosen sample had deep scratches, which initiated some secondary cracks during loading. Consequently, the NDT-response shows some disturbances caused by these cracks.

Table 1. The flaws manufactured for the study.

Number	Length (l)	Depth (a)	Note
1	9.6	3.8	Opening increased ; loading 1
2	9.8	3.3	Opening increased ; loading 2
3	9.5	3.5	Opening increased ; loading 3
4	10.2	2.8	(deepest point destroyed during sample preparation)
5	10.4	3.2	

2.1 NDT-inspection

The UT-measurements were carried out with two phased array systems: Omniscan (RD Tech) with 16 elements 5MHz angle probe for shear waves and MultiX (M2M) with linear 64 element 5MHz probe with 1 mm pitch (Imasonic). Omniscan was calibrated for the measurement using notches of different sizes. The MultiX was calibrated using one notch to produce high focus to the area of interest. For the measurement 20 elements were used to avoid too high focusing. The passive aperture was 15 mm. The width of the notch was 1 mm in 20 mm depth.

2.2 Destructive analysis

The specimen was first cut to 5 pieces each containing a single crack with an abrasive cutter. Then, each crack was sectioned by a precicion cutter (Struers Accutom-50). The location of sectioning was carefully selected to be near, but not at, the deepest location of the crack. Next, a metallographic sample was prepared from the piece still containing the deepest location of the crack. The sample was first grinded with SiC-papers and then polished with 1 µm diamond paste. Special care was taken in sample preparation to avoid any changes to crack opening. In particular, the time used in diamond polishing was minimized, in order to minimize increase of opening caused by rounding of the crack edges. Also, no etching was applied for the same reason. For each crack, the metallographic sample was prepared and photographed twice, to ensure that the measured values are not affected by variation in the sample preparation. After preparation, the samples were photographed by an inverted (metal) microscope.

The crack tip opening was measured from digital micrographs by fitting a measurement circle to the tip location. Radius of this circle was reported. The greatest available magnification was used to obtain the best possible accuracy in tip measurements. However, the opening of some flaws was so small, that it could not be reliably measured with magnification available in optical microscopy. The crack opening at the crack mouth and along the crack depth was measured from the digital micrographs by custom made image analysis tool.

3 Results

3.1 Destructive analysis

Figure 3 shows the crack opening measured from different samples. The measured crack tip opening and crack mouth opening values are summarized in Table 2.

Table 2. Crack tip opening (CTO) and crack mouth opening (CMO) values measured (in µm). For cracks 1, 4 and 5 two CMO values are reported; these values correspond to opening before and after the opening treatment, respectively.

Number	CTO	CMO
1	1.4	110 / 160
2	0.4	92 / 96
3	0.2	110 / 145
4	<0.05	77
5	0.1	100

3.2 NDT analysis

Figures 4 shows characteristic NDT-response of each of the cracks before and after the altering treatment. The sample was also inspected with a phased array probe (linear array probe with 64 elements from which were used 20 elements, pitch was 1 mm) set-up after the alteration of the opening. The results of this inspection are shown in Figure 5.

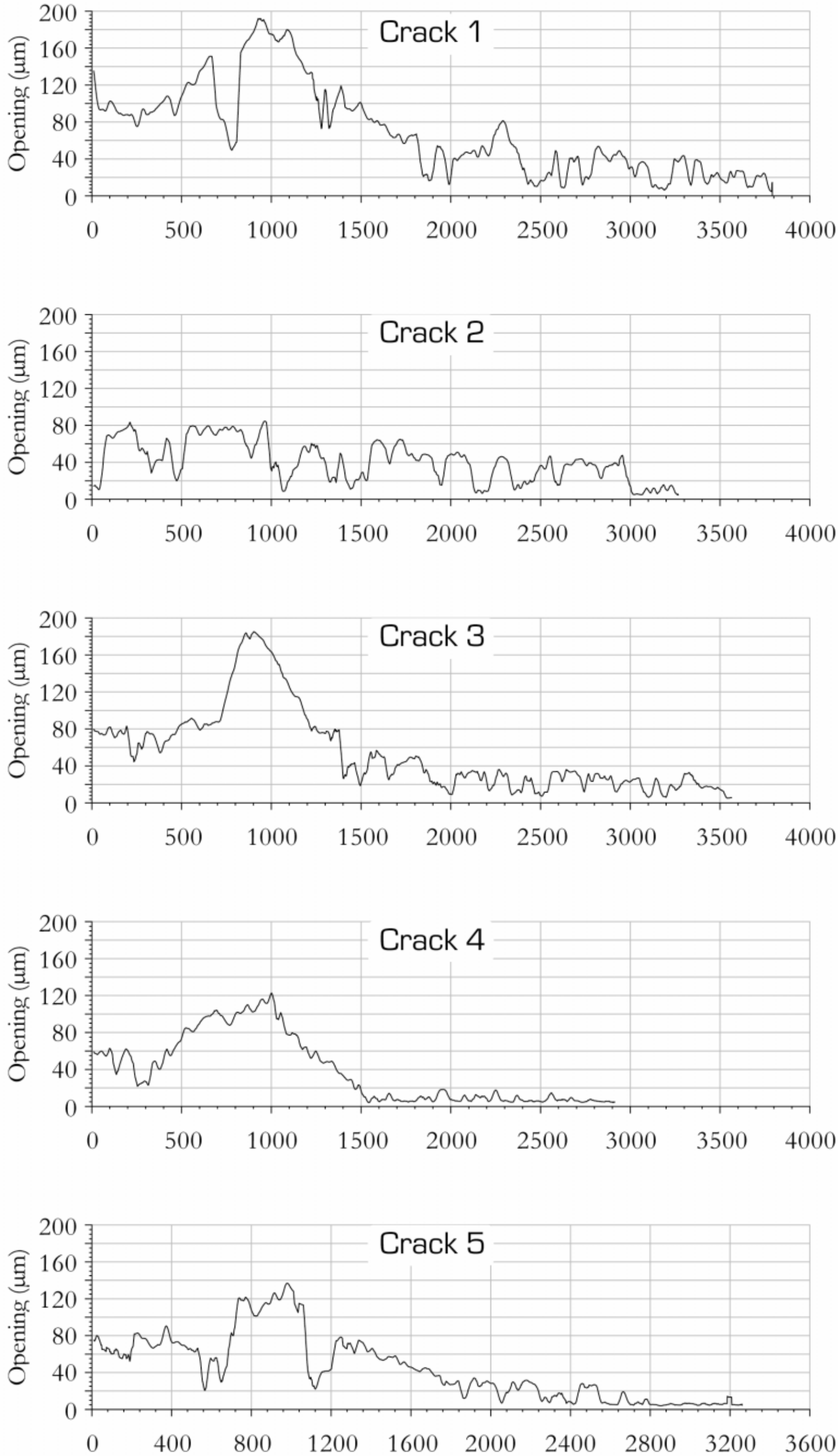

Figure 3. Measured crack opening as a function of depth (in µm).

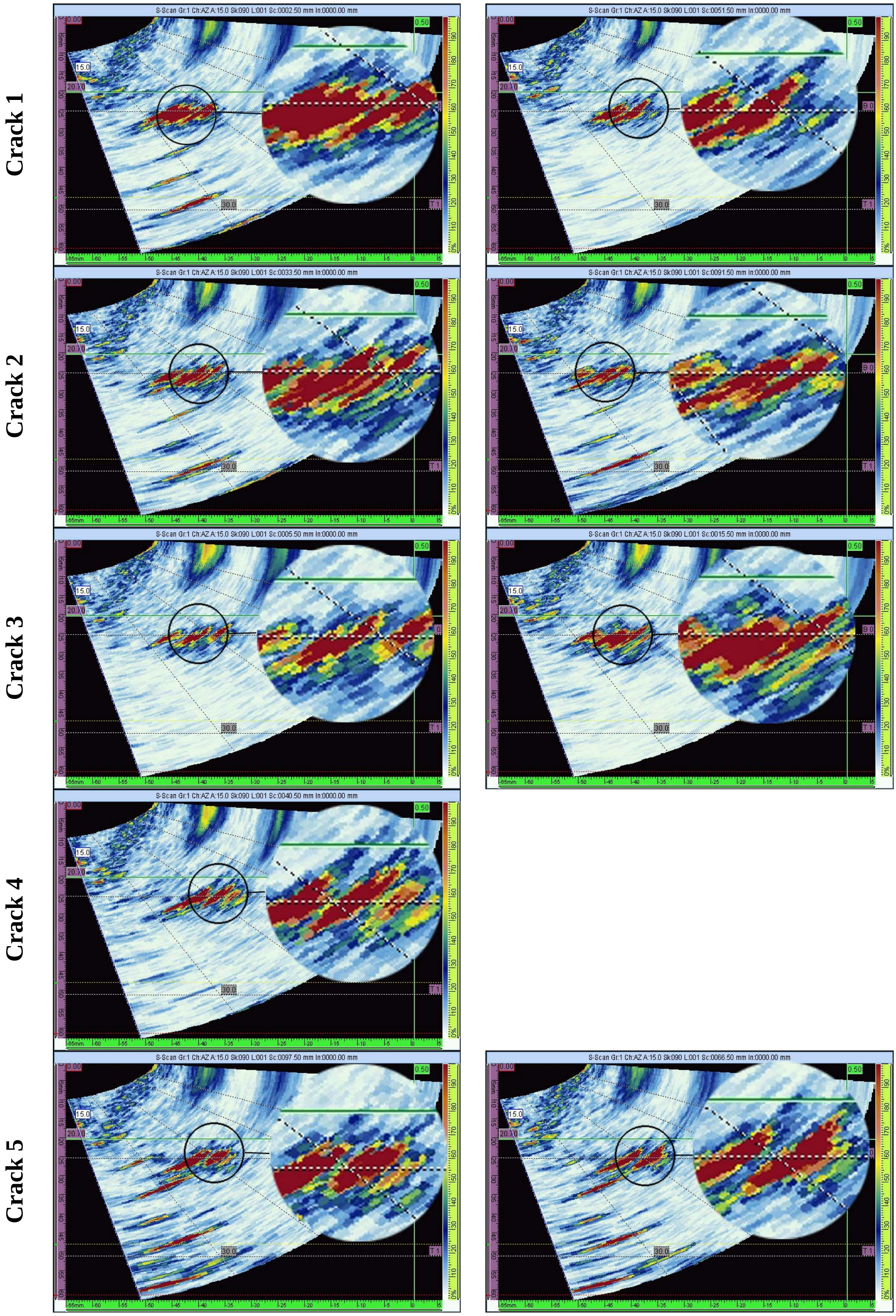

Figure 4. Phased array inspection results before (left side) and after (right side) modification of the flaw opening. Crack 5 did not experience any opening treatment. Thus, the differences in images for Crack 5 reflect the differences in inspection.

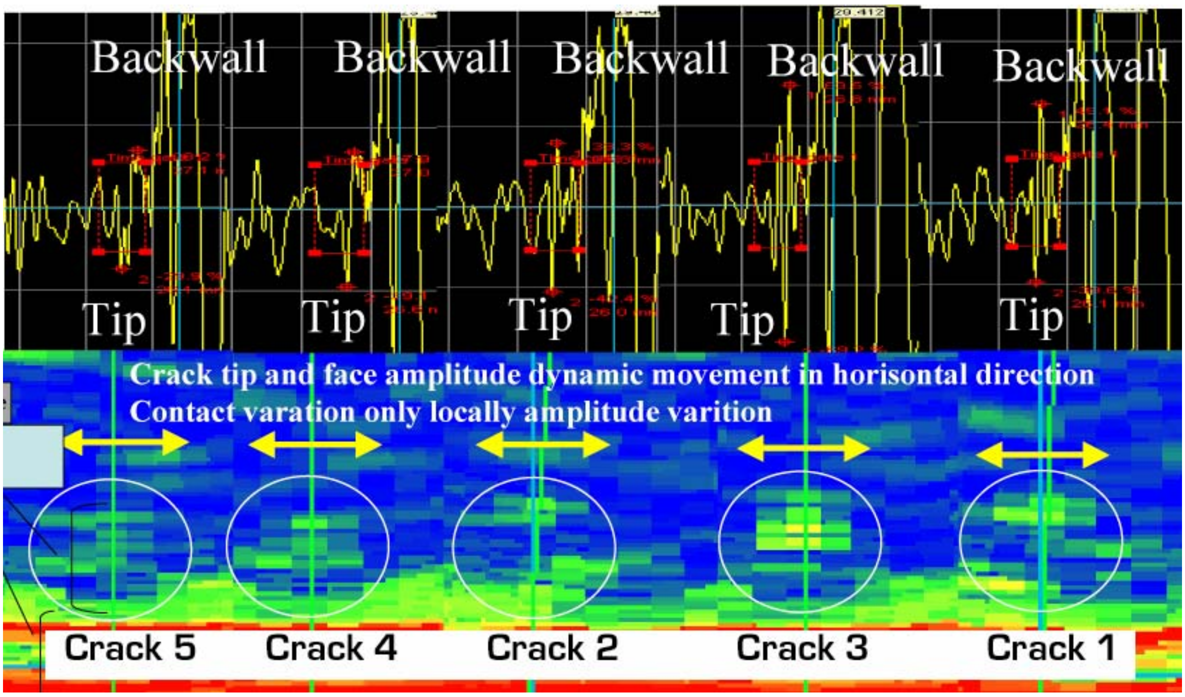

Figure 5. Phased array measurement results by focusing 5 MHz probe with 20 elements in the depth of 20 mm.

4 Discussion

Table 2 shows, that the crack tip opening in Trueflaw cracks after production was rather small. The small crack opening typical to the cracks is a result of the crack growth process driven by the high crack tip stress concentration. This feature is shared by all natural cracks that grow due to the crack tip stress concentration, including thermal fatigue cracks, fatigue cracks and stress corrosion cracks. A blunt crack does not have the required stress concentration for crack growth and thus it would not grow. On the other hand, crack-like flaws that do not require the high crack tip stress concentration for growth, e.g. solidification cracks, do not necessarily show as small crack opening or as sharp tip.

The crack opening increases with increasing loading due to crack tip blunting. The Trueflaw artificial crack production method is an accelerated process. Whereas in the actual power plants, when cracks appear, they typically form after years of service, the production of artificial thermal fatigue cracks only takes hours or days. This acceleration is achieved by using loads that exceed the service loads and higher frequency of the cyclic loading. Due to the greater loads, the crack opening in Trueflaw cracks is expected to be similar or a little greater than in actual service-induced cracks. However, most of the acceleration is gained during the initiation phase of the crack, which does not affect the crack opening. Consequently, it is expected that the difference in opening of Trueflaw cracks and real service-induced cracks is minimal.

The values shown in Table 2 can be directly compared with the values shown in Figure 1 and 2. This comparison shows, that the initial condition of Trueflaw cracks is similar to many service-induced cracks. With the alteration in opening, the cracks can be adjusted to represent wider variety of service-induced cracks. However, at least corrosion fatigue cracks exhibit so great crack tip openings, that even in the altered condition, Trueflaw cracks remain much tighter than those cracks.

The crack opening through the whole length of the crack can be adjusted by applying different thermal loads. Comparison of different cracks in Figure 3 and Table 2 show that the crack opening, and especially the important crack tip opening, can be changed markedly after flaw production. The crack tip radius shows increase by factor of 10. Figure 3 shows, that the crack opening is altered throughout the crack length.

Also the NDT-results presented in Figure 4 show significant difference between the different cracks. In particular, the crack tip amplitudes show clear increase with increasing crack tip blunting.

5 Conclusions

The crack opening of Trueflaw cracks is expected to be similar or slightly greater than opening of actual service-induced cracks. This view is also supported by the comparison with the data available in the literature for natural cracks.

The typical crack opening values of artificial cracks produced by other means than Trueflaw technique is clearly bigger than that of most types of service-induced natural cracks. Thus, if crack opening is considered to be a significant factor for the inspection of NDE method in question, artificial flaws with big openings can not be recommended for these flaw types.

The crack tip sharpness of Trueflaw cracks is considered similar to service-induced cracks. These features are expected to be shared by all types of cracks, that grow due to the crack tip stress concentration, including fatigue cracks and stress corrosion cracks.

The opening of existing Trueflaw cracks can be altered to have bigger values, if so desired. The increase of opening changes the ultrasonic response of the cracks.

6 References

[1] Wåle, J. & Ekström, P. 1995. Crack Characterisation for In-Service Inspection Planning. SKI-project 14.4-940389, SAQ/FoU report 95/07, SAQ Kontroll Ab, Stockholm, Swerige.

[2] Lemaitre, P., Iacono, I. & Vergucht, P. (eds.) 1999. Results of the Destructive Examination of the ENIQ Pilot Study: Defect Catalogue. ENIQ Report 19, EUR 19024 EN, JRC Petten, The Netherlands.