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RELIABILITY CONSIDERATIONS FOR ULTRASONIC TESTING AT CRACK FIELDS IN LARGE FORGINGS

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ABSTRACT

Hydrogen flaking may occur in large forgings, if the chemical composition of a component meets unfavorable manufacturing conditions. Crack fields due to hydrogen flaking were for example found during ultrasonic inspections in two Belgian reactor pressure vessels in 2012. This led to intensified research with the focus on advanced approaches for detection and assessment of crack fields.

In practice, ultrasonic testing often is the only possible nondestructive testing technique to detect and size flaws in the volume of large forgings. The accuracy of the sizing of defects depends on the interaction of used ultrasonic transducer, material, defect orientation, and sound path. The influence of the focusing of the sound beam is topic of the investigations shown in the following.

Ultrasonic experiments with different commonly used ultrasonic transducers were applied to large test blocks with hydrogen flakes. Advanced ultrasonic testing techniques using conventional phased array and dual matrix arrays were additionally used. Sound field simulations with CIVA complete the investigations.

Sizing of flaws is commonly done by the 6dB drop method. The limits of the ultrasonic indication are set where the maximum amplitude drops by 6dB. The size of the indication is often referred to as size of the flaw. It is common knowledge that sizing of cracks lying parallel to the surface by this method overestimates flaws when they are smaller than the sound beam. The sound beam is narrowest in the focus area of the ultrasonic probe and widens with depth. Thus, the sizing gets more inaccurate if the flaws lie deeper in the test block. In this paper a comparison was done between indications sized with ultrasonic testing and indications sized with magnetic particle testing and radiographic testing. In the last step approaches to increase the focusing of ultrasonic transducers were performed in simulation and experiment.

INTRODUCTION

A high amount of ultrasonic indications were found during in-service inspections in the reactor pressure vessels (RPV) of the units Doel 3 and Tihange 2 in nuclear power plants in Belgium. These indications were subject of different investigations in the following. De Bruycker et al. (2016) showed that the hydrogen flakes will not lead to unexpected behavior under irradiation. Chaouadi et al. (2016) concluded that the fracture toughness of the material is not reduced by hydrogen flakes. Structural integrity assessment was carried out by Lacroix and Dulieu (2016) according to the ASME XI and adapted to the indications found in the RPV. The fitness for service could be confirmed and led to the restart of the units in November 2015. For further insight, a large set of material tests were carried out to create an RT_{NDT} trend curve for structural integrity assessment by Gérard et al. (2016). This curve was used for structural integrity assessment performed by Dulieu and Lacroix (2016) and marked the flaws in the reactor pressure vessels as harmless.

The safety evaluation by Roussel (2016) also led to the conclusion that the impact of hydrogen flaking is acceptable for the serviceability of the RPV during normal, abnormal and accident service conditions. However, research is ongoing with the aim to improve the current assessment models (Gauder 2018).

The initial inspections were done by ultrasonic testing (UT). Thus, UT was also a matter of investigations and UT results were evaluated by Moussebois and Ancrenaz (2016) at large test blocks from steam generator cells containing hydrogen flaking.

UT takes place repeatedly at the Doel 3 and Tihange 2 RPV to monitor changes in the indications patterns that may be caused by crack growth. Especially the formation of connections of different cracks of the crack field should be excluded. UT was performed in the RPV of Doel and Tihange in 2015, 2017 and 2019/2020 (see AFCN reports) and no change in the indication pattern was visible. Thus, it is concluded with a high reliability that no crack growth takes place during operation.

It is necessary to evaluate the reliability of the used NDE technique for a safe assessment of a component. The reliability of NDE is often described using the probability of detection (POD). POD-curves can be derived by statistical methods from experimental data (Gandossi 2010). The POD curve shows the probability to detect a flaw for each given size. The curve has a certain S-shape and the reliability of the NDE technique is higher, the steeper the incline of the curve is. The experimental investigation of a POD-curve requires a certain amount of measurement, which must be independent from each other. Former investigations led to the conclusion, that the independency of indications is not necessarily given in a crack field (Juengert 2021). Thus, investigations at crack fields, which generally deliver a high amount of indications cannot be easily transferred to POD curves.

However, the probability to detect a flaw is only one part of the reliability of an NDE technique. The ability to do a reliable sizing of indications is crucial for the assessment of components, as the flaw size is relevant to the life time. Sizing of ultrasonic indications in general is done using the 6dB drop technique, which is described in Appendix D of DIN EN ISO 16827 (2014) . This technique tends to overestimate flaws when the sound paths are long, which was also mentioned by Moussebois and Ancrenaz (2016). An overestimation of the indications leads to a more conservative assessment and does not bear any safety risks. However, the investigation of the inaccuracy will lead to a more realistic assessment. The accuracy of sizing of hydrogen flakes is the topic of this paper.

EXPERIMENTS

The aim of the investigations shown in this paper, was to quantify the accuracy of sizing for ultrasonic inspections at tests block containing crack fields caused by hydrogen flaking. The test blocks were manufactured in a research project for Component Safety in Germany in the 1980s (see MPA FKS). A lower bound melt of a reactor pressure vessel steel was used to cast and forge a slab. The chemical composition and the cooling conditions led to building of hydrogen flakes in the slab. Many observations and investigations were done at this slab, but some parts of the slab are still present at the MPA Stuttgart. These test blocks were used for ultrasonic testing and several test setups were applied (Juengert 2018). It showed that the dataset could not be used for POD calculation (Juengert 2021), but a series of observations concerning the accuracy of sizing, sometimes referred to the probability of sizing, could be made.

Two different test blocks were used for the investigations. The sizes are listed in Table *1*. Both test blocks contained a crack field caused by hydrogen flaking. Test block TK1 was afterwards used as material for test specimen for destructive tests. Three slices of the TK1 were investigated further with NDE. They are labeled ABA, ABB and ABC as shown in Figure 1.

Table 1: Size of test blocks

Test block	**TK1**	**TK2**
Length [mm]	375	360
Width [mm]	233	258
Height [mm]	773	790

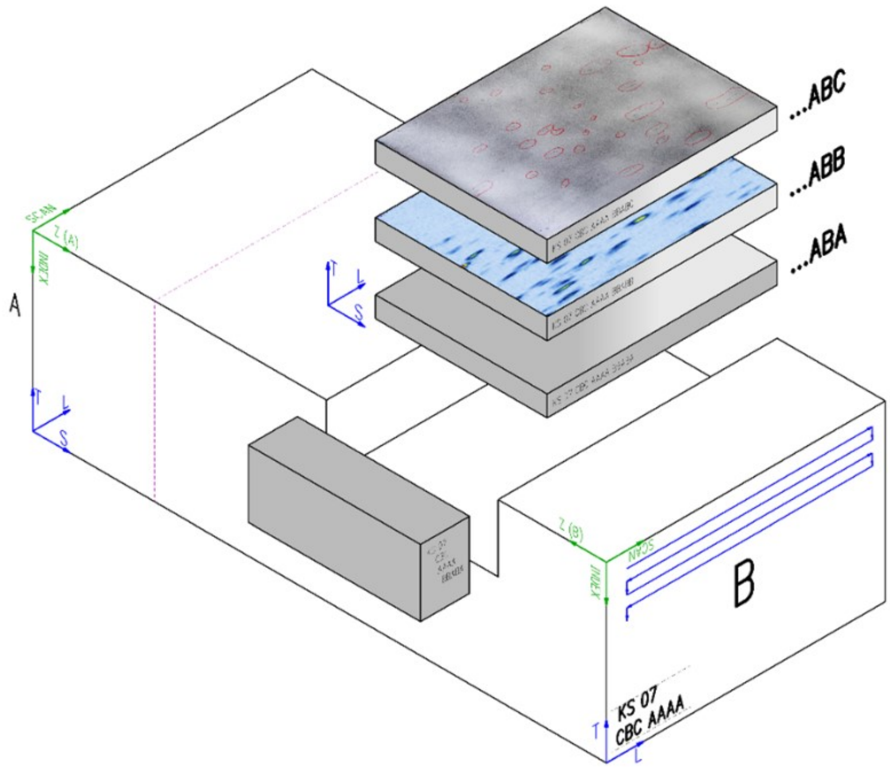

Figure 1: Test block TK1 with cut slices

Ultrasonic Testing

Ultrasonic testing was performed at the test blocks TK1 and TK2 using normal single element probes as well as normal linear array probes from the faces A and B marked in Figure *1*. The probes are listed in Table 2. The use of higher frequencies was possible at the TK1. The microstructure of TK2 showed a higher attenuation and the use of lower frequencies was required.

Table 2: Used ultrasound transducers for the investigation at test blocks TK1 and TK2

Label	Frequency [MHz]	Used at TK1	Used at TK2	type
B2SN	2	-	+	Single element
B4SN	4	+	-	Single element
DMA	2,25	-	+	Matrix array
3L64	3,5	-	+	Linear array
5L64	5	+	-	Linear array

Mechanized UT was performed from the faces A and B of the test blocks. The results from UT using single element normal probes are shown in Figure 2. The crack field in TK1 was located in the middle of the front half of the test block. In test block TK2 the crack field covers the front corner.

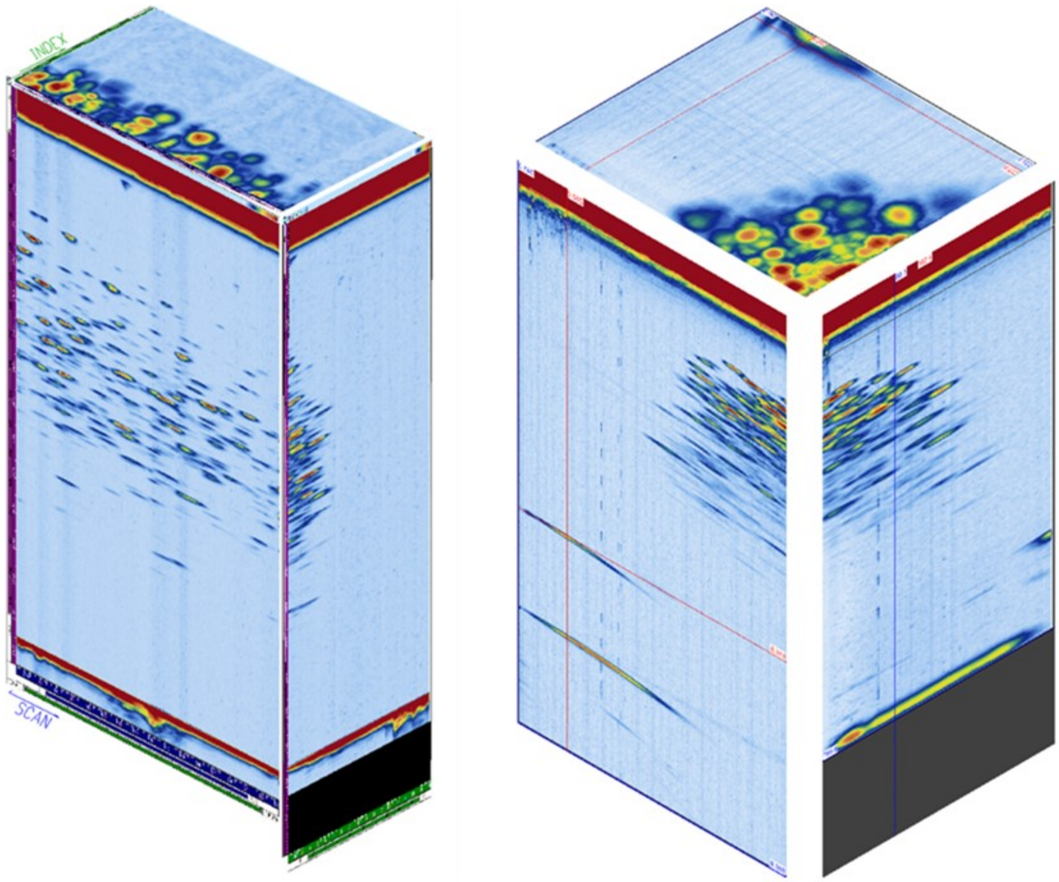

Figure 2: Results from mechanized UT at TK1 (left) and TK2 (right)

Verification

Three plates were cut from TK1 according to the cut pattern in Figure 1. Magnetic particle testing (MT) was now possible at the cut surfaces. The reduced wall thickness of 28 mm also allowed radiographic testing (RT) at the cut slices. As can be seen from Figure 2 left, the main part of the crack field of TK1 lies in plate ABC. The combined results from MT and RT of the plate ABC are shown in Figure 3. The indications from the MT testing at the former front of the test block are marked in blue, the MT indications from the inner side are marked in orange. The RT indications are shown in black. It can be seen that some indications are detected by MT and RT (e.g. indication No 7, No 45). Some indications are only detected by RT and are not visible with MT. This means that the flaw is located in the volume of the plate and does not reach one of the surfaces (e.g. No 19, No 15). Some indications are only found with MT and do not have a corresponding RT indication. This happens when the cracks are located in an unfavorable way with regard to the X-Ray beam cone. Furthermore, the wall thickness of 28 mm limits the resolution for small cracks in the RT images. It can be seen that each NDE technique has its own limitations and its own probability of detection.

The MT indication lengths are measured by the visible size at the surface. The RT indications lengths are measured in the digital images. The sizing results of MT and RT may differ for the same indications, as each testing technique has physical limits. For the verification the maximum of both indications lengths was taken.

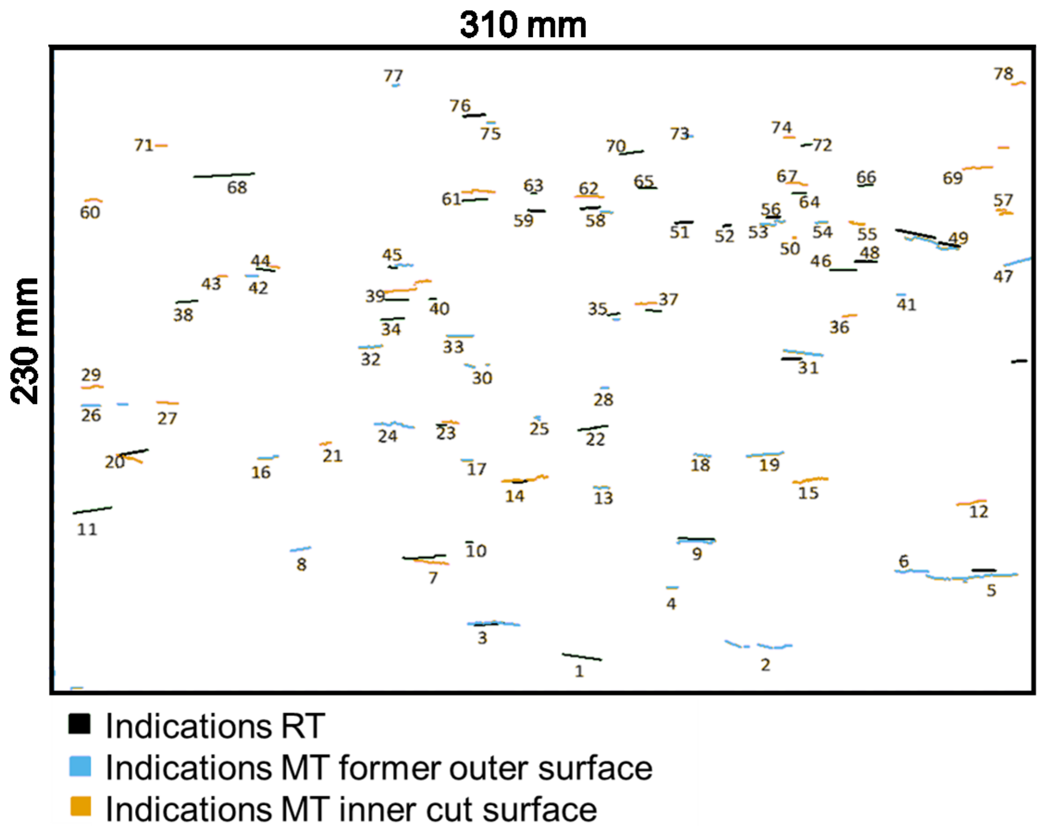

Figure 3: Indications detected with MT (blue, orange) and RT (black) at the plate ABC cut from the test block TK1

RESULTS OF SIZING

Sizing of UT indications took place using the 6dB drop technique. The boundaries of an indication are set, where the maximum amplitude drops by 6 dB, that means the amplitude drops to half of the maximum, while moving the transducer along the indication. This is a standard technique and described in the standards like DIN EN ISO 16827. The technique is quite accurate for small sound paths in the region of the maximum beam focusing of an ultrasonic transducer. It gets less accurate for large sound paths, for diverging sound beams and for indications smaller than the sound beam width in the depth of the flaw. If the indication is smaller than the sound beam width, the sizing result is mainly the width of the sound beam.

The sizes of the indications detected at TK1 are estimated using the 6dB drop. The distribution of indication lengths is shown in Figure 4. The mean indication length of all detected indications was estimated to 17 mm.

Due to the cutting of the test block, a verification of the indication lengths was possible by MT and RT testing. Each MT or RT indication was linked to an UT indication if possible. It can be seen from the overall number of indications detected with UT compared to MT/RT, that not all flaws could be detected with UT. This is caused by shadowing of indications that lie deeper in the crack field.

It turned out, that the mean indication length of the MT and RT testing was estimated to only 7 mm. As these indications are caused by the same flaws like the UT indications, it is clearly visible, that the UT indications are overestimated. However, the test blocks were big even compared to large components like RPV and sound paths between 150 mm and 600 mm were necessary to reach the cracks. Sound beam divergence for these sound paths cannot be neglected and is the main cause of the overestimation of the flaws.

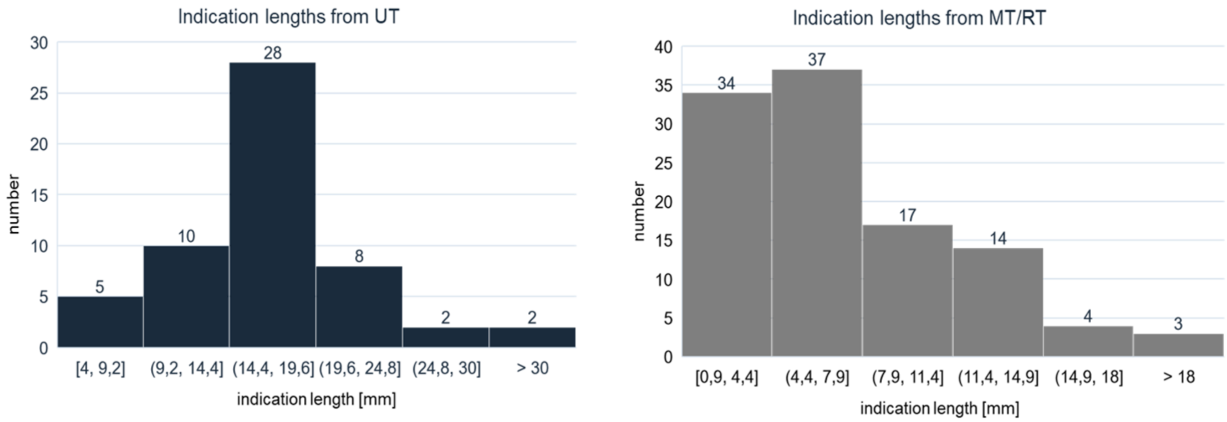

Figure 4: Distribution of indication sizes with UT (left) and MT/RT (right)

SOUND FIELD OPTIMIZATION

Test block TK2 was used in the following to perform sound field optimization. Due to a different microstructure the attenuation in the test block was higher compared to the test block TK1 and transducers with a center frequency of 2 MHz had to be used. As can be seen in Figure 5 the focus of the sound beam for the used single element transducer lies in 34 mm depth. The main part of the crack field in TK2 is located deeper than 120 mm in the test block, thus sound beam divergence plays a major role.

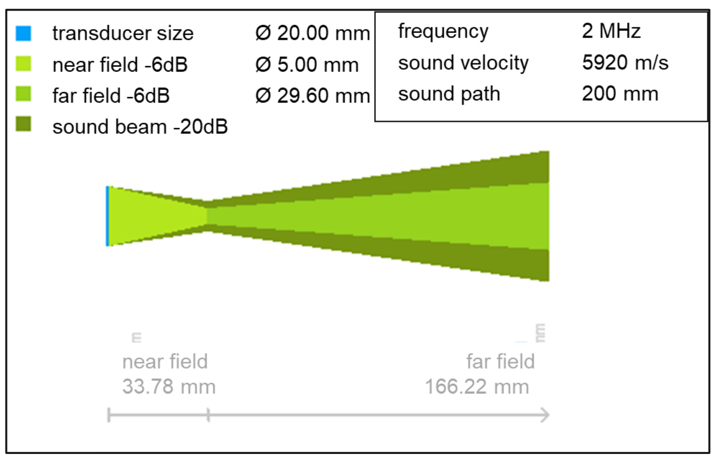

Figure 5: Sound beam of an ultrasonic normal probe with 20 mm diameter and 2 MHz for a sound path of 200 mm

CIVA simulations were used to investigate a transducer setup with an optimized sound field focusing in greater depth. In Figure 6 the results of the simulations for a 2 MHz linear array transducer with 64 elements are shown. Focus depth between 10 mm and 400 mm were set as aim, respektively. It can be seen, that the focus point moves deeper in each image for the focus depths of 10 mm, 35 mm, 50 mm and 75 mm. In the last four images for the focus depth of 100 mm to 400 mm, no significant changes of the sound fields are visible. This is caused by the dimensions of the transducer. For a focusing in deeper regions, the spacing of the elements in the transducer would need to be increased.

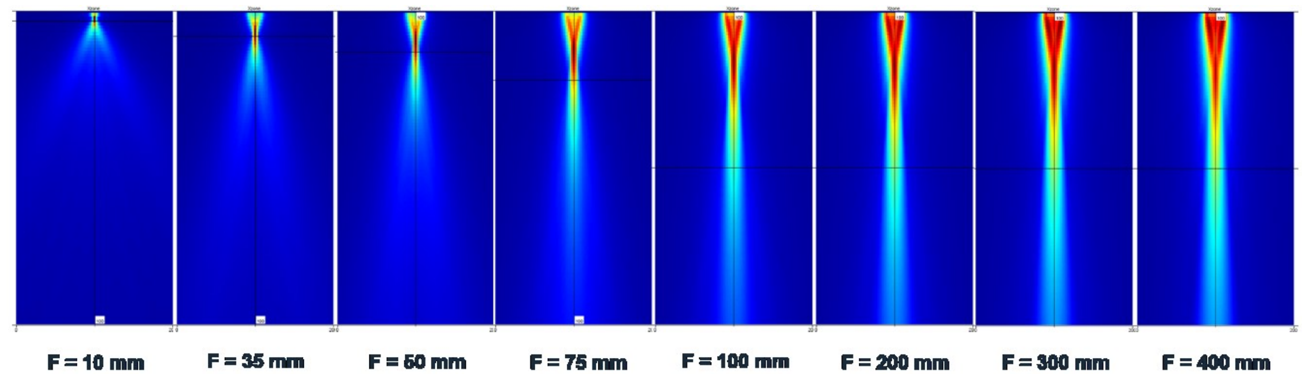

Figure 6: Sound field simulations for a 2 MHz linear array transducer with 64 elements for different focus depths

Phased array probes with significantly larger element spacing are not available. However, the focusing may be possible with dual matrix array probes, also known as transmit-receive array probes. They combine two matrix array probes, one array probe for transmitting and one array probe for receiving the ultrasonic pulse. In general, these two arrays are mounted on a wedge together without significant offset. It is also possible to separate the two probes and create a greater offset. For this setup CIVA simulations took place for different offsets between transmitter and receiver. The results can be seen in Figure 7. In the left image the sound field simulation without transducer spacing for a focus depth of 25 mm is shown. In the middle picture the focus depth was moved to 126 mm, which would be the start of the crack field in TK2. However, there is no big change in the sound field compared to the 25 mm focus depth. In the right image, a physical offset of 25 mm between transmitter and receiver probe was realized. Now the focus of energy is lowered to the aimed region.

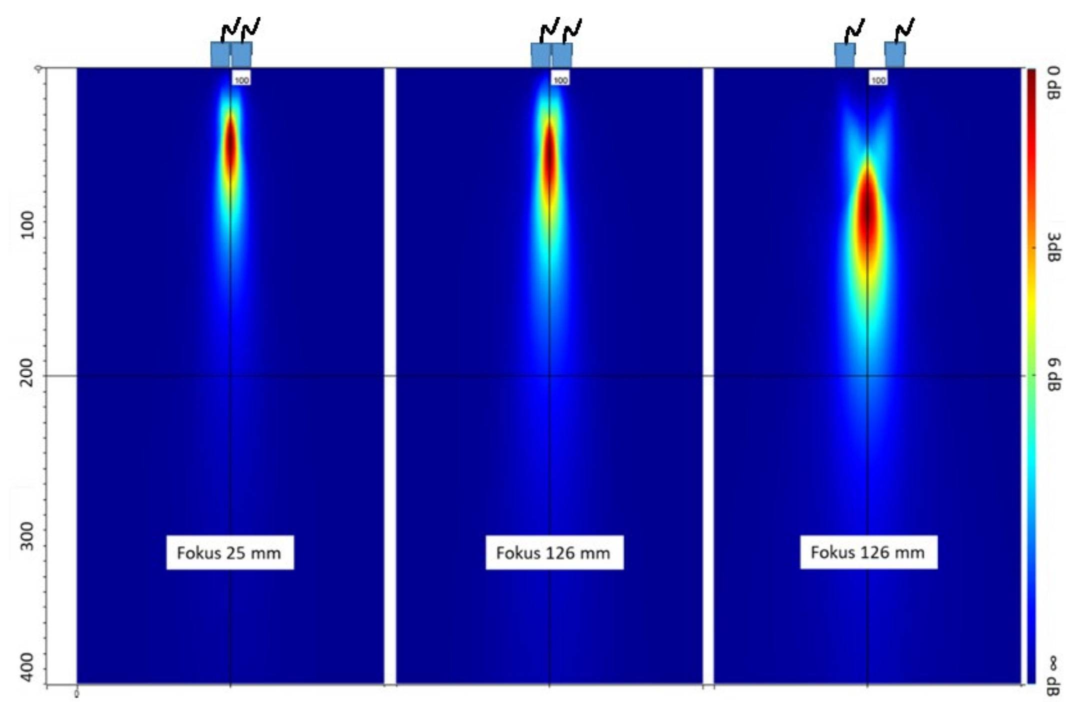

Figure 7: Sound field simulations for dual matrix array configurations

In the next step sizing was done at artificial flaws in the CIVA simulations. Idealised rectangular flaws with 5 mm, 10 mm and 20 mm length were put in different depths of the test block: 50 mm, 126 mm and 175 mm. In each configuration the signal response was analysed and the size was derived using the 6dB drop technique. The results are shown in Table 3. With the normal probe (B2SN) the size of the smallest flaw is overestimated by more than 100 % in all depths. As shown before, the focus of this transducer lies in 34 mm depth, so sound field divergence leads to this overestimation. The sizing is quite accurate for the biggest flaw (20 mm length) in all depths.

The use of the dual matrix array probe with focus of 126 mm and no spacing between the probes increases the accuracy of sizing for all depth, although there still is an overestimation of more than 60% for the smallest flaws. If an offset of 25 mm between the two array probes is used, the accuracy of sizing is not improved compared to the setup without offset for the flaws in 50 mm and 126 mm depth. However, an improvement could be achieved for the smallest flaw in 175 mm depth. Thus, it could be shown, that the use of array probes in transmit-receive-constellation with an offset allows a higher focusing of the sound field for long sound paths.

Table 3: Results from sizing of simulated flaws in different depths.

	l [mm]	d = 50 mm			d = 126 mm			d = 175 mm		
		l [mm] measured	Diff. [mm]	Diff. [%]	l [mm] measured	Diff. [mm]	Diff. [%]	l [mm] measured	Diff. [mm]	Diff. [%]
B2 SN	5	10	5	100	17	12	240	22	17	340
	10	14	4	40	16	6	60	22	12	120
	20	20	0	0	19	-1	5	20	0	0
DMA without Offset	5	8	3	60	14	9	180	20	15	300
	10	12	2	20	14	4	40	17	7	70
	20	20	0	0	20	0	0	20	0	0
DMA 25mm Offset	5	8	3	60	14	9	180	18	13	260
	10	12	2	20	14	4	40	16	6	60
	20	20	0	0	20	0	0	20	0	0

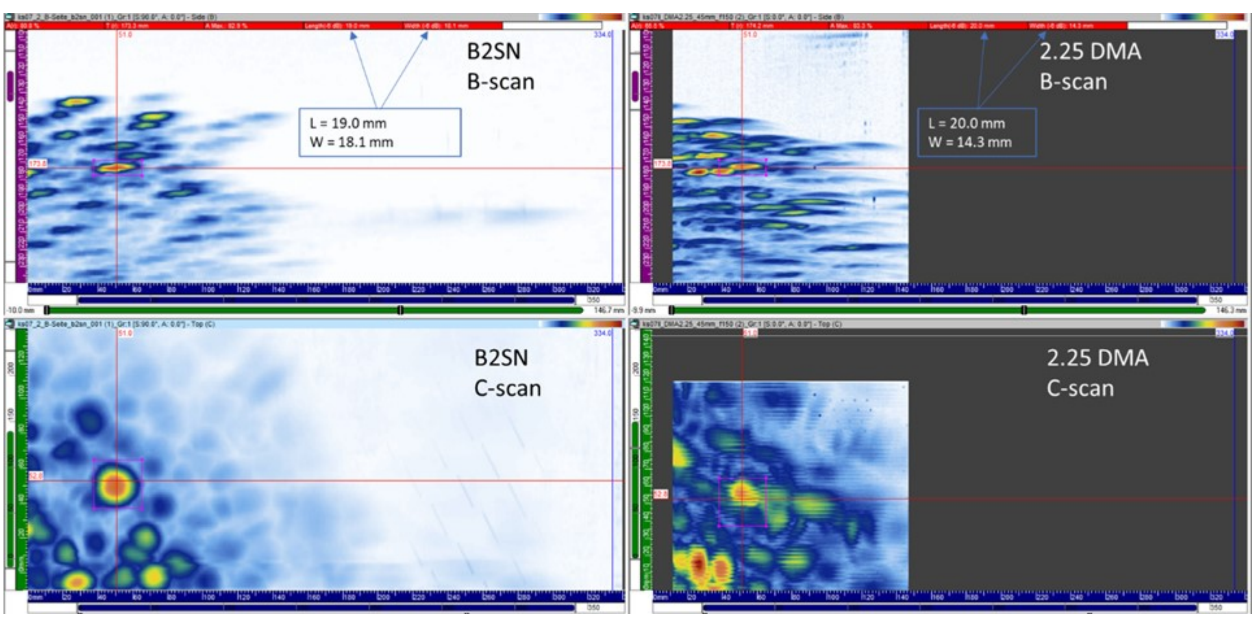

Figure 8: Results from UT with single element 2 MHz normal probe (left) and 2.25 MHz dual matrix array probe with 25 mm offset (right).

In the next step the setup with offset was applied to the test block TK2 and compared to the results gained with the single element normal probe. One indication could be identified in both measurements (x = 51 mm, y = 53 mm, z = 173 mm). The sizing of the indication in length was nearly similar with 19 mm and 20 mm, respectively. The width of the indication was sized with 14 mm in the dual matrix setup, compared to 18 mm with the normal probe. However, the test block TK2 was too complex to do a proper verification of the setup. Thus, test blocks with artificial flaws of known size will be used for further investigation.

DISCUSSION AND CONCLUSION

The accuracy of sizing is crucial for a reliable assessment of components containing cracklike flaws. Investigations at test blocks with a large amount of hydrogen flaking were carried out with different ultrasonic probes. Mainly single element ultrasonic probes were used for the sizing of the indications by the 6dB drop technique. The indication lengths from UT were compared to the results from MT and RT testing at parts of one of the test blocks investigated. It turned out, that the sizing using UT overestimates the crack sizes. Mean length from UT sizing were 17 mm, compared to 7 mm from RT and MT sizing. The overestimation is caused by the long sound paths and the sound field divergence. If the sound beam is wider than the flaw length, the 6 dB drop technique mainly delivers the size of the sound beam in the given depth.

Simulations with CIVA were used to investigate the possibilities of moving the focal spot in greater depth by the use of phased array ultrasonic probes. For linear array probes the focal spot could be moved to a depth of about 100 mm. The focusing in greater depths is not possible due to the dimensions of the probes. A setup with two matrix array probes applied with a certain offset then was investigated by simulations. In a first experiment the setup was realized and measurements took place. However, more investigations with simpler test blocks with known flaws are necessary to verify the effect experimentally.

The investigations were carried out in a research project against the background of the hydrogen flakes in the Belgian reactor pressure vessels. It has to be mentioned that the sound paths during the ultrasonic inspections in the Belgian RPV are much smaller than the sound fields in the test blocks. Furthermore, the used probes in Belgium were chosen to focus in the region of the crack fields during additional inspections after the indications were found for the first time in 2012. The overestimation of indication length during the inspections in the RPV therefore is much smaller and does not affect the reliability of the assessment or of the follow-up inspections.

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