DEFECT DETECTION AND SIZING TRIALS USING THE TOTAL FOCUSING METHOD AND SCATTERING COEFFICIENT MATRIX WITH A LINEAR PHASED ARRAY

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ABSTRACT

Novel NDT techniques based on the use of ultrasonic phased arrays have been the subject of much academic research in recent years. In particular, the Total Focusing Method and Scattering Coefficient Matrix post-processing techniques have been developed at Bristol University for improved defect imaging and small defect characterisation as part of research funded by the UK University Research Centre for NDE (RCNDE). Potentially, these techniques offer many advantages over conventional pulse echo and phased array sector scanning techniques. In order to improve understanding of the limitations and capabilities of these techniques in a realistic industrial inspection, AMEC organised a “blind trial” test of these techniques on test specimens containing realistic defects on behalf of RCNDE.

Several 60 mm thick welded ferritic test specimens containing simulated planar and volumetric weld defects of different orientations and locations were examined by Bristol University in open and blind trials. The details of one specimen were revealed to Bristol for the purposes of the open trial, enabling an inspection procedure to be developed for the use of the Total Focusing Method and Scattering Coefficient Matrix on the remaining blind trial test specimens.

This paper reports the findings from this project and reveals evidence of the capability and limitations of these techniques and the overriding need for optimised inspection design to achieve the most effective inspection results in real industrial inspections.

INTRODUCTION

Many new techniques have been developed by academic research departments to take advantage of the flexibility of phased array ultrasonic probes. Often, these techniques have been described as “novel”. In NDT, a novel approach can be useful to increase the capability of an inspection by providing a fresh technique independent of existing analysis tools. However, any new analysis technique will require experimental testing to provide evidence of its capability and to identify its region of applicability.

When a technique is in its infancy, it is often tested against a known defect population. This allows the technique to be shown to work against a range of defect species. Optimisation of the technique takes place until the defect is detected and determined to be of the correct size and character. The results are published and the technique labelled as being proficient in the detection and analysis of that particular defect type. Often, despite good intentions, these results feed in to the perception that the technique is capable of detecting a particular species of defect in all circumstances. However, the limiting factor of the capability of a technique is not just limited to the nature of the defect. It can rely upon a host of other parameters such as the geometry and material of the test subject, the crystal arrangement, frequency, size and placement of the ultrasonic probe etc. In order for a technique to be relied upon in an industrial application, it must have a defined inspection procedure to remove variation between inspections that could reduce this capability.

An inspection procedure is a set of instructions to be followed by an inspection operator. If designed and followed correctly, the variation due to operator choice is removed and the written inspection procedure will allow the inspection to be deployed with confidence in industrial applications.

The aim of this project was to test the novel ultrasonic techniques incorporated within Bristol University's Phased Array Full Matrix Capture (FMC) software package named Bristol Array Inspection (BRAIN). This software includes several post-processing algorithms including the Total Focussing Method (TFM) and the Scattering Coefficient Matrix (SCM). In order to achieve the goal of testing this system, the following tasks were required:

- A working inspection procedure was to be developed as part of this project in order to provide a repeatable inspection against which the performance can be assessed.
- An open trial was to be carried out to allow the development of the inspection procedure.
- A witnessed blind trial was to be conducted to test the performance of the operator following the procedure.
- To improve confidence in the capability of the techniques under test, destructive examination was to be conducted on defects in one of the ferritic steel welded test specimens.

For this project, Bristol University was responsible for the procedure development and for carrying out the open and blind trials. AMEC assessed the procedure and the open and blind trials, providing feedback and guidance where required. AMEC was also responsible for conducting the destructive examination.

INSPECTION PROCESSING ALGORITHMS

The BRAIN software includes many phased array post-processing algorithms based on data collected using the Full Matrix Capture technique. This paper is not intended to be a detailed narrative on the inner workings of these techniques. However, to aid in the understanding of the techniques featured in this paper, a brief description is provided below.

FULL MATRIX CAPTURE (FMC)

Full Matrix Capture is a technique whereby every element of a phased array probe is individually pulsed to generate sound that is received on every element including the transmitter. Thus, an a-scan is collected from every combination of transmitting and receiving elements across a specified range. These data can be stored for post-processing at a later time by summing together the a-scans with specific delays attached to each individual a-scan. It has been hailed as a technique that allows data to be processed multiple times from a single data set due to it recording every a-scan possible at a given probe position. This technique was used in this project to collect data from the phased array probe for later processing.

TOTAL FOCUSSING METHOD (TFM)

The Total Focussing Method is an imaging technique applied to FMC data. For a linear phased array probe, a two-dimensional grid is specified in the same plane as the probe. The FMC data are reconstructed to sum together the individual amplitude values that could have originated from each cell in the grid. Cells located at the true signal position will sum together in such a way as to dominate cells containing no true defect. In essence, the TFM image is focussed at every individual cell in the user-specified grid, with each cell incorporating data from multiple angles of incidence. This technique was used in this project to perform defect detection and location along with initial characterisation and sizing.

SCATTERING COEFFICIENT MATRIX (SCM)

This technique takes a single pixel in a TFM image and extracts each constituent of its amplitude. These constituent amplitude values are displayed as a function of incident and reflected beam angle. The resultant plot can be interrogated to provide information on the nature of a defect (planar or volumetric), the orientation of a defect (if planar) and the size of a defect. This technique was used in this project to perform defect sizing and characterisation, if deemed necessary by the initial interpretation of the TFM analysis.

INSPECTION SPECIFICATION

Three test specimens were available for this project, all of ferritic construction with geometry as described in Figure 1 a double-V ferritic butt weld, with the caps ground flat, runs across the width of the specimen. A series of volumetric and planar defects are located along its extent. These defects are typical of manufacturing and in-service defects:

- Lack of fusion at the weld interface
- Porosity
- Slag
- Rough crack
- Smooth crack

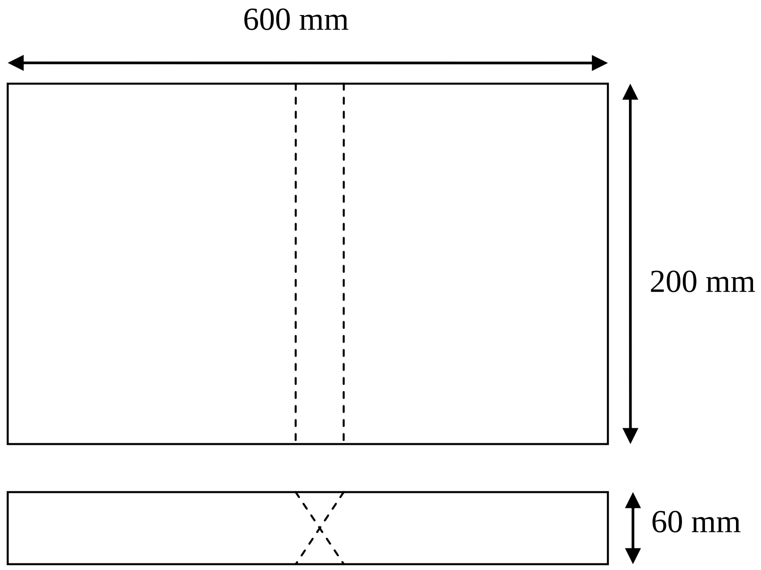

Figure 1: Test Specimen Geometry

An inspection specification was prepared by AMEC containing details of the planned trial process and reporting requirements. This was supplied to Bristol University at the project start and included details of the test sample dimensions, inspection volume and likely defect types to allow Bristol University to target the inspection procedure development.

DEVELOPMENT TRIAL PROCESS

Three specimens were used in this process: 4419-01, 4419-02 and 4419-03. 4419-02 was inspected independently from both major surfaces thus effectively increasing the total number of specimens to four. When inspected from the opposite surface, the specimen was labelled BT01. It was not revealed at the time of the inspection that the test specimen was the same and as such will be treated as a separate fourth sample from this point onwards.

Figure 2 depicts the flow of the development trials on each of the four test samples. Feedback was provided following the inspection of each sample, which was used to develop the procedure prior to the next stage.

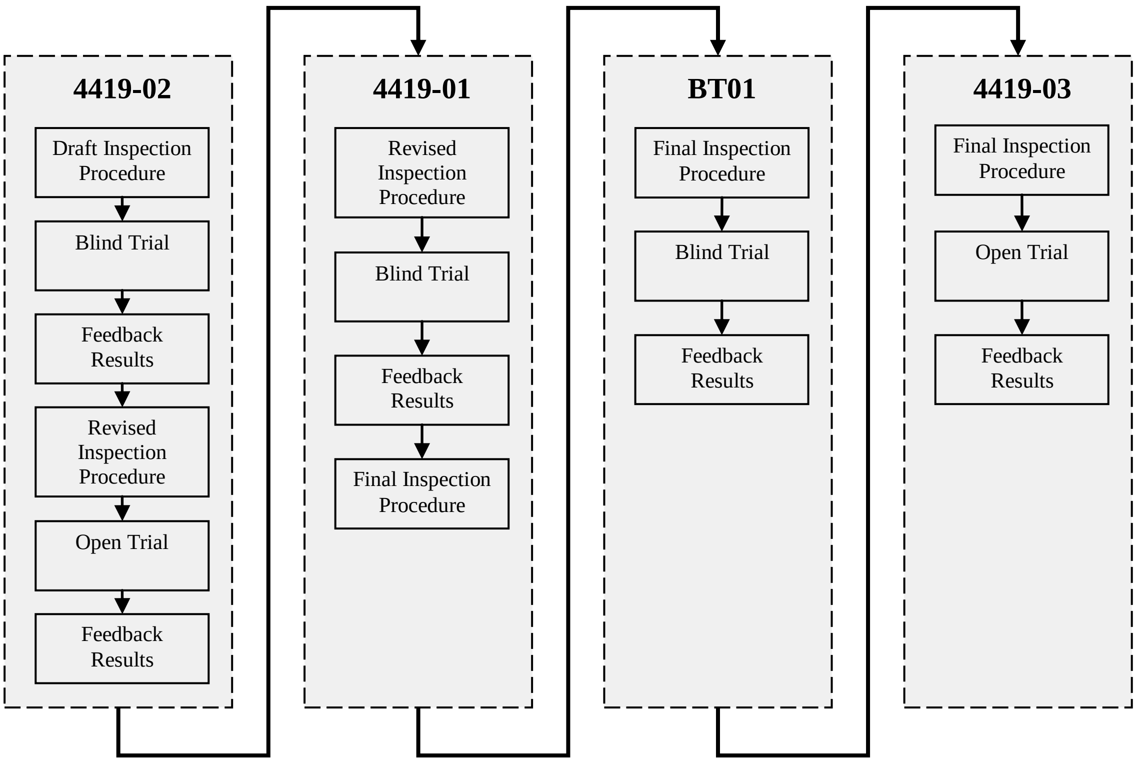

Figure 2: Flowchart of the Inspection Procedure Design and Testing Process

INSPECTION OF 4419-02

The first inspection to take place was carried out on the welded test specimen 4419-02. The purpose of this inspection was to develop the draft procedure to comply with the inspection specification and to define the parameter settings for use within BRAIN.

1. A blind inspection of 4419-02 was performed using the draft inspection procedure.
2. Results were submitted to AMEC in the form of TFM images (B and D scan) along with accompanying tabulated results listing the suspect defect volume dimensions and judgements on defect character based on a draft defect characterisation procedure.
3. Feedback was provided on the submitted results with the intended defect population details.
4. Revisions made by Bristol to the draft inspection procedure.
5. 4419-02 was re-inspected in an open trial using the revised inspection procedure.
6. Results submitted to AMEC for assessment.

INSPECTION OF 4419-01

The second inspection to take place was carried out on the welded test specimen 4419-01. The purpose of this inspection was to test out the revised procedure against an addition set of defects and allow further development of the procedure to comply with the inspection specification.

1. Blind inspection of 4419-01 took place using the revised inspection procedure.
2. Results submitted to AMEC for assessment.
3. Feedback given by AMEC on the comparison of the submitted results with the intended defect population details.
4. Following a further revision to the defect characterisation procedure, a final inspection procedure was produced

INSPECTION OF BT01

Following a review of the defects in the remaining test samples, it was decided to perform this final blind trial on test sample 4419-02 from the opposite inspection surface to that inspected previously (with the test sample identified as BT01). The inspection of test sample BT01 was performed as follows:

1. Blind inspection of BT01 using the final inspection procedure
2. Results submitted to AMEC for assessment.
3. AMEC compared the results with information on intended defect types and locations in test sample BT01.

INSPECTION OF 4419-03

It was thought to add benefit to this project to use the final specimen as a test of sizing and characterisation only. The defect locations were provided to Bristol.

1. Open inspection of four identified defect regions in 4419-03 using the final inspection procedure (for characterisation only)
2. Results reported to AMEC for assessment.

RESULTS

Table 1 - **Table 7** present the sizing results of all intended defects within the test samples. The intended size for each defect (as specified in the manufacturing drawings) is presented alongside the measured size.

RESULTS FOR 4419-02

ID	**Length (mm)**			**Height (mm)**		
	Intended	**Measured**	**Difference**	**Intended**	**Measured**	**Difference**
E	23	21	-2	4.9	5.5	0.6
F	10	27	17	2.3	7.5	5.2
G	10.1	10	0.1	2.5	2.2	-0.3
H	21.5	21	-0.5	5.4	5.5	0.1

Table 1: Sizing results from 4419-02

As observed in Table 1, defects E, G and H were all sized within a reasonable tolerance. However, Defect F was significantly over-sized in both length and through-wall extent. Figure 3 shows the TFM image of this defect. The rough nature of this defect can be observed in the spread of small reflected facets of sound rather than a single large reflected signal. In fact, this defect is a buried vertical rough crack, which makes it particularly difficult to defect. This particular defect was chosen for destructive analysis (see Figure 5) and was measured to have a through-wall extent of 1.49 mm at its mid-point. This confirms that this defect was over-sized in the through-wall dimension and not the result of a mistake made during the defect manufacturing process. The true length of the defect was not recorded during the destructive examination.

4419-02 was used to develop the characterisation techniques and so no defects were characterised on this sample.

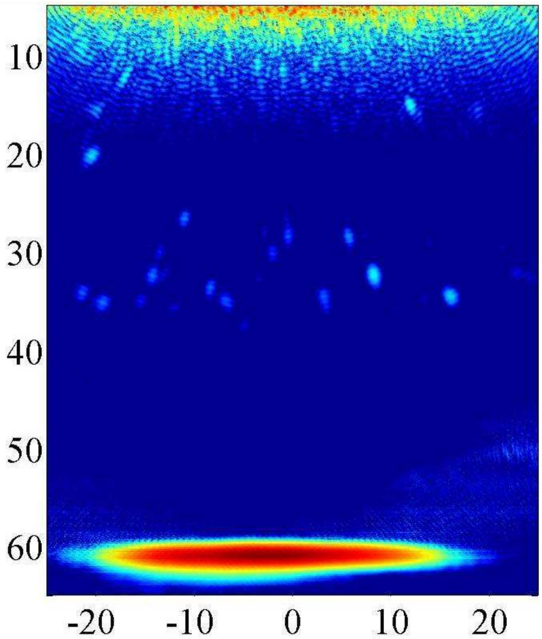

Figure 3: Defect F in Specimen 4419-02 with probe parallel to defect

RESULTS FOR 4419-01

Table 2 presents the sizing results from the sample 4419-01. Defect D was not identified as reportable and so was not sized or characterised. It was noted on the final list of defects but was not carried forward on the grounds of low amplitude. As a result of this, the threshold criteria were modified in the inspection procedure. Defect D is small (2 mm through-wall) and is distant relative to the probe, being located near the far surface. All other defects are within a reasonable tolerance.

ID	Length (mm)			Height (mm)		
	Intended	Measured	Difference	Intended	Measured	Difference
A	9	11	2	2.1	7	4.9
B	18	21	3	5	8	3
C	6.8	7	0.2	1.9	4.5	2.6
D	8	-	-	2	-	-

Table 2: Sizing results from 4419-01

Of the detected planar defects, both were characterised as rough instead of smooth. The images of these defects showed some amplitude variation across the length of the defects and hence this classification. Traditional fixed-beam angle inspections have been carries out on these samples and a variation was also noted. However, this variation was small (a few dB) and so the defects were interpreted as smooth. More work will need to be conducted into TFM as it fuses together data from multiple incident angles and so the interpretation of traditional "pattern" indications is not as straightforward.

It was interesting to note that Defect A was misclassified as a lack of fusion. This defect was intentionally used to test a common misclassification. Two parallel horizontal lines of slag, one directly above the other, could give the appearance of two diffracted signals from the tips of a planar defect. This defect emphasised a benefit of traditional multiple fixed-beam ultrasonic inspections where an analyst could study each beam angle independently to assess the reflected energy for each angle and attempt to achieve specular reflection to distinguish the two defect types. Additional amplitude criteria were inserted into the procedure as a result of this defect.

ID	Defect Type	
	Intended	**Measured**
A	Two Parallel Slag	Lack of Fusion
B	Lack of Fusion	Rough Crack
C	Smooth Crack	Rough Crack
D	Lack of Fusion	-

Table 3: Characterisation results from 4419-01

RESULTS FOR BT01

All defects in the sample BT01 were sized within a reasonable tolerance.

ID	Length (mm)			Height (mm)		
	Intended	**Measured**	**Difference**	**Intended**	**Measured**	**Difference**
E	23	22	-1	4.9	6	1.1
F	10	11	1	2.3	3	0.7
G	10.1	10	-0.1	2.5	2	-0.5
H	21.5	21	-0.5	5.4	5	-0.4

Table 4: Sizing results from BT01

The characterisation results for defects E, F and G were correct. To al intents and purposes, the result for Defect H was correct given that the intended and measured defect types are both rough and planar – Rough Lack of Fusion was only specified given the location of the crack on the weld fusion face.

ID	Defect Type	
	Intended	**Measured**
E	Lack of Fusion	Lack of Fusion
F	Rough Crack	Rough Crack
G	Slag	Slag
H	Rough Crack	Rough Lack of Fusion

Table 5: Characterisation results from BT01

RESULTS FOR 4419-03

All defects in this sample were sized within a reasonable tolerance.

ID	Length (mm)			Height (mm)		
	Intended	**Measured**	**Difference**	**Intended**	**Measured**	**Difference**
I	25	30	5	5	2	-3
J	8	10	2	8	10	2
K	15.1	18	2.9	5	5	0
L	6.3	5	-1.3	1.9	2	0.1

Table 6: Sizing results from 4419-03

The characterisation results for Defects I and K were both correct. The result for Defect L was reasonable given that the intended and measured defect types are both rough and planar. As in BT01, a Rough Lack of Fusion was only specified given the location of the crack on the weld fusion face. Defect J, however, was incorrect. Upon feedback of the defect type, it was noted that this was the first porosity observed in this process and so it was not directly linked in to the procedure. The defect type was given as a rough crack because of the multiple individual signals observed on both defect types. Differences were noted between the signals of the two defect types by way of the voluminous features of porosity – this would differentiate these in the future.

ID	Defect Type	
	Intended	**Measured**
I	Lack of Fusion	Lack of Fusion
J	Porosity	Rough Crack
K	Rough Crack	Rough Crack
L	Rough Crack	Rough Lack of Fusion

Table 7: Characterisation results from 4419-03

DESTRUCTIVE EXAMINATION

A destructive examination, followed by metallographic examination was carried out to confirm the true nature of the defects in the test sample 4419-02 / BT01. This allowed a comparison to be drawn between the TFM images and the optical microscope image of the defect cross section. Defect E is intended to be lack-of-fusion 23 mm in length and 4.9 mm through-wall tilted at 11°. The destructive examination of this defect can be seen in Figure 4. The through-wall extent of this defect was observed to be 5.8 mm and tilted at 7.8°.

Figure 4: Destructive examination of Defect E in Specimen 4419-02 / BT01

Defect F is intended to be a vertical rough crack 10 mm in length and 2.3 mm through-wall. The destructive examination of this defect can be seen in Figure 5. The through-wall extent of this defect was observed to be 1.49 mm. The gape of this defect is observed to be very tight, which would act to reduce the ultrasonic reflection at certain areas of the defect. The roughness is not clearly observed in this plane.

Figure 5: Destructive examination of Defect F in Specimen 4419-02 / BT01

Defect G is intended to be a horizontal line of slag 10.1 mm in length and 2.5 mm in diameter. The destructive examination of this defect can be seen in Figure 6 which depicts a cross section along the length of the defect. The true length is 9.52 mm and the through-wall extent was observed to be 2.45 mm.

Figure 6: Destructive examination of Defect G in Specimen 4419-02 / BT01

Defect H is intended to be a rough crack 21.5 mm in length and 5.4 mm through-wall tilted at 30°. The destructive examination of this defect can be seen in Figure 7. The through-wall extent of this defect was observed to be 4.28 mm and tilted at 36.3°. Its rough nature can be clearly observed.

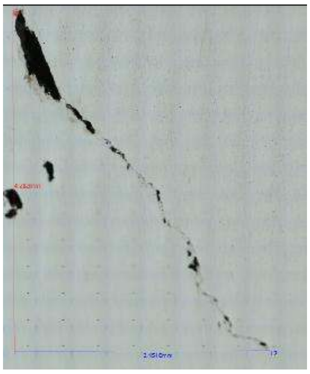

Figure 7: Destructive examination of Defect H in Specimen 4419-02 / BT01

DISCUSSION

The open and blind trials and associated procedure development provides important information on the strengths and weaknesses of FMC imaging techniques for the inspection of ferritic butt welds and their potential use as part of a diverse and redundant inspection procedure for such welds.

The importance of good inspection design in ensuring full weld coverage and optimised defect discrimination and characterisation for the full range of potential defect types has been reinforced. The inspection process was independently witnessed throughout. As a result, there were no performance weaknesses that could be attributed to human reliability factors.

The sizing of defects provided, in general, good results. Defect F in 4419-02 was grossly oversized during the initial trial. However, a revision was made to the procedure following this. When inspected as part of BT01, a good result was achieved on this defect. On average, defects were oversized more often than they were undersized and by a larger amount. This is likely to be partly due to the small size of most defects in the inspected test samples.

Some false calls relating to spurious echoes were noted in the analysis of FMC data. In most cases, these indications were sentenced as insignificant point indications following the application of the characterisation process. Some of these echoes were also noticed and sentenced as such during conventional pulse-echo inspections. Inevitably, with improved FMC imaging techniques, the cost of higher sensitivity is the increase in false call rate from small insignificant reflectors. This is reminiscent of the TOFD technique. Care is needed therefore in selecting a reliable calibration technique regarding inspection sensitivity and selecting a robust characterisation process. Also, further optimisation of the FMC, TFM and SCM inspection procedure for the full range, types and orientations of likely defects would increase the amplitude difference between very small (innocuous) and larger defects, so simplifying defect identification and discrimination.

CONCLUSIONS

The testing of the FMC/TFM post-processing algorithms available within the BRAIN software in this development trial has

1. prompted the development of effective FMC/TFM inspection procedures for ferritic welds which can be further optimised for improved defect detection, sizing and characterisation/discrimination
2. demonstrated the capabilities of the FMC/TFM algorithms and procedures in a simulated industrial application
3. provided valuable insights into the strengths and weaknesses of the FMC/TFM algorithms and identified areas for further research and development
4. provided the first known testing of the use of the BRAIN software and TFM- based inspection procedures in a realistic industrial inspection application
5. Rules have been created for differentiating between defects and noise and to characterise defects
6. Routes have been identified for facilitating rapid FMC/TFM imaging technology transfer into industry as part of a diverse and redundant inspection procedure

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