DET NORSKE VERITAS

Energy Report

Shaw Pipeline Services Phased Array AUT Qualification

Shaw Pipeline Services

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MANAGING RISK

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Summary:

The Shaw Phased Array AUT system has been subjected to a general qualification trials with objective to establish the performance of the system. The system is well documented from the tests performed and operational aspects have been found satisfactory. In summary, the performance can be described as follows (for details see main text):

- The system will reliably (defined by a 90% POD value at 95% confidence level) detect defects with length > 4 mm down to 1.0 mm in height, with a detection threshold at 20% of the response from given reference reflectors.
- Height sizing was performed with an overall average oversizing of 0.4 mm. The observed 5% fractile against under-sizing is at -0.8 mm (i.e. less than 5 % probability for a defect to be under-sized more than 0.8 mm).

These results are regarded valid for all future girth weld projects for the Shaw phased array AUT scanner where the welds used in this qualification (J-preparation GMAW in 20" / 25.4 mm pipe) are found relevant, provided certain prerequisites given in section 7.3 of this report are met.

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CONCLUSIVE SUMMARY

The Shaw Phased Array AUT system has been subjected to general qualification trials with the objective to establish the performance of the system. A total of nine (9) girth weld pipe test coupons of 20” x 25.4 mm WT, J-prep GMAW, with seeded defects have been subject to trials for reliability assessment. The tests also included repeatability tests on calibration blocs and temperature sensitivity trials, and the full scope of this qualification includes the tests required for qualification according to DNV OS-F101, Shell DEP 37.81.42.35-EPP and Exxon Mobile GP 72-03-04. The system is well documented from the tests performed and operational aspects have been found satisfactory. In summary, the performance can be described as follows (for details see main text):

- The system will reliably (defined by a 90% POD value at 95% confidence level) detect defects with length > 4 mm down to 1.0 mm in height, with a detection threshold at 20% of the response from reference reflectors of 3 mm FBHs and 1 mm surface notches.
- Height sizing was performed with an overall average oversizing of 0.4 mm. The observed 5% fractile against under-sizing is at -0.8 mm (i.e. less than 5 % probability for a defect to be under-sized more than 0.8 mm).

It is observed some differences in detectability and height sizing accuracy among the different weld zones. The hot pass zone appeared as the most challenging, and is determinative for the observed general detectability. This might have relevance only for some critical and specialised applications, for these cases a +6 dB increase of gain to the hot pass channel at scanning is recommended to improve detectability.

These results are regarded valid for all future girth weld projects for the Shaw phased array AUT scanner where the welds used in this qualification are found relevant, provided project specific prerequisites and certain prerequisites given in section 7.3 of this report are met.

1 INTRODUCTION

The Shaw phased array automated ultrasonic testing (PA-AUT) equipment has been subject to qualification trials in order to establish the general performance of the system. Performance is evaluated as mainly detectability and vertical height sizing uncertainty. The system is recently developed, and no experience from earlier projects has been gained. The purpose for this general qualification has been to document independently the performance of the Shaw phased array system for normal applications. The outcome of this qualification and the gathered results are supposed to be used as historical data to reduce the scope of work in future project specific qualification involving this AUT system.

2 BASIS

The basis for this qualification work has been: DNV OS-F101 [1], Appendix E, Shell specification DEP 37.81.42.35-EPP Qualification of Automated Ultrasonic Inspection (AUT) Systems [2] and Exxon Mobile Technical Specification GP 72-03-04 [3]. These documents are also basis for the qualification procedure: The guidelines for qualification of Shaw Pipeline Services Phased Array System, DNV report No. 2008-1-20E339 [4]. Further, the guidance given in the Nordtest TechReport 394 [5] is followed, as far as applicable. Further details were given on witnessing and guidance during the qualification work.

3 OBJECTIVES

The main objective of the qualification work was firstly to document the Shaw AUT system performance according to DNV OS-F101, 2007 edition [1], Shell specification DEP 37.81.42.35-EPP [2], and Exxon Mobile Technical Specification GP 72-03-04 [3].

Since this is a general qualification of the system, no girth weld acceptance criteria are involved in the evaluation of the performance. The performance is measured according to the methods attributed to different requirements given in the specifications, and the results should therefore be directly applicable for relevant applications with specific acceptance criteria.

According to DNV OS-F101 the basic requirements are:

- A POD of 90% at a 95% confidence level (a 90%|95% POD) has to be documented for a defect height smaller or equal to the smallest allowable defect height in the group of defects in question.
- The 5% limit against under-sizing of vertical height has to be established

According to Shell DEP 37.81.42.35-EPP the criteria are:

- For use on projects containing steel catenary risers, SCRs: Capability to detect defects down to 0.3 mm height within the 2 mm layer at inner and outer surface of the pipe, and down to 0.8 mm height for buried defects.
- For use on flowlines: Capability to detect defects on ID or OD surface with height down to 0.5 mm, and down to 0.8 mm for buried defects.
- Uncertainty requirements given for different applications, ranging from a 0.3 mm mean uncertainty for surface defects on risers to max 1.0 mm mean uncertainty for defects on flowlines. Requirements also includes maximum uncertainty allowed.

Beside this, repeatability and the influence on the performance from important operational factors like elevated temperature are investigated.

4 REFERENCE DOCUMENTATION

[1] Det Norske Veritas Offshore Standard OS-F101: Submarine Pipeline Systems 2000 (DNV OS-F101), version 2004.

[2] Shell specification DEP 37.81.42.35-EPP Qualification of Automated Ultrasonic Inspection (AUT) Systems

[3] Exxon Mobile Technical Specification GP 72-03-04

[4] Guidelines for NDE Reliability Determination and Description, Nordtest TechReport 394, Nordtest, Espoo, Finland, Approved 1998-04

[5] Guidelines for qualification of Shaw Pipeline Services Phased Array System, DNV report No. 2008-1-20E339

5 DESCRIPTION OF QUALIFICATION PROCESS AND CONTENTS

The AUT testing was entirely carried out by Shaw Pipeline Servives (SPS). Trial welds were supplied by Allseas Engineering bv., and included 9 J-preparation GMAW Girth welds 25.4 mm nominal thickness, 20" diameter. Steel grade X65, bevel 6˚. A total of 74 defects were included for further analysis.

All welds were scanned in total four times. Two independent teams of operators were both scanning once in clockwise direction (CW), and once in counter-clockwise direction (CCW).

The performance of the system was also verified by scanning the weld at room temperature and elevated temperature as per process during the production of the pipeline.

Positions for macro sectioning were marked up on the weld using the AUT scanner, to recognise the precise position. At least three salami slices were done for each macro section position, at 2 mm distance between each other. For surface breaking defects, one slice was usually done at each position. All defects chosen for macro sectioning have been given ID-numbers of type 2-1. The first number refers to the trial weld, the second is the sequential number of defects taken from the particular weld. These defects are also attributed to a macro postion, which is given in mm from the defined scanning start point. The ID-number for the macro and the position for each macro section were hard stamped in the material close to the weld. Two marks were hard stamped at a distance of 10 mm clockwise from the first macro position, as a reference mark. Trial welds ready for macro sectioning is shown in Figure 1.

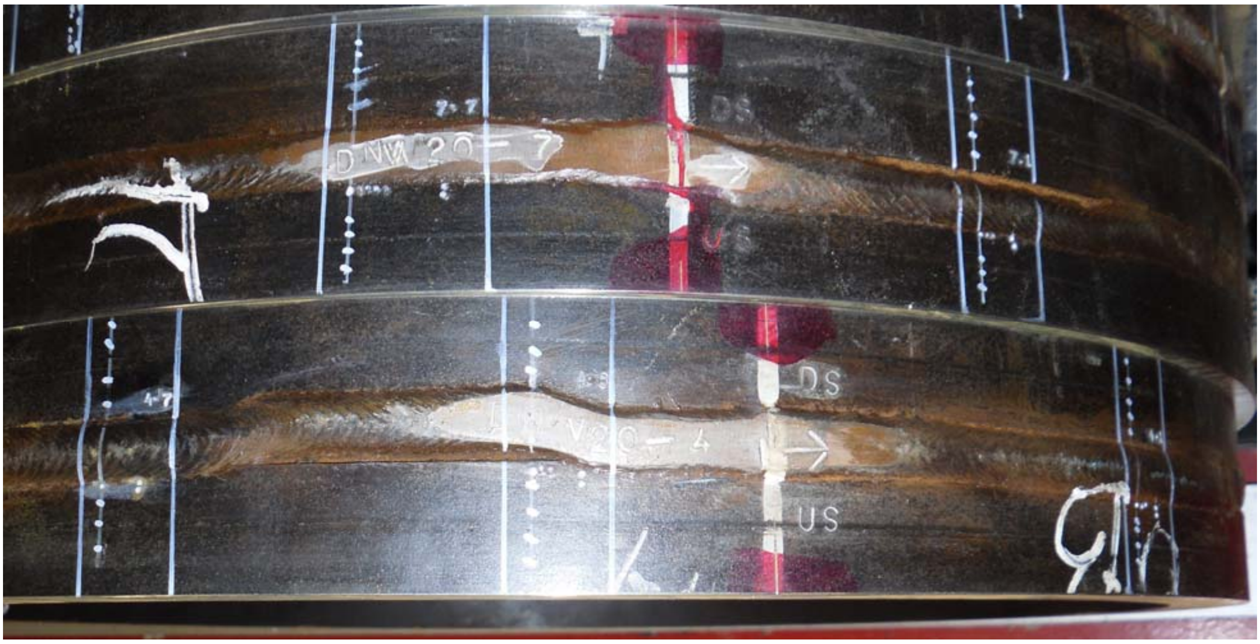


Figure 1: Trial welds 7 (upper) and 4 (lower) ready for macro sectioning after immersion ultrasonic testing. White marks indicates macro positions.

Weld macro cross-setions were prepared and measured by DNV Ohio. Section slices were cut by a high precision saw, ground and etched before they were photographed.

The procedure of calibration of the system uses 3 mm Ø FBHs embedded, 2 mm Ø FBHs for the hot pass channels, and 1 mm surface notches set to 80% FSH. The recording threshold for pulse echo was set to 20% FSH.

Supplementary radiography was performed for reference before AUT scanning. Radiography was carried out by Vinçotte-Nederland using Level 2 certified personnel. There were no defects found by radiography which were not detected by AUT. On the other side, there were a few defects detected by AUT and confirmed by macro sectioning, but not found by radiography.

Supplementary immersion ultrasonic testing was performed on eight of the welds after AUT scanning by Conam Inspection, Ohio. Prior to immersion scans, the welded pipes were cut on both side of the weld with 1” distance from the weld and the cut surface, as seen on Figure 1. The cut surface was ground. Immersion ultrasonic testing scans followed a general testing procedure. The welds were scanned by 0˚ focused probe at a distance 5 mm from the flat surface of the welded ring. It was performed xy-scans, where the echo within a time window corresponding to a depth between 1” and 1.35” was recorded. This corresponds to the half of the weld closest to the probe. All trial weld rings were scanned twice, at up-stream and down-stream weld bevel side.

One trial weld was subject to macro sectioning and immersion ultrasonic testing after the main analysis, mainly to confirm detectability in the hot-pass channel. The immersion testing for this weld was performed by Southwest Research Institute, Texas. Macro sectioning was performed by Bodycote, Houston. The immersion UT results were in general found to be in good correspondence with the AUT-scanning results, but there were no significant defects that was certainly seen exclusively on the immersion scans.

A compilation of qualification results is found in Appendix 2.

5.1 Analysis Extent

5.1.1 90% POD at 95% Confidence

POD analysis is performed to comply with the requirements in DNV OS-F101. In a normal project specific qualification, the result from the POD analysis is used with project specific acceptance criteria on defect heights derived by ECA. For this situation, the defect height that shows 90% POD at the 95% confidence level is the important value to assess, because this is regarded as the defect height for which the AUT system reliably will detect almost all defects. 90% POD refers to the fit of the collected defect height detection data and the statistical model used, and means the value where 9 out of 10 defects will be detected according to the data. The 95% confidence interval used refers to the actual collected data and how well the data fits to the estimated POD. 95% confidence is the security limit which has a less than 5% probability that the real POD is even below. There is a considerable amount of conservatism in the detectability requirement of 90% POD at 95% confidence level for the smallest acceptable defect height, and the defect heights that fulfil this requirement after the qualification are regarded to be certainly detected by the AUT system.

5.1.2 50% POD at 95% Confidence

In the analysis, the vertical defect height at 50% POD at 95% confidence level is also mentioned. This value has no reference to the DNV OS-F101, but is included as a benchmark for the detection of the AUT system. 50% POD refers to the defect height where one can expect 50% of the defects to be detected, which is the defect height of detection on average. When the 90% POD defect height refers to the certainly detected defect size, the 50% POD height indicates the defect height it is fair to claim that the system is capable to detect. This value can be regarded as the normal, expected detection performance of the system.

5.1.3 Detection Capabilities, Shell

The criteria for detection given in Shell DEP 37.81.42.35-EPP are more vague than in DNV OS-F101, it is required that the AUT shall be capable to detect defects at certain sizes. The Shaw PA-AUT system has been able to detect defects smaller than the limits given through this qualification. However, no further guidance is given for how to assess the detection capability. This requirement is therefore not further discussed in this report.

5.1.4 Defect Height Sizing

Evaluation of defect height sizing accuracy is an important part of AUT qualification. In DNV OS-F101 this accuracy is attributed to the project specific acceptance criteria. It is specified that the AUT system shall show reliable detection of the smallest “allowable” defects according to the acceptance criteria with less than 5% probability of under-sizing. This calls for an evaluation of the margin that needs to be added to the the 90%|95% POD-value for detectability, a 95% limit against under-sizing for which at least 95% of all the sized defects shows less under-sizing.

Shell DEP 37.81.42.35-EPP has more specific criteria to height sizing accuracy attributed to application, on mean accuracy and maximum deviation from reference macro measured. The criteria for the different applications valid for a pipe wall thickness of 25 mm or less are given in the Table 1 below. It is assumed that the requirements of Table 1 will be applied with common sense and knowledge gained through the qualification.

Table 1

Application	**Mean Sizing Error ± mm**	**Maximum Sizing Error ± mm**
Riser - Surface Defects	0.3	1.0
Riser – Buried Defects	1.0	1.5
Flowline/Pipeline – Surface Defects	1.0	1.5
Flowline/Pipeline – Buried Defects	1.0	2.0

6 RESULTS

6.1 Analysis prerequisites

The analysis is based on information acquired by the Shaw AUT Phased Array scanner, witnessed by DNV. The information includes original AUT weld scans and reports, and macro sectioning images prepared by DNV Ohio.

Positions for macro sectioning were chosen at areas with usually not more than one defect present, and preferentially on areas of the defects with an apparently uniform height. Some indications with low pulse-echo response were included in order to assess detectability. The qualification data includes a reasonable range of defect sizes and defect types. In total 71 independent defects are included in the analysis, which is sufficient to give a fair description of the system’s performance. Each defect is scanned twice, clockwise (CW) and counter-clockwise (CCW) by two different operators, in total four different scans for each defect.

6.2 Detectability

The Probability of Detection (POD) analysis serves as the main measure of reliability for qualification according to DNV OS-F101. The intention is to assess the smallest defect height the system will be able to reliably detect, which here is denoted as the detectability. It is worth mentioning that defect length will influence the POD, as the area of the defect surface is the important measure when it comes to reflection of ultrasonic energy. In general, the data collected for this qualification shows that the defects disregarded by this system usually have both small height and are very short, with typical length of 4 mm or maybe shorter.

6.2.1 General Detectability

Figure 2 shows the general Probability of Detection (POD)-curve for all the observations acquired during the qualification together. On average, the system shows detection of defects at a height of 0.6 mm, shown in Figure 3. This defect height corresponds to the 50% POD-value, which can be regarded as the measured detectability of this AUT system. The analysis shows a 90% POD at 0.8 mm, which is the actual fit to the present results with 50% confidence (confidence on average). The 90% POD height with 95% confidence is at 1.0 mm, which can be regarded as the conservative estimate of defect height of guaranteed reliable detection. This system is well suited to detect 0.5 mm defects, but according to the various unverifiable uncertainties attributed to detection, DNV does not guarantee for detection of defects below 1.0 mm.

It is worth mentioning that the general POD does not take into account different detectability among the zones. As it will be discussed in this section, the detectability in the hot-pass channel has perhaps the most impact on this general POD. Some degree of uncertainity might then be expected for this curve.

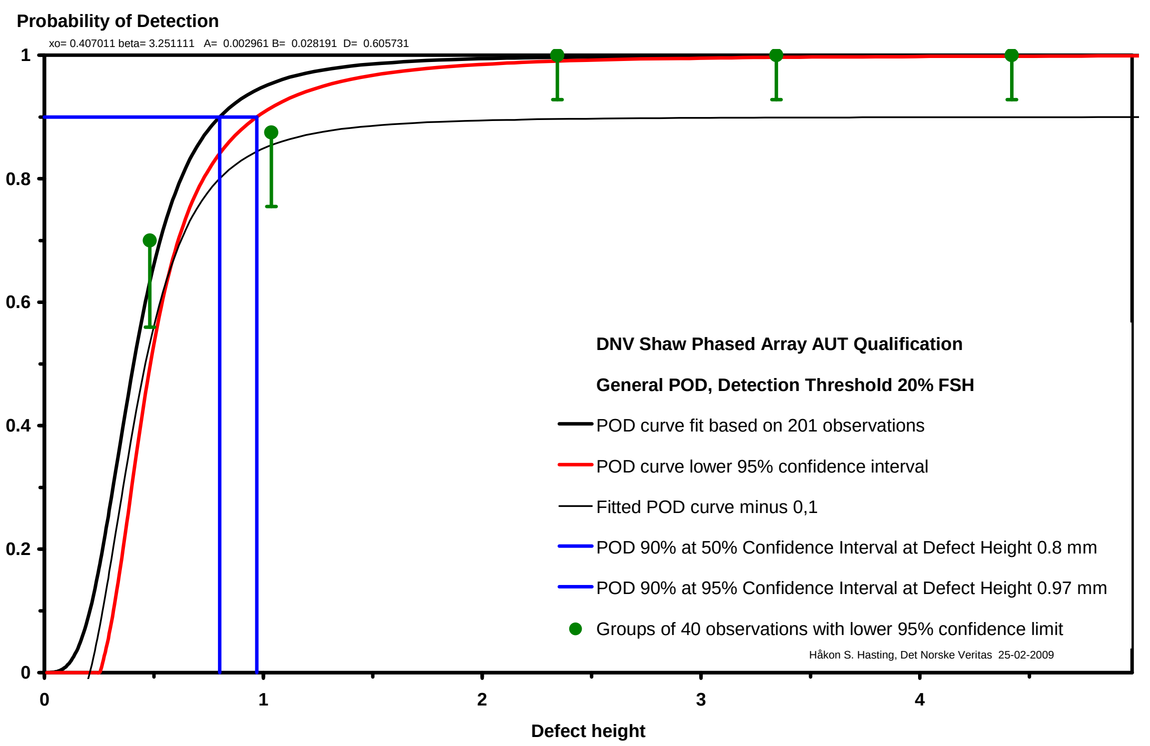


Figure 2: POD-curve for general detection, 90%|95% POD indicated

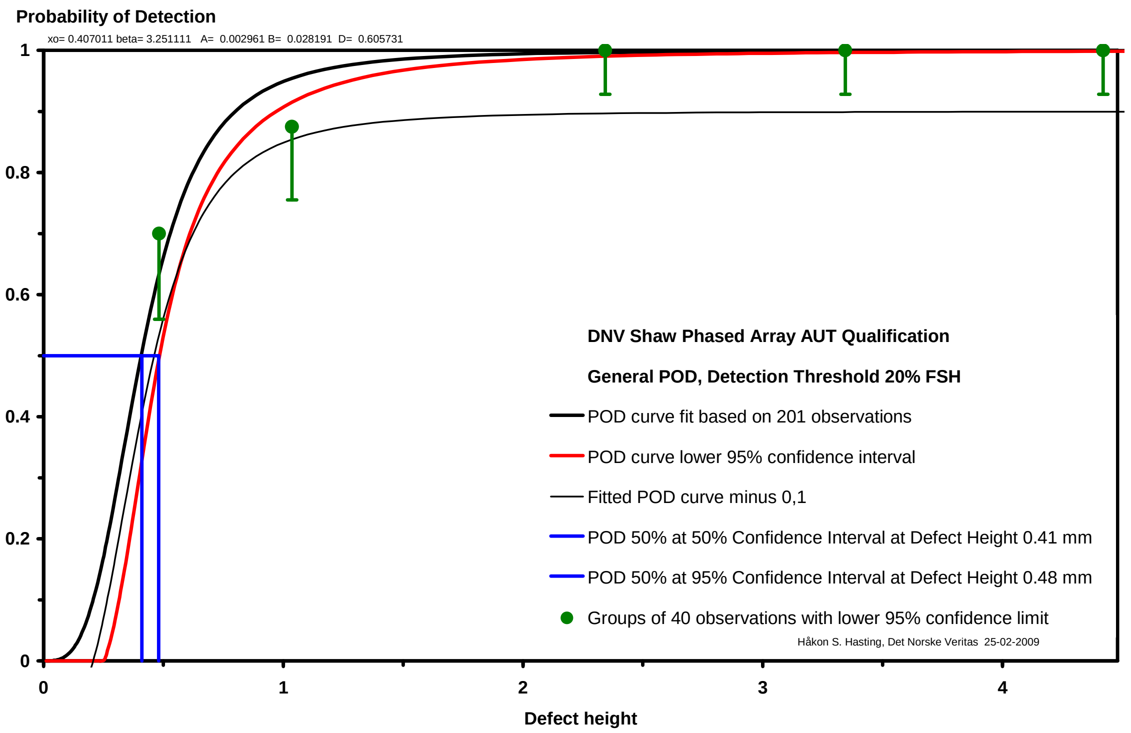


Figure 3: POD-curve for general detection, 50%|95% POD indicated.

6.2.2 Detectability in Root

The sensitivity of detection of surface breaking defects in the weld root area is regarded as very good. No considerable defects are recognised as disregarded of this kind the root area. The general trend is evident response from defects of even insignificant dimensions, as shown in Figure 4. The indistinct indications found in root area were from small pores, which can be regarded as volumetric defects. Due to the lack of reasonable defects disregarded by the system within the qualification data, no POD-curve is presented for root.

The pulse echo response in the root is sensitive to root geometry, for instance from excess penetration and small misalignment. An example is given in Figure 4.

More uncertainty is attributed to buried defects near the root, in particular those present in the hot-pass area. These will be commented on in section 6.2.6.

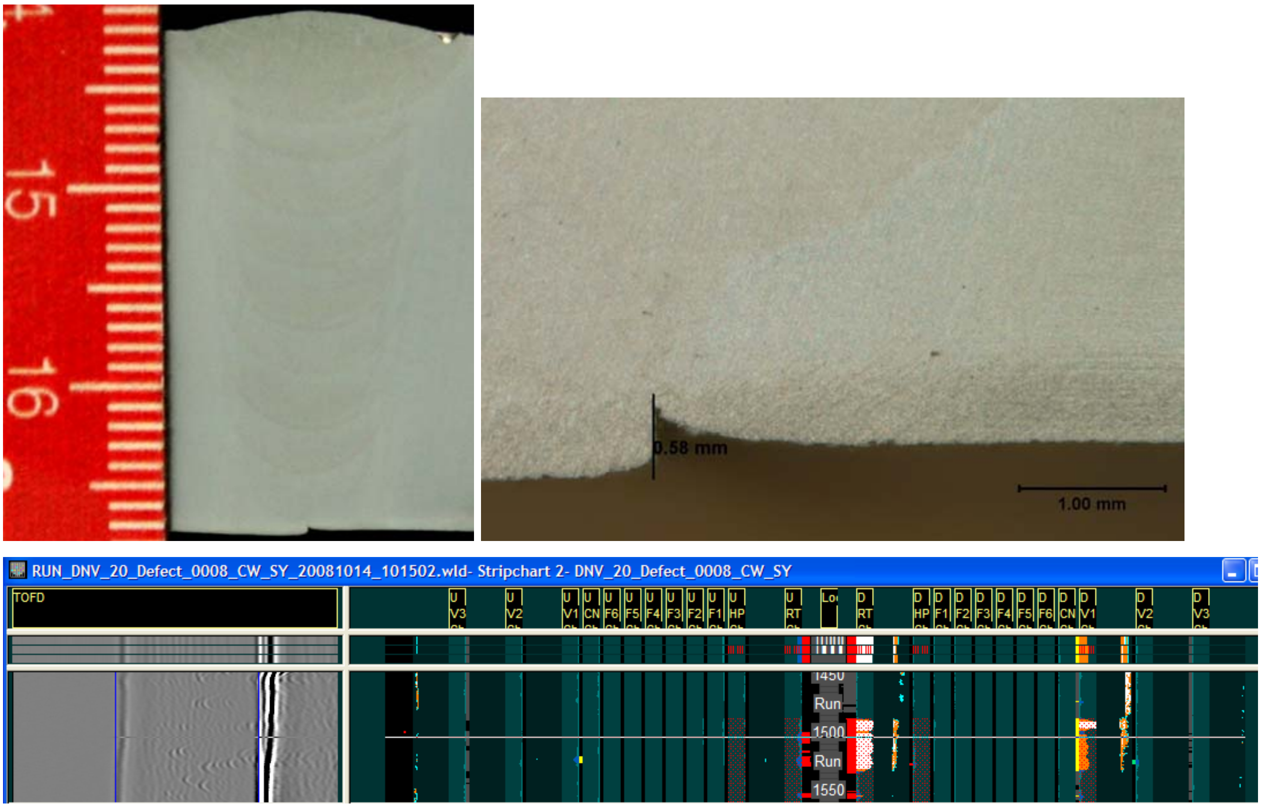


Figure 4: Small root misalignment of a measured maximum of 0.6 mm giving saturated signal in root channel, defect 8-7. US-side to right on figures.

6.2.3 Detectability of Embedded Defects

The detectability of embedded defects shown in Figure 5 is considerably better than the general POD. In this curve, the embedded hot pass-defects among the data are let out, in order to give a reasonable evaluation of the detection performance of the majority of the weld. If the embedded hot pass defects are included, the POD-curve will appear close to the general POD-curve of Figure 2.

For embedded defects at the weld bevel, the average detection, 50% POD, is estimated to 0.5 mm. The 90% POD value at 50% confidence is estimated to 0.7 mm, while the 90% POD at 95% confidence level is found at 0.85 mm.

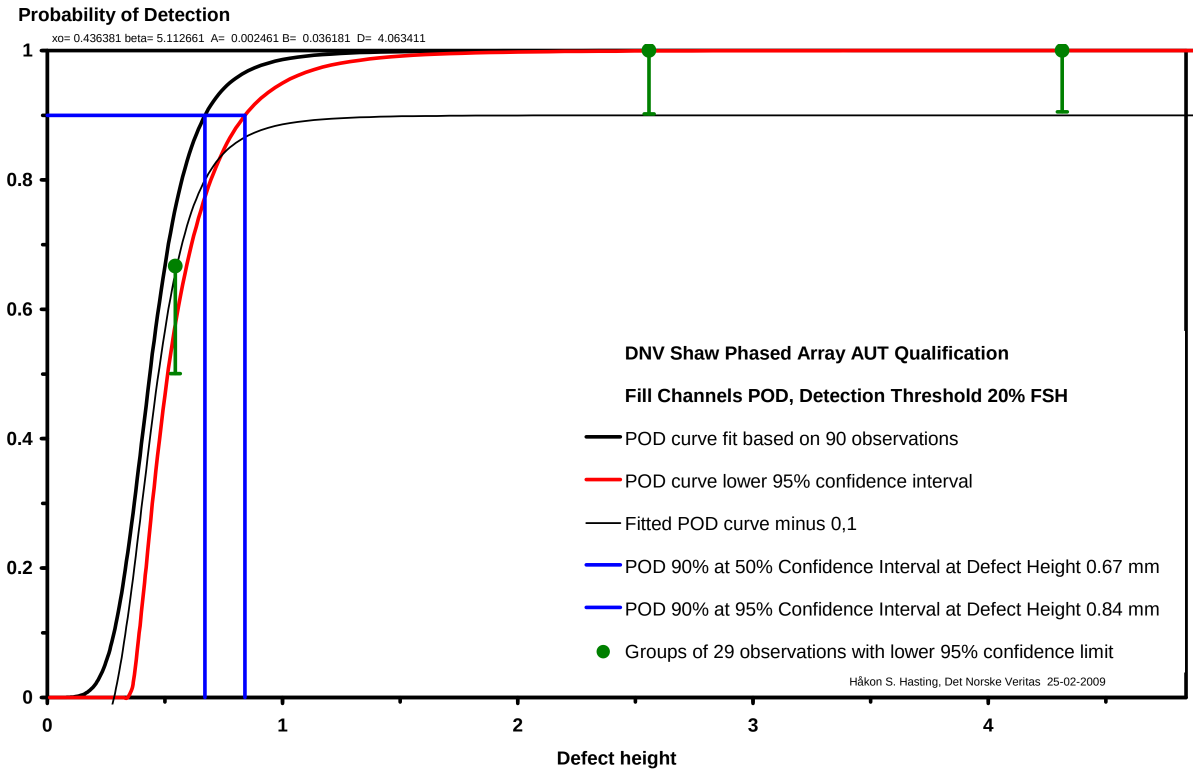
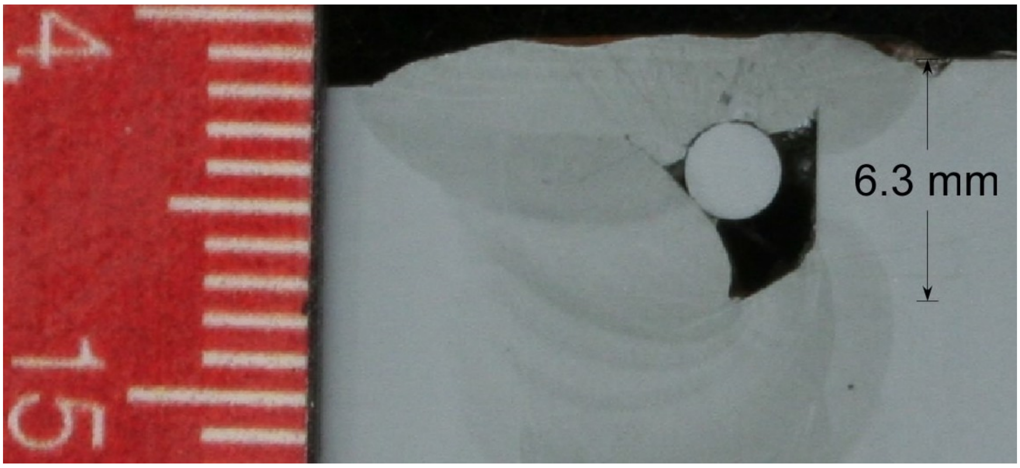


Figure 5: POD embedded defects.

6.2.4 Detectability in Cap

There are no disregarded defects at cap recognised during the qualification, with an applied detection threshold of 20% FSH with 1 mm notch calibration at 80% FSH. Without any disregarded defects, it is not possible to establish any POD-curve. The smallest surface breaking defect investigated at the outer surface had a height about 1.6 mm, with echo responses well above 100% FSH (saturation). For sub surface defects reported with amplitude in the cap-zone, the detectability is regarded to correspond with the general POD. An example of detection of sub surface defects is shown in Figure 6.



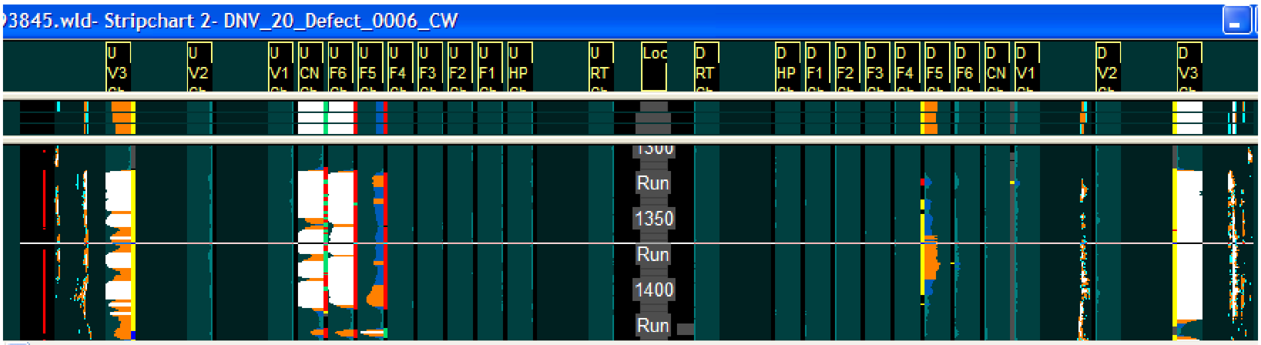


Figure 6: Sub-surface defect 6-5, position 1381 mm, with strong echo response in the cap-channel (CN).

6.2.5 Detection of Volumetric Defects

Volumetric defects are properly detected by the Shaw phased array AUT system. Detection of purely volumetric defects is not included in the general POD of Figure 2. However, a POD for the volumetric defects is probably irrelevant to make. This is due to the sensitive and complementary detection abilities for this kind of defects by TOFD, and to a need of a breakdown to position and type of defects in order to give a fair description. The qualification data material does not contain sufficient data for such extensive analysis, and it is very hard to locate defects disregarded by the sensitive ToFD when the signal in the volumetric pulse-echo channels is low.

The detection limit for volumetric defects appears to be at small and short defects, typically small pores. Very small inter-run lack of fusion flaws close to the weld bevel are picked up by the volumetric channels as well. Two examples are given in Figure 7 and Figure 8, which shows the volumetric flaws in the data material that appears to be at or below the detection limit.

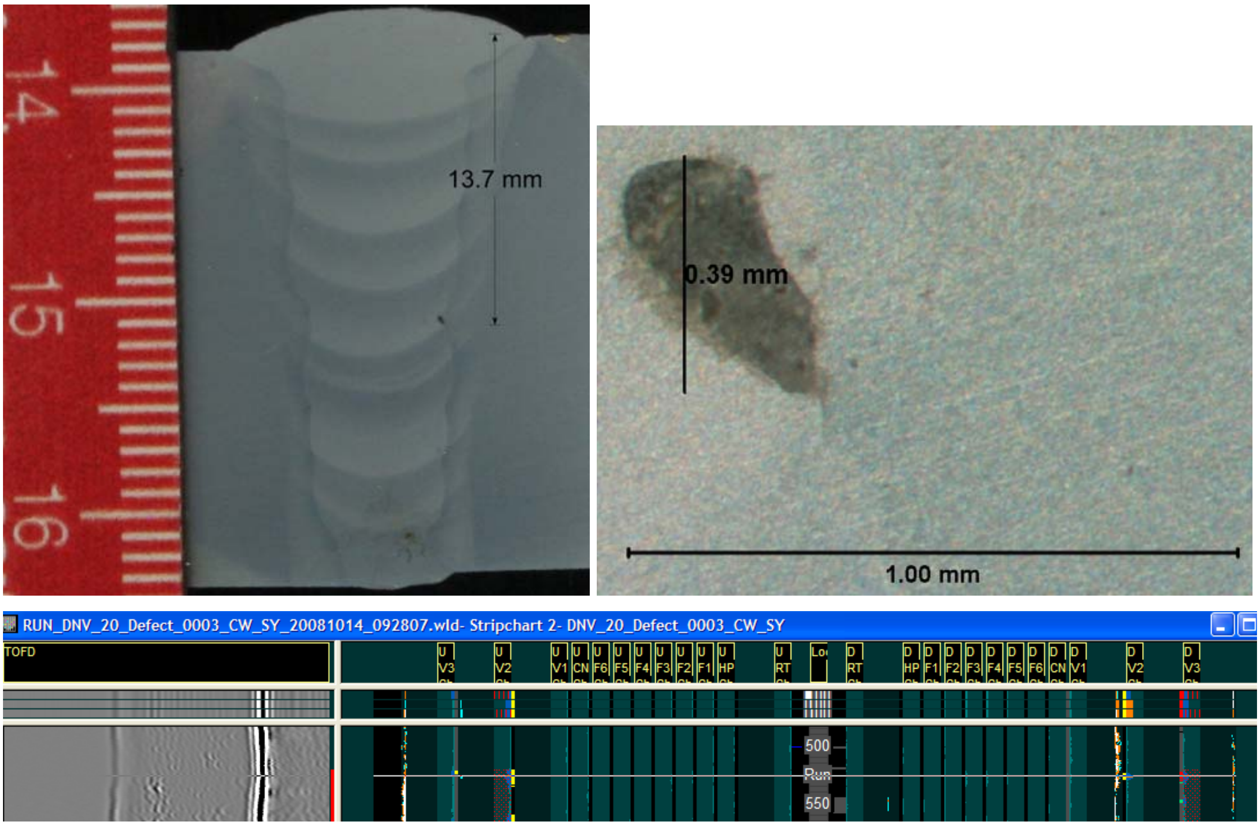


Figure 7: Volumetric defect picked up by small signal in volumetric pulse-echo channels, defect 3-1 at position 527 mm US-side. Reported amplitude between 13% and 21% FSH.

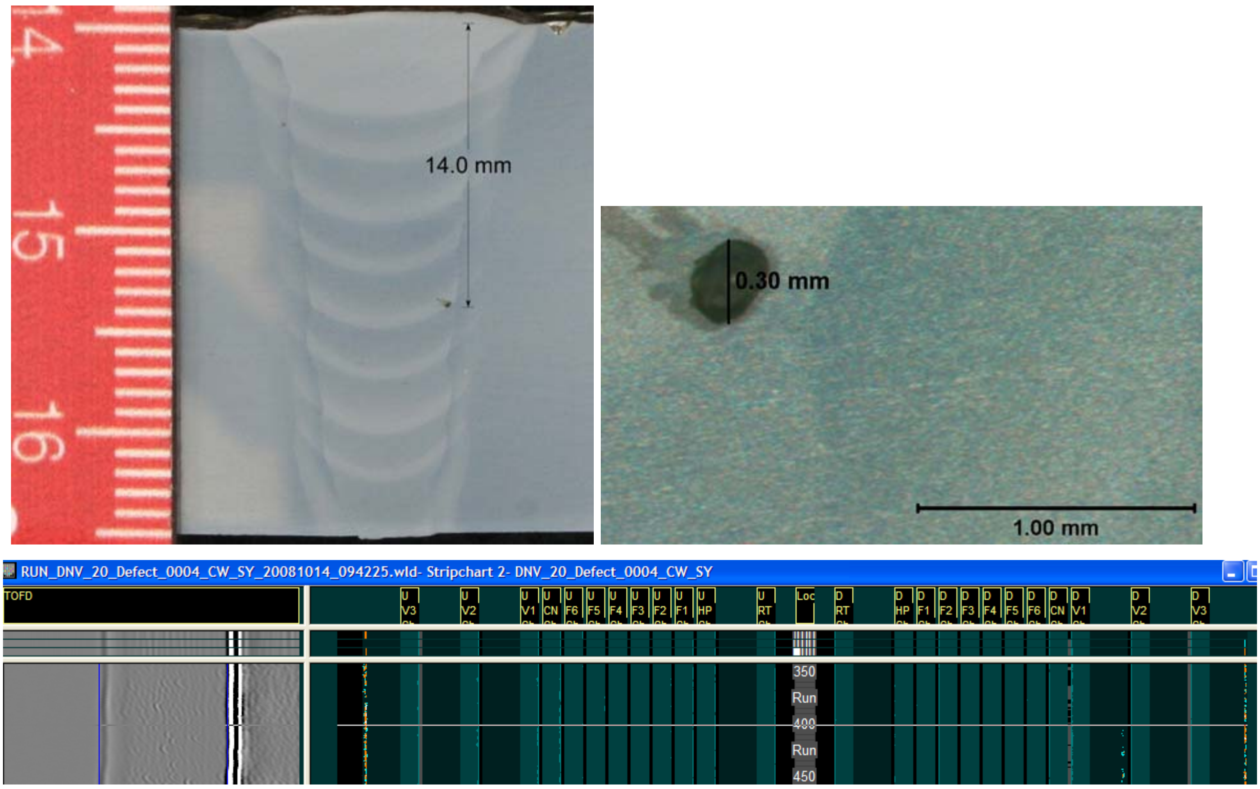
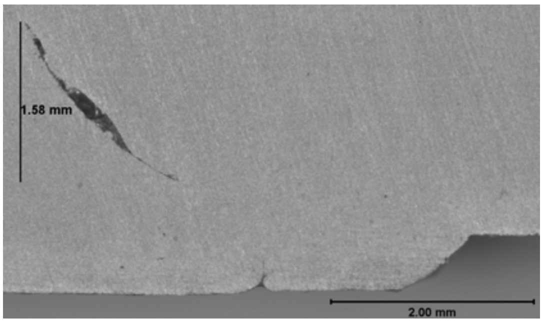


Figure 8: Small pore found in macro section of a “clean cut”, defect 4-2 at position 400 mm.

6.2.6 Detectability at Weld Bevel in Hot Pass

The trials showed some small defects at weld bevel certainly not detected by the AUT system, in addition to the volumetric defects mentioned in section 6.2.5. They were found occasionally at the macro sections, and common for all were their position in the hot pass channel. Hot pass is challenging for detection due to the curved bevel shape. The results from this qualification indicate that detection in hot-pass limits the overall detectability of the AUT system.

Figure 9 is macro images of defect 4-1, which at position 116 mm shows a lack of fusion in hot pass, 1.58 mm high. The depth of this indication is measured to be 24.0 mm at the bottom of the indication. This defect is not present at the neighbour macro section at 114 mm, and is measured to only 0.32 mm height at the opposite neighbour position at 118 mm. The defect is therefore rather short, likely less than 4 mm. In addition, 1.6 mm is probably at the peak height of this defect, and the height declines fast on both sides. The total area this defect covers on the weld bevel is small, this is one part of the reason that no indications are seen for this relatively high defect in hot pass on the AUT scan.

a) 

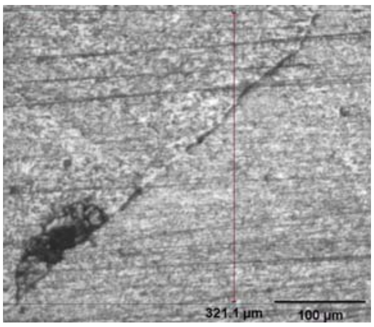
b) 

Figure 9: Defect 4-1. a) Macro at position 116 mm, b) Macro at position 118 mm, c) AUT scan of the same area. Defect on DS side.

A somewhat longer non detected defect is seen in hot pass on macros for defect 7-7. The defect is present on four macros from 1562 mm to 1568 mm, and is regarded to be at least 8 mm long. The vertical height is measured to about 0.8 mm, as shown in Figure 10. This defect might be attributed to indications in TOFD, but these are not clear.

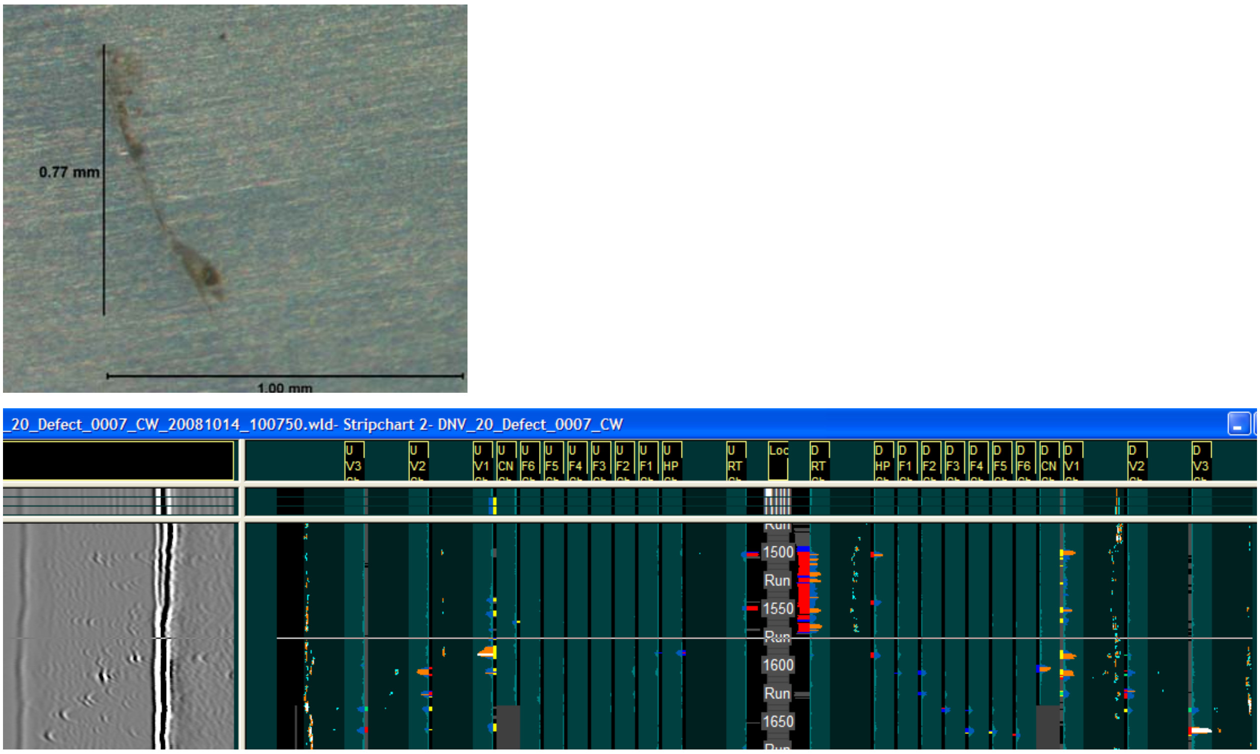


Figure 10: Defect 7-7. Macro at position 1566 mm and AUT scan of the area in question. Defect on DS-side

Based on the results above, another trial weld were subject to AUT scanning and macro sectioning to confirm detectability in hot pass, denoted weld 1. Four positions with small indications in hot pass were selected for macro sectioning. For this weld amplitude signal in hot pass were corrected by +6 dB. The AUT height sizing of these indications showed significant over-sizing, probably due to the increased sensitivity. Correction by 6 dB in hot-pass is recommended for critical applications where detectability of defect sizes of Figure 9 and Figure 10 are needed.

6.3 Height Sizing Accuracy

6.3.1 General Height Sizing Accuracy

The general height sizing accuracy is found to be a systematic over-sizing of slightly less than 0.4 mm. The 95% limit against under-sizing is at -0.74 mm under-sizing, Figure 11. This means that the qualification shows a less than 5% probability of larger under-sizing than this value. Volumetric defects are not included in this figure. In total 194 observations on AUT height measurements are included in the analysis. The results are tabulated in Table 2. As seen in Table 2, it appears to be significant differences in height sizing accuracy between root, fill and cap defects.

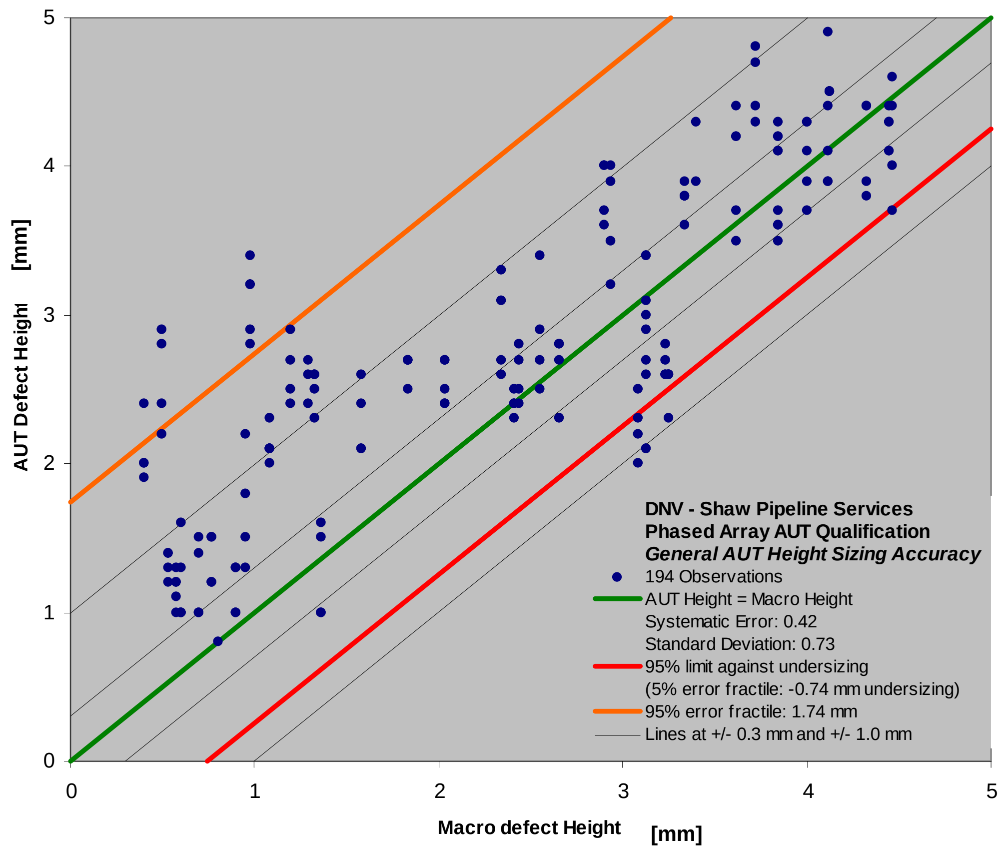


Figure 11: General height sizing accuracy plot.

Table 2

Defect type	No. defects	Systematic Error / Mean sizing error [mm]	95% limit against under-sizing [mm]	95% limit against over-sizing [mm]
General	194	0.4	-0.7	1.7
Surface-root	59	0.8	-0.8	2.2
Embedded	82	0.3	-0.4	1.3
Surface-cap	53	0.2	-0.8	1.0

6.3.2 Root Height Sizing Accuracy

For all the defects investigated in the root area, there is a systematic over-sizing of 0.8 mm. However, the 95% limit against under-sizing is found at 0.8 mm under-sizing, as shown in Figure 12.

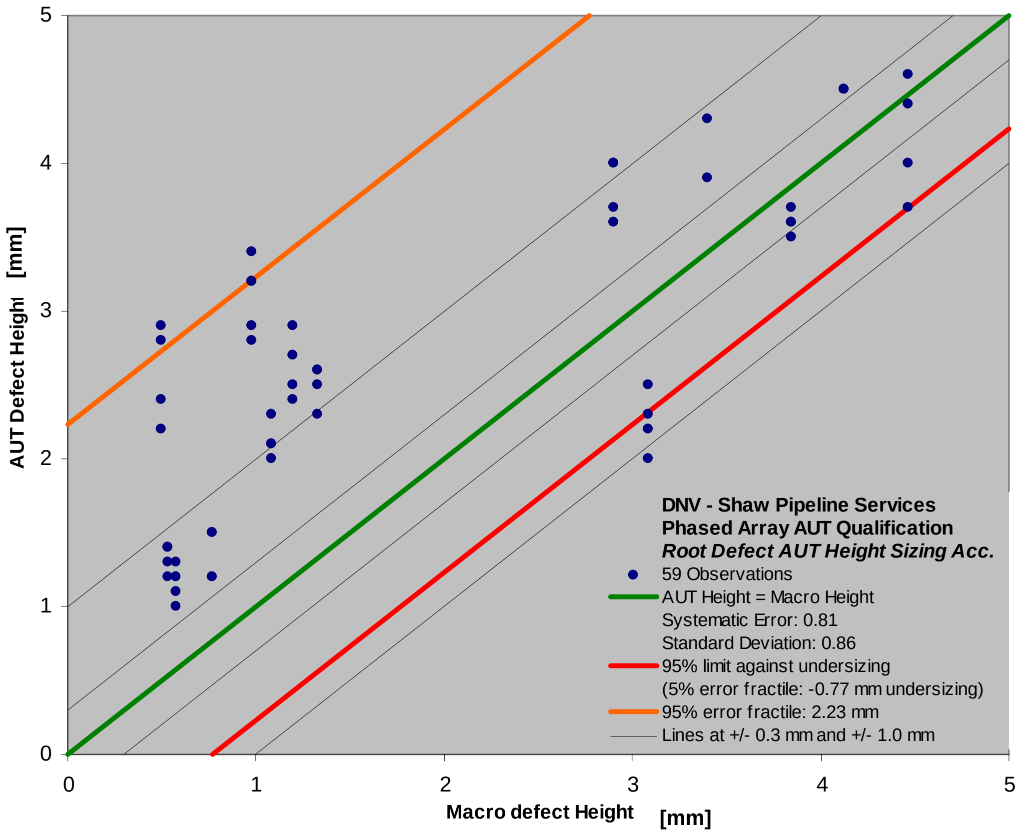


Figure 12: Height sizing plot for root area.

A table of the height sizing accuracy distribution in the root is given below.

Table 3: Height sizing accuracy distribution in root. Intervals of 0.5 mm sizing error.

Root	Oversizing					Undersizing		
Sizing error [mm]	**> 2.0**	**2,0 to 1.5**	**1,5 to 1.0**	**1,0 to 0.5**	**0,5 to 0.0**	**0,0 to-0.5**	**-0,5 to -1.0**	**< -1.0**
# Defects	5	7	12	15	9	6	4	1
% of total	2.6	3.6	6.2	7.7	4.6	3.1	2.1	0.5

When looking closer at the background data, under-sizing and over-sizing seem to be attributed to different types of defects. The main over-sizing is found for typically small lack of root fusion, misalignment or excess penetration type of defects, i.e. mostly geometrical defects. The pulse-echo indications for these defects tend to be relatively low, below 100%, and with no clear indications in hot pass-channel. An example is given in Figure 13 from defect 8-3. The macro shows a defect height of 1.08 mm, while the height has been interpreted to between 2.0 and 2.3 mm from the AUT scan.

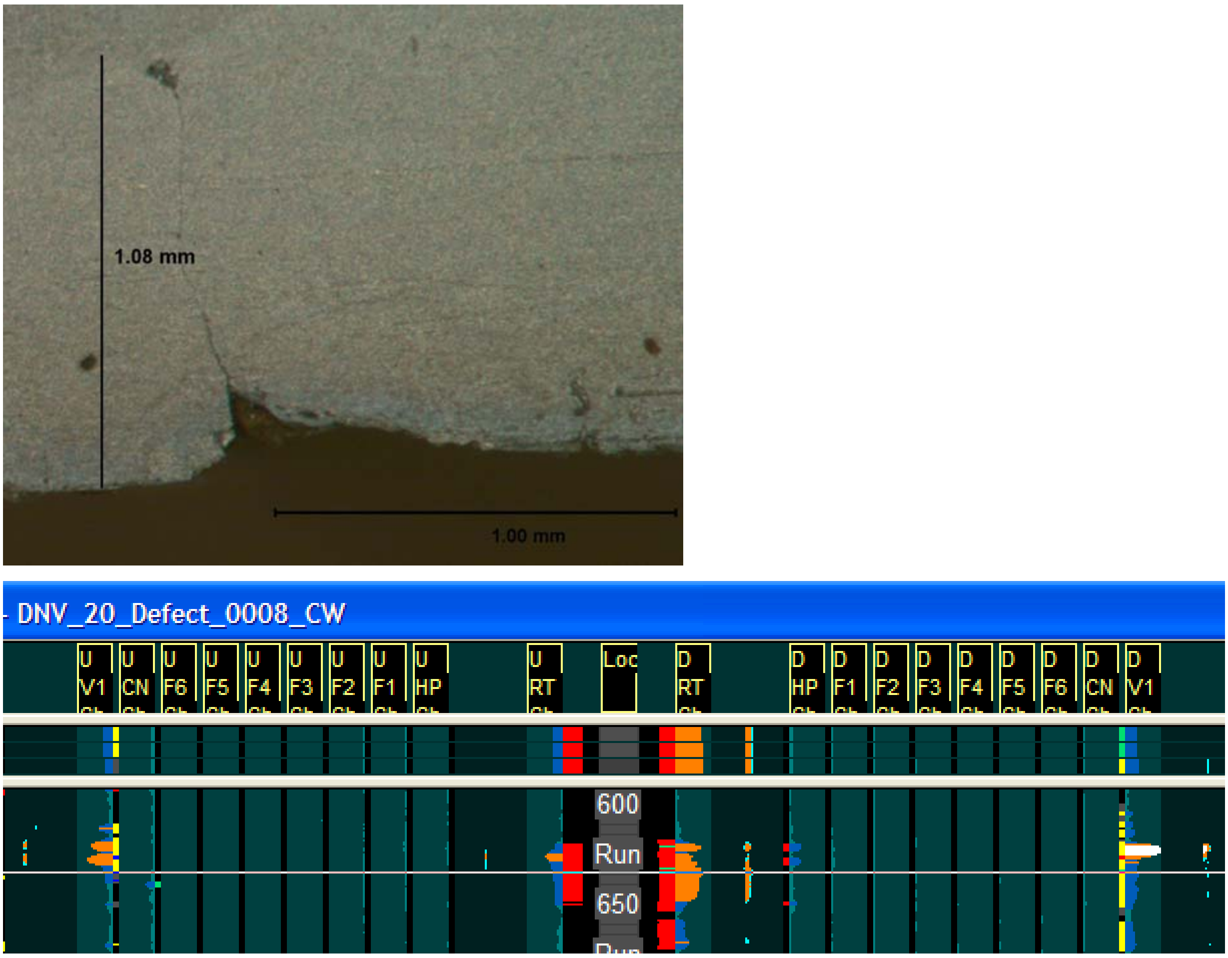


Figure 13: Root indication in Defect 8-3. Macro indicates a defect height of 1.1 mm, height has been interpreted to between 2.0 and 2.3 mm from AUT scan.

A tendency of under-sizing is seen for more severe lack of fusion type of defects, which go into hot pass channel as well. These types of defects accounts for all the under-sizing found among root defects, and the under-sizing applies for 3 out of 5 such defects within the qualification data. This under-sizing might be attributed to the somewhat lower detectability of the hot pass channel seen during the qualification trials, described in section 6.2.6.

The most severe under-sizing is found for defect 4-7, shown in Figure 14. Macro shows a height of 3.1 mm, while the AUT scans have been interpreted to show defect heights of 2.0 to 2.5 mm. The AUT scan indicates a sharp peak height, this is confirmed by the neighbour section 2 mm apart which shows a height of 2.4 mm. Other similar defects are defects 2-3, 5-5, 7-5 and 1-3. Defect 1-3 was height sized with a +6 dB correction for the hot pass signal, and was significantly over-sized. This correction of the hot pass signal appears then to reduce the risk of under-sizing in root.

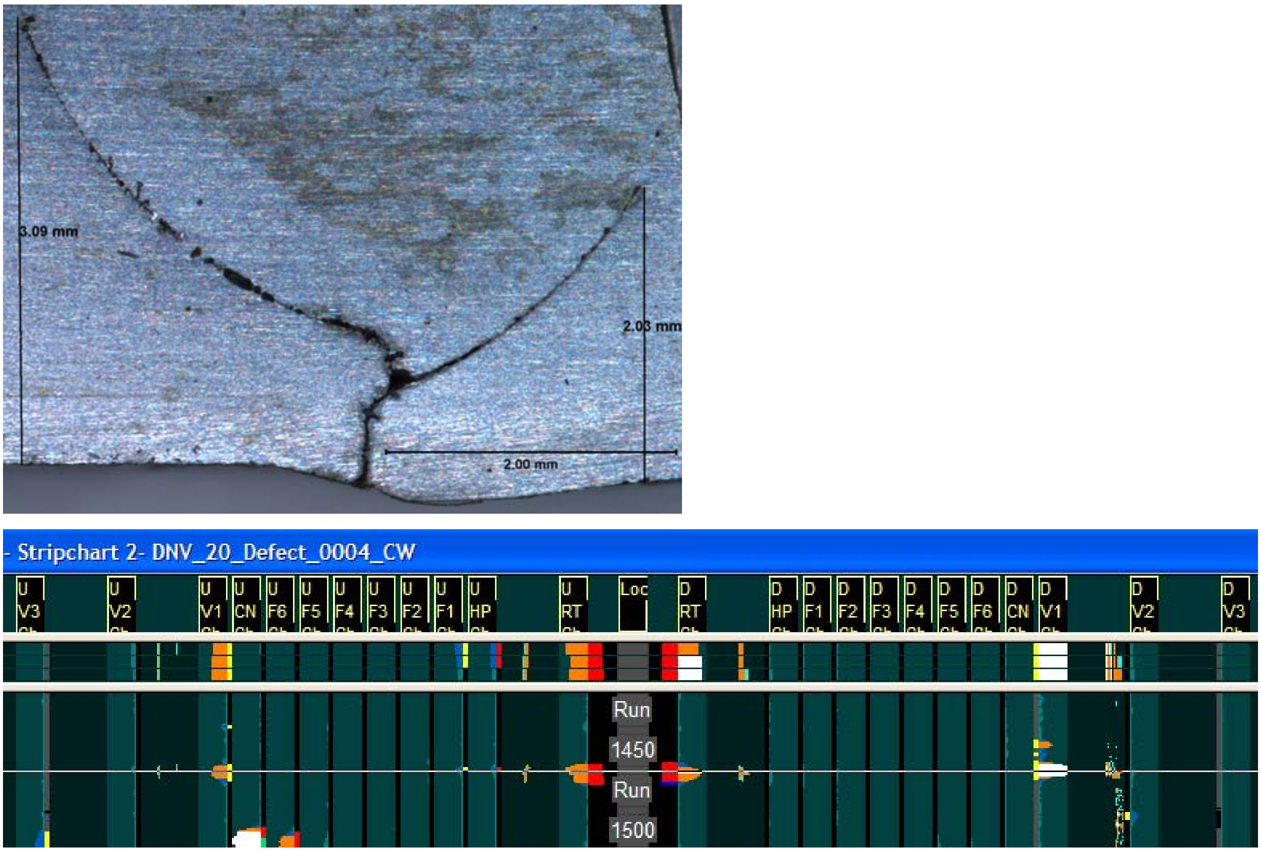


Figure 14: Root indication in Defect 4-7 at position 1464 mm. Macro indicates a defect height of 3.1 mm, height has been interpreted to between 2.0 and 2.5 mm from AUT scan. US-side to right on macro.

6.3.3 Embedded Defects Height Sizing Accuracy

For the embedded defects investigated, there is a systematic over-sizing of 0.3 mm. The 95% limit against under-sizing are found at -0.4 mm under-sizing, as shown in Figure 15.

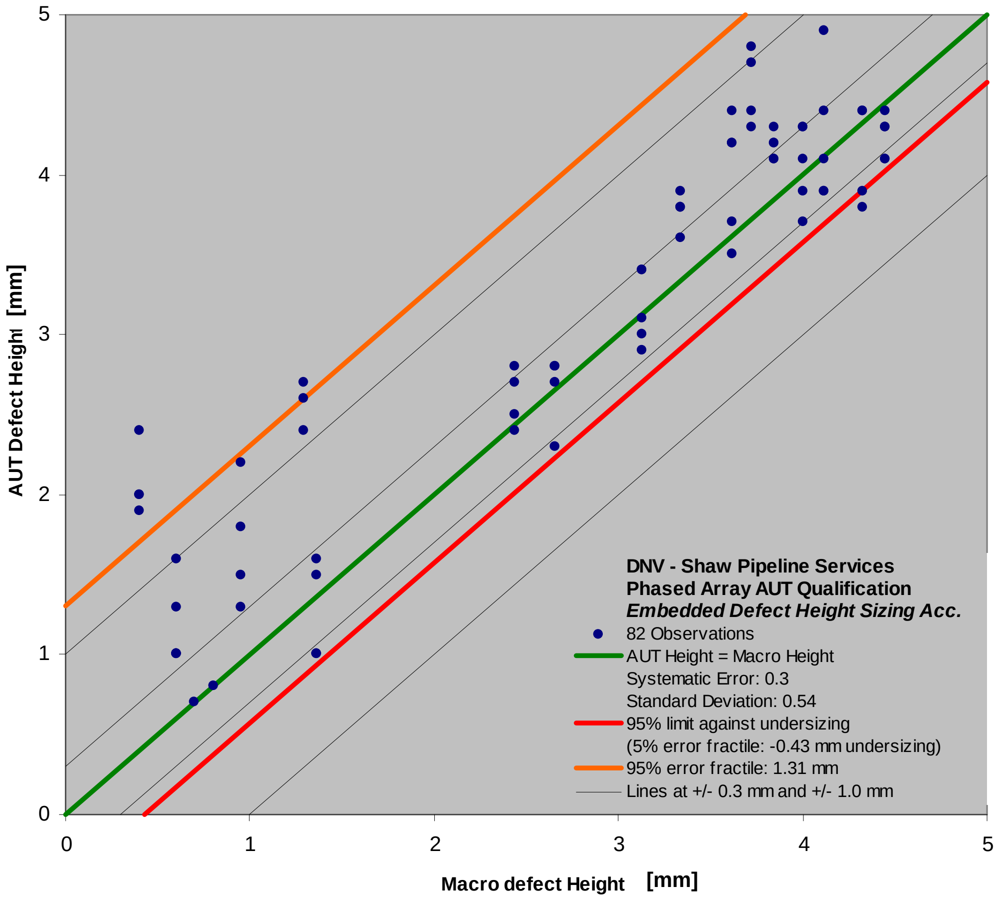


Figure 15: Height Sizing Accuracy for embedded defects.

A table of the height sizing accuracy distribution for embedded defects is given below.

Table 4: Height sizing accuracy distribution embedded defects. Intervals of 0.5 mm sizing error.

Embedded	**Oversizing**				**Undersizing**	
Sizing error [mm]	**2.0 to 1.5**	**1.5 to 1.0**	**1.0 to 0.5**	**0.5 to 0.0**	**0.0 to-0.5**	**-0.5 to -1.0**
# Defects	3	7	15	30	24	3
% of total	1.5	3.6	7.7	15.4	12.4	1.5

6.3.4 Surface-cap Defects Height Sizing Accuracy

Sufcace-cap defects are found to have a systematic over-sizing of 0.2 mm. The 95% limit against under-sizing are found at about 0.8 mm under-sizing, as shown in Figure 16.

The most evident under-sizing found for cap defects is attributed to the type of surface defects shown in Figure 17. The small tail at the bottom of the defect, continuing inside the steel at a difficult direction for the sound beam reflection probably accounts for the under-sizing.

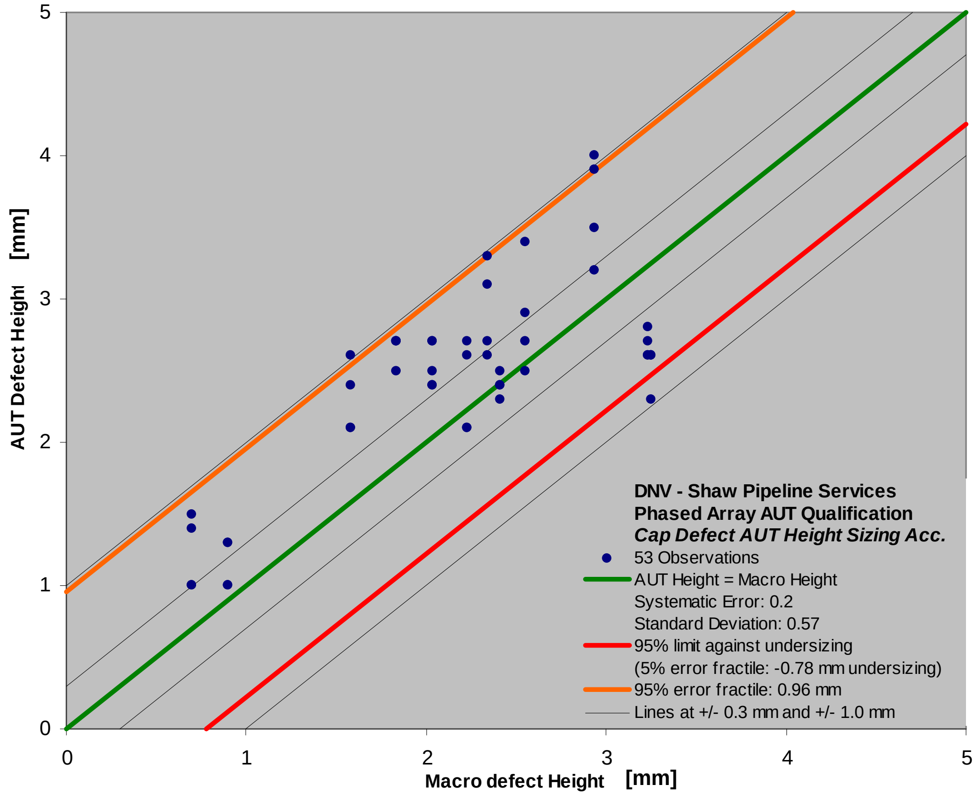


Figure 16: Height Sizing Accuracy for surface-cap defects

A table of the height sizing accuracy distribution for cap defects is given below.

Table 5: Height sizing accuracy distribution for cap defects. Intervals of 0.5 mm sizing error.

Cap	Oversizing			Undersizing	
Sizing error [mm]	**1.5 to 1.0**	**1.0 to 0.5**	**0.5 to 0.0**	**0.0 to-0.5**	**-0.5 to -1.0**
# Defects	1	17	18	8	9
% of total	0.5	8.8	9.3	4.1	4.6

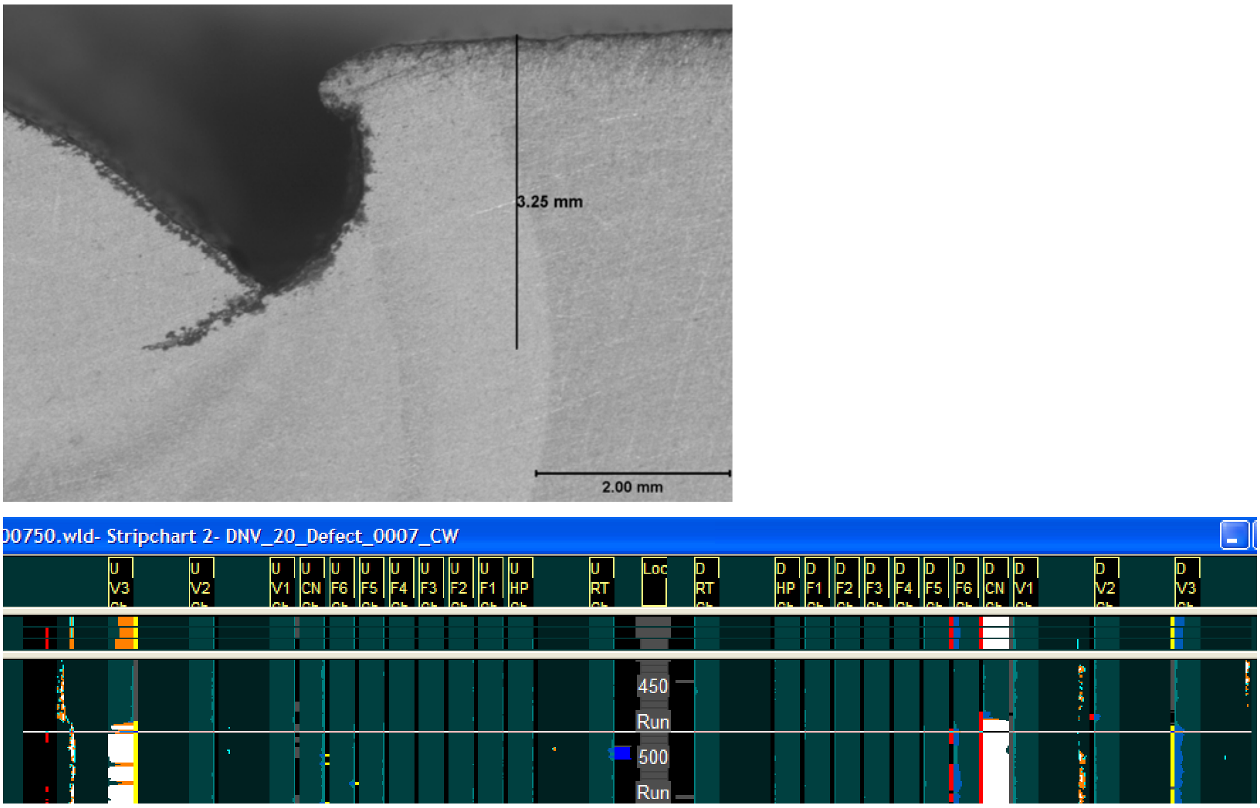


Figure 17: Surface-cap defect 7-3 at position 485 mm. Macro indicates vertical defect height of 3.25 mm, AUT reports 2.6 mm. DS-side to right on macro.

6.4 Probability of Rejection Analysis

Rejection of defects based on an AUT reported defect height rejection threshold is investigated, so called probability of rejection (PoR). Since the height sizing inaccuracy is inherent the reported height, the PoR includes both detection capabilities and height sizing inaccuracy.

When applied in qualification trials, the criterion for the smallest allowable defect size is at least a 85% PoR at a 95% confidence level, according to DNV OS-F101. The 85% PoR accounts for both a 90% POD and a 95% probability of avoiding under-sizing. The defect height at 85% PoR at 95% confidence level shall be equal to or below the smallest “allowable” defect height in the acceptance criteria.

Figure 18 shows how the estimated PoR-values at 50% and 85%, both at 95% confidence level, varies with increasingly set PoR threshold. The 50% PoR-value is the defect size that will be rejected on average, which might serve as a useful benchmark on how the system performs compared to the threshold AUT height. For instance, if all defects with reported AUT height of 2 mm are rejected, Figure 18 shows that one can expect to reject defects with height of 1.2 mm on average. Here, the X-axis denoted PoR threshold is attributed to the AUT reported height. Figure 18 suggests that there might be a tendency of good detectability and over-sizing for smaller defects heights, within the interval of 1.0 mm to 2.5 mm, where the average real defect height rejected is found lower than the threshold set on AUT reported height. For larger defect heights above 2.5 mm, the AUT rejection threshold shows good accordance with the real defect size on average.

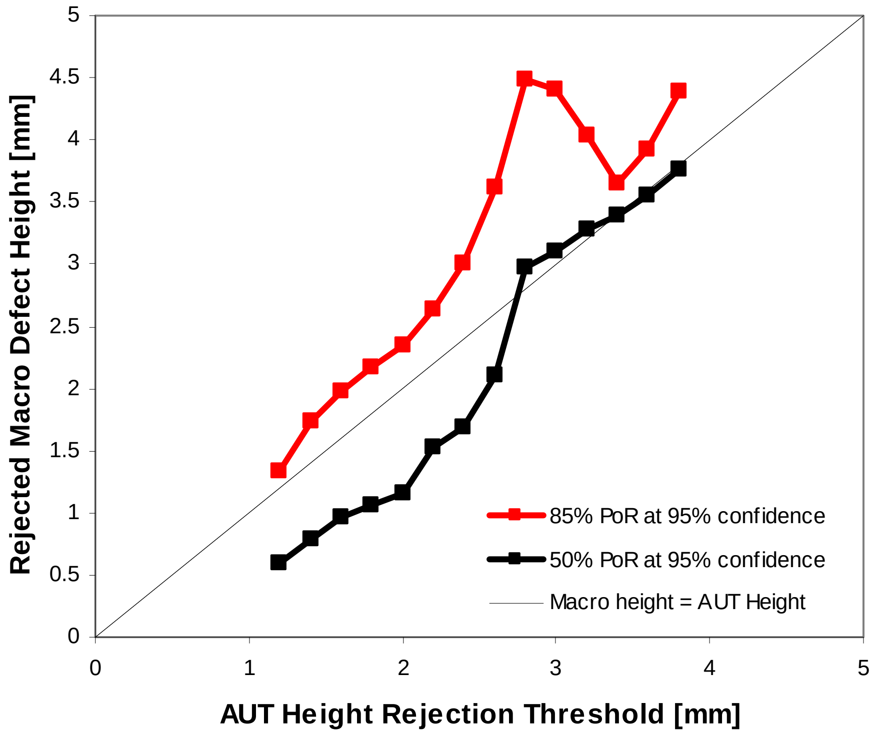


Figure 18: Results of PoR-analysis for varying rejection limits of AUT reported height.

The 85% PoR-value is a more conservative approach to establish AUT system performance, and can be used to directly set the height allowance for the system. In contrast to the average 50% PoR-value, this value is focused on the smallest defects rejected at the set threshold. In Figure 18 the 85% PoR-values suggest to add a 0.5 mm height allowance for defects reported smaller than 2.5 mm. The anomalous peak seen at around 3 mm is mainly attributed to large over-sizing of some smaller defects, which cause a poor fit between the dataset and the statistical model used. This is also attributed to the relatively low number of defects larger than 3 mm within the qualification data, which enlarges the uncertainty. It is therefore regarded to have no relevance for the height allowance. In general, the height allowance found in the PoR-analysis is in accordance with the under-sizing height allowance of 0.8 mm established in height sizing accuracy section 6.3.1.

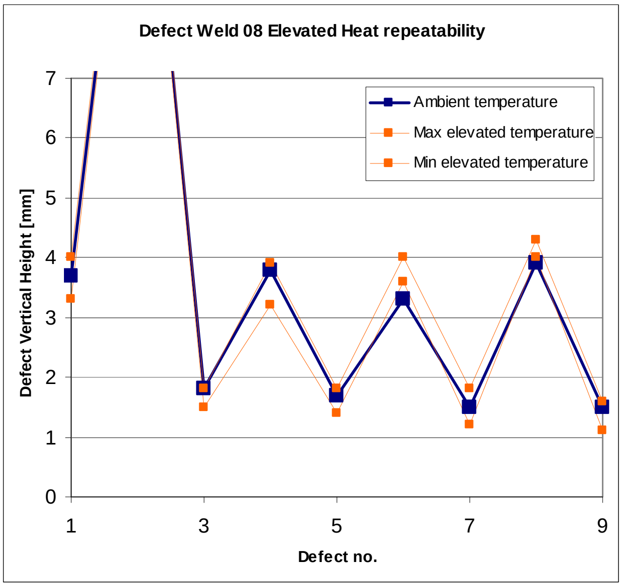
6.5 Repeatability

The pre-examination repeatability test scans on calibration blocs show sufficient consistency for repeated scans, with no deviation from initial scan more than ± 2 dB. In general, the test scan series are found to give deviations well within ± 1 dB. No evident differences in repeatability are seen between the scan series of different conditions, e.g. 12 o'clock, 6 o'clock, vertical (2G) or 45 degree (6G) positions. The same applies for the 1mm offset scans performed. The full results of these tests can be found in Appendix 1.

The repeatability of this AUT system is also included in the reliability analysis through use of both clockwise (CW) and counter-clockwise (CCW) scans in the analysis.

6.6 Temperature Sensitivity

The high temperature test scans shows good consistency between scans at ambient temperature and scans at elevated temperature. This is illustrated in Figure 19 and 20, where the height of the defects found and measured in test welds 8 and 9 is plotted, for ambient temperature scan and maximum and minimum values found within the 15 elevated temperature scans. There are 9 defects identified in both welds, in total 18 different defects. From these figures it is evident that the temperature is not a critical factor of uncertainty for the Shaw Phased Array AUT system. The measurement done at ambient temperature appears to fall in between the maximum and minimum height measurements found at elevated temperature. The deviations in height measurements from average value for the elevated temperature scans are found to usually be of less than 10%, which can fully be attributed to the repeatability performance of the system rather than temperature.



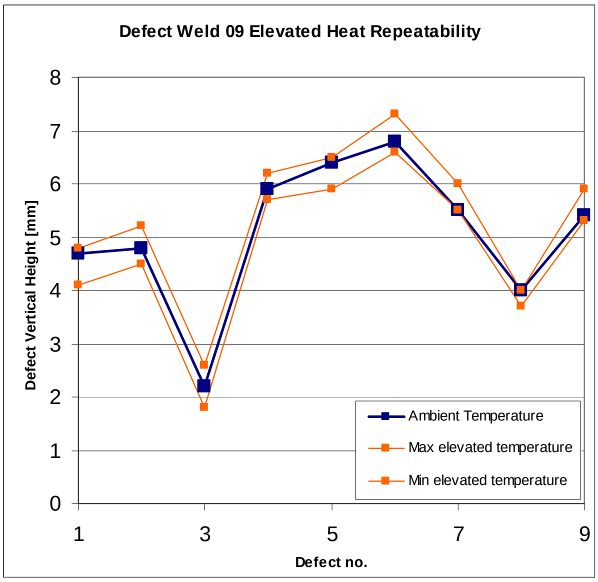


Figure 19 and 20: Elevated temperature repeatability and ambient scan for defects in respectively weld 8 and weld 9.

Temperatures measured just before the scanning and the time between finishing of each scan are summarised in Table 6.

Table 6: Elevated temperature scans

	Weld 8		Weld 9	
Scan series	**Temperature ˚C**	**Time min.**	**Temperature ˚C**	**Time min.**
1	96.5	4:38	99	3:12
2	96	3:49	94	2:45
3	94.9	3:06	98	2:36
4	96.6	3:15	96	2:41
5	96.	3:18	97	3:13
6	93.5	3:00	98	2:38
7	94	3:17	98	2:41
8	96	2:56	96	2:53
9	96	3:11	98.8	2:42
10	98	3:31	98.2	3:04
11	100.7	2:45	100.7	2:45
12	99	2:11	99.8	2:50
13	94.6	3:06	96.8	2:40
14	97	2:38	101	2:48
15	96	3:12	101.6	3:00

The information from the high temperature scans is included in the height sizing accuracy evaluation, which means that the sizing error figures presented in section 6.3 are valid for scanning at 90˚C. These results clearly states that the Shaw PA AUT system will perform the same at 90˚C as at ambient temperature, and trial scans done at ambient temperature are fully representative for the system performance at elevated temperature.

6.7 Supplementary NDT

6.7.1 Radiography

Results from supplementary radiography were in good agreement with the AUT results, also when it comes to defect sizes and position. The Shaw PA AUT system were able to detect clearly all the defects found by radiography. Radiography was able to identify most of the larger and severe defects, but missed some defects as well. These were mainly short defects and small pores, but also severe defects with defect heights more than 3 mm, 4-7 and 7-5, were recognised not detected by radiography. Both are defects in root and hot pass, described in section 6.3.2.

6.7.2 Immersion Ultrasonic Testing by Conam Inspection

Results from supplementary immersion ultrasonic testing done by Conam Inspection were in good agreement with the AUT results for embedded defects in fill channels, for position, size and shape. The resolution appears to be good in the immersion scans, but the results show signs of scanning not optimised for this application. Detection in cap and root is random and severe defects are missed in these areas, for instance the defects 4-7 and 4-8.

Immersion scans are showing volumetric defects and areas with porosity very well, and the correspondence with porosity indications in TOFD scan is good.

6.7.3 Immersion Ultrasonic Testing by Southwest Research Institute

Results from supplementary immersion ultrasonic testing for one weld done by Southwest Research Institute were found to be in good agreement with the AUT results for all defects, for position, size and shape. The test procedure for this scan was clearly better optimised for girth welds than for the welds scanned by Conam Inspection.

Figure 21 shows results from immersion scan compared to AUT scan and macro section for root defect 1-3. The defect is a lack of root penetration, which moves into hot-pass as lack of fusion in the challenging curvature for echo reflection. Both the AUT and immersion UT are able to pick up this defect.

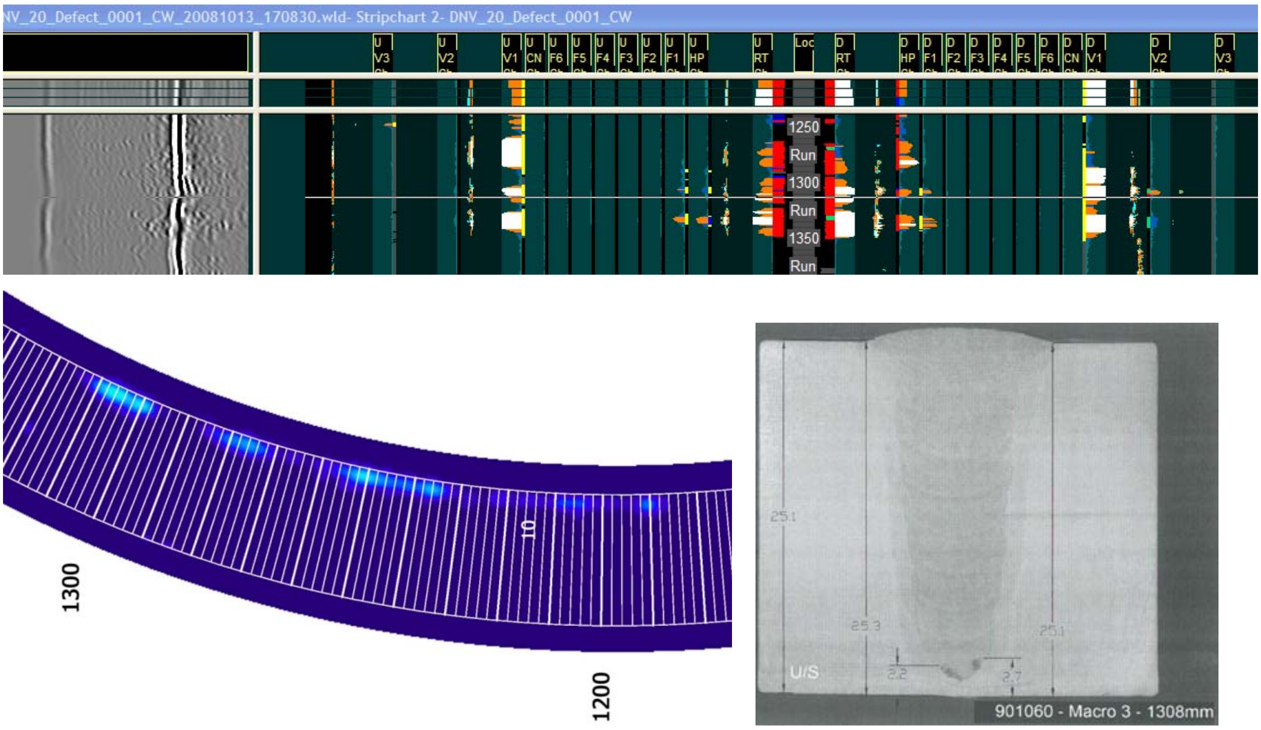


Figure 21: AUT-scan, immersion UT scan and macro section at position 1308 of defect 1-3. The scale on immersion UT scan appears shifted compared to AUT scan, macro position is at position about 1276 mm on immersion UT scan. Macro shows defect height of 2.7 mm at DS-side.

7 CONCLUSIONS

7.1 Introduction

The Shaw Phased Array AUT-system has been subject to qualification trials with respect to examination of girth welds. The qualification work has been done under agreement between Shaw Pipeline Services and Det Norske Veritas AS, and in significant interaction with Allseas Engineering bv. The qualification trials have covered 9 GMAW J-preparation welds in pipes of dimensions 25.0 mm x 20", which have been subject to trials for reliability, repeatability and heat influence. In total 74 defects were included for further analysis and welds were scanned four times: By two independent operators, and in CW and CCW direction for each operator.

7.2 Performance data

These are the results of the qualification, which is the documented performance of the Shaw Phased Array AUT System for detection of the weld configuration used for the trials, and also valid for similar configurations.

7.2.1 Detectability

The detectability on average for the Shaw phased Array AUT system is in general found to at 0.5 mm vertical defect height. This is the defect height one can expect the system to detect, the 50% POD-value at 95% confidence level. This value is regarded valid for defects longer than 4 mm.

Reliable detection at 90% POD with 95% confidence is in general found at 1.0 mm. This is the value relevant for the requirements in DNV-OS-F101.

The break-down on detectability for root, embedded and cap defects separately shows better detectability as the general for embedded and cap defects. The 90% POD at 95% confidence defect height is 0.84 mm for embedded defects. The root detectability is in general found somewhat better than the general detectability. Detection in hot pass is identified as the limiting factor of the general detectability of this AUT system. Detectability has been evaluated for a standard recording threshold of 20%.

7.2.2 Height Sizing Accuracy

The height sizing accuracy is found to be at 0.4 mm over-sizing on average, with a 5% limit for over-sizing at 1.5 mm and a 5% limit against under-sizing at -0.8 mm.

Break down on height sizing accuracy for root, embedded and cap defects separately shows similar figures, the most considerable deviations are a higher occurrence of over-sizing for root defects and less under-sizing for embedded defects.

Root channel appears to be very sensitive to geometrical defects, these accounts for the over-sizing seen within this weld area. At the same time, there is seen under-sizing of larger defects in the root area that moves into hot pass. A +6 dB increase of gain to the hot pass channel at scanning is recommended in order to avoid under-sizing of larger lack of root fusion defects, moving into hot-pass.

7.2.3 Repeatability

Repeatability tests on calibration block shows no deviations in amplitude response from calibration holes and notches on repeated scans compared to an initial scan of more than ± 2 dB.

7.2.4 Temperature

The Shaw Phased Array AUT system detection is seen to be unaffected by a trial temperature between 90˚C and 100˚C. Extensive heat trials at this temperature range showed deviations within the range of amplitude variations attributed to repeatability. Temperature in this range is therefore not regarded as a critical parameter of detection or height sizing of this AUT system.

7.3 Prerequisites

The performance documented in this report for the Shaw Pipeline Services Phased Array AUT system is regarded relevant for general use on carbon steel pipelines with similar weld bevel angles. These results can be used as basis for project specific qualifications trials, and hereby limit the required scope of qualification work. This is valid provided the prerequisites included in the conclusions below are met

No changes shall be made to the system including hardware, software and operating manuals and procedure that will influence the performance of the system with respect to defect detection and sizing, compared to what was achieved during the qualification. Care should be taken, and effects assessed, especially with respect to defect height sizing, when zone heights are changed.

Detailed inspection technique documents, similar to the ones used during the qualification, shall be used for relevant welds in question taking material thickness and variations, bevel preparation details and other relevant items into consideration.

The same type and size of reference reflectors (3 mm FBHs embedded, 2 mm FBHs hot pass and 1 mm surface notches) shall be used as during the qualification trials. A change in reflector sizes will require a reassessment of detection as well as sizing abilities.

Qualified personnel shall be used.

7.4 Materials

Girth welds shall be made in similar material pipe, with the similar type of weld bevel preparation and the same welding methods, as used during the qualification, without major changes. Changes in bevel angels within few degrees or small changes in root bevel preparation are not considered major, as long as the set-up of the AUT system takes this into account.

Wall thicknesses are to be between 12 mm and 40 mm, and pipe diameters above 8”.

7.5 Validity

5.1 The qualification has unlimited validation, given the prerequisites in section 7.3 are met.

APPENDIX
1
REPEATABILITY TRIAL RESULT DATA

- o0o -

Calibration bloc repeatability trials result

DownStream Band Offset Repeatability Tests

DS Offset Scans (% FSH)						
Reflector	INITIAL	Cal No: 01	Cal No: 02	Cal No: 03	Max dB Variance	Min dB Variance
D/S RT	79.5	71.2	71.7	71.7	0.9	1.0
D/S HP	78.7	72.4	71.7	71.7	0.7	0.8
D/S Fill 1	81.9	80.3	80.3	80.3	0.2	0.2
D/S Fill 2	83.0	77.2	77.2	76.4	0.6	0.7
D/S Fill 3	82.7	83.5	83.5	84.3	-0.2	-0.1
D/S Fill 4	89.8	85.0	86.6	85.0	0.3	0.5
D/S Fill 5	78.7	78.7	78.7	80.3	-0.2	0.0
D/S Fill 6	84.3	79.5	77.2	78.0	0.5	0.8
D/S CN	77.2	70.9	69.3	68.5	0.7	1.0
D/S Vol 1	78.7	75.6	76.4	76.4	0.3	0.3
D/S Vol 2	82.7	80.3	79.5	78.0	0.3	0.5
D/S Vol 3	83	78.0	78.0	77.2	0.5	0.6

US Offset Scans (% FSH)						
Reflector	INITIAL	Cal No: 01	Cal No: 02	Cal No: 03	Max dB Variance	Min db Variance
U/S RT	85	84.3	82.7	85.0	0.0	0.2
U/S HP	89	96.1	95.3	96.1	-0.7	-0.6
U/S Fill 1	86.6	73.2	73.2	73.2	1.5	1.5
U/S Fill 2	83.5	83.5	83.5	83.5	0.0	0.0
U/S Fill 3	83.5	78.0	78.0	78.0	0.6	0.6
U/S Fill 4	85.8	84.3	84.3	84.3	0.2	0.2
U/S Fill 5	84.3	91.3	91.3	90.6	-0.7	-0.6
U/S Fill 6	83.5	71.7	72.4	71.7	1.2	1.3
U/S CN	82.7	73.2	72.4	73.2	1.1	1.2
U/S Vol 1	85.8	82.7	85.0	84.3	0.1	0.3
U/S Vol 2	88.2	82.7	82.7	80.3	0.6	0.8
U/S Vol 3	81.1	81.9	81.1	81.1	-0.1	0.0

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APPENDIX
2

RELIABILITY TRIAL DATA

Weld - Defect ID	Macro [mm]			Defect Length [mm][1]	AUT Height [mm]				Amplitude [%FSH]				Channel
					Operator 1		Operator 2		Operator 1		Operator 2		
	Position	Height	Depth		CW	CCW	CW	CCW	CW	CCW	CW	CCW	
2-1	50	2.66	13.6	67	2.8	2.7	2.8	2.3	99	89	93	88	F4
2-2	80	1.36	13.8	67	1.6	1.5	1	1	28	26	23	26	F3
2-3	1202	4.13	25.4	66	4.5	4.5	4.5	4.5	150	126	174	127	RT
3-1	527	0.39	13.7	57	2.1	2.1	2	2	14	21	13	21	V
3-2	900	3.72	22	99	4.4	4.7	4.3	4.8	158	163	168	149	F1
3-3	935	4.33	21.6	99	4.4	4.4	3.8	3.9	151	160	151	157	F1
3-4	1156	0.95	8.1	89	2.2	1.8	1.5	1.3	48	50	54	48	F5
3-4_2	1154	0.66		89	1	1	1	1	100	100	100	100	V
4-1	112	0.53	24.1	82	1.4	1.3	1.2	1.4	20	23	44	22	RT
4-2	400	0.3		0	0	0	0	0	0	0	0	0	V
4-3	675	2.23	5.8	89	2.7	2.6	2.1	2.1	81	74	81	78	CN
4-3_2	673	0.7	4	89	1.4	1.5	1	1	27	50	32	65	CN
4-4	710	2.55	6	89	2.7	2.9	2.5	3.4	80	99	96	122	CN
4-4_2	713	1.1	4	89	1.8	1.9	1.7	2.1	100	100	100	100	V, CN
4-5	1085	1.84	1.8	125	2.7	2.5	2.7	2.7	121	124	124	113	CN
4-6	1176	2.34	2.3	125	3.1	2.7	3.3	2.6	135	114	143	112	CN
4-7	1464	3.09	25	28	2	2.2	2.5	2.3	121	141	122	146	RT
4-8	1564	1.58	1.6	75	2.6	2.1	2.4	2.1	116	104	115	103	CN
5-1	515	0.17	10.2	90	1	1	1	1	100	100	100	100	V
5-2	523	0.52	11	90	1.6	1.5	1	1	100	100	100	100	F4, V
5-3	986	1.29	19.3	67	2.4	2.4	2.7	2.6	31	30	29	32	F2
5-4	1171	0.4	5.3	94	2	1.9	2.4	2	74	62	96	56	F6
5-5	1490	4.47	25	89	4.6	4.4	4	3.7	154	151	165	158	RT
6-1	436	0.9	4.3	134	1.3	1.3	1	1	30	32	31	28	CN
6-2	463	2.94	3.9	134	3.5	3.9	3.2	4	114	156	116	176	CN
6-3	995	0.55	11.8	114	1	1	1	1	100	100	100	100	V
6-4	1155	2.44	19.6	85	2.8	2.7	2.5	2.4	111	106	117	101	F2
6-5	1381	5.1	6.3	126	4.7	4.2	4.1	4.4	199	172	188	178	CN
6-6	1554	0.69	8.7	51	1	1	1	1	100	100	100	100	V
7-1	78	3.23	3.2	114	2.7	2.6	2.8	2.6	128	124	129	120	CN
7-2	234	4.25	24.2	33	15.6	16.2	15.6	15.6	100	100	100	100	TOFD
7-3	485	3.25	3.3	103	2.6	2.6	2.6	2.3	121	122	122	113	CN
7-4	498	2.41	2.41	103	2.4	2.3	2.5	2.4	115	112	117	113	CN
7-5	643	3.85	25	122	3.7	3.6	3.5	3.6	160	190	160	180	RT
7-6	1229	0.77	25	85	1.2	1.2	1.5	1.5	49	64	58	68	RT
7-7	1562	0.8	25.4	73	2.6	2.5	2.3	2.6	76	60	61	64	RT
8-1	177	10.4	22.3	34	12.9	12.8	13	12.8	100	100	100	100	V
8-2	498	2.04	2	94	2.5	2.4	2.7	2.4	117	119	124	111	CN
8-3	632	1.08	25	105	2	2.1	2.1	2.3	71	70	90	78	RT
8-4	1200	0.98	25	84	2.9	3.4	2.8	3.2	117	119	101	107	RT
8-7	1510	0.58	25	94	1.2	1.1	1.3	1	109	105	109	106	RT
9-1	118	4.45	19	85	4.3	4.4	4.1	4.1	155	148	151	148	F2
9-2	136	3.34	18.9	85	3.8	3.9	3.8	3.8	142	133	144	132	F2

[1]As reported during one of the AUT scans; - or, as estimated from Macros: >0: observed in one Macro, >2: observed in two Macros 2 mm apart, etc.

9-3	347	4.12	13.5	88	4.1	3.9	4.4	3.9	149	156	167	152	F3
9-4	469	1.95	6.9	88	1.5	1.2	1.0	1.1	40	43	30	40	F5
9-4_2	471	6.33	10.9	88	6.1	6.0	5.6	5.5	231	206	211	204	F5
9-5	516	0.6	7	88	1.3	1.6	1	1	36	32	32	32	F5
9-5_2	516	3.62	11.4	88	4.2	4.2	3.5	3.7	137	158	161	156	F5
9-6	987	4	16.7	88	4.3	3.7	3.9	4.1	167	152	157	157	F3
9-7	1189	3.85	13.4	90	4.1	4.1	4.3	4.2	147	150	160	158	F4
9-8	1224	4.42	13.5	90	5.5	5.5	5.1	5.2	161	179	179	172	F4
9-11	1342	3.13	10.3	95	3.4	3.1	3	2.9	98	118	108	104	F4
3-2_a	900	0.6	24.5	> 2									RT
3-3_a	935	0.4	12.9	> 2									F4
4-1_a	116	1.68	24	> 2									HP
4-2_a	400	0.3	14	> 0									F3
4-3_a	675	0.16	11	> 0									F6
4-4_a	703	0.54	13	> 2									V
4-4_b	705	0.63	16	> 2									V
4-4_c	713	1.9	13	> 0									V
4-4_d	720	0.4	13	> 0									F3
4-8_a	1562	0.57	17	> 6									F2
4-8_b	1566	0.55	18	> 4									V
5-2_a	523	1.1	5	> 0									V
5-3_a	983	0.5	7.5	> 0									F5
6-2_a	465	0.4	11	> 0									F4
7-5_a	647	0.9	18	> 0									V
7-6_a	1227	0.9	22.7	> 0									HP
7-7_a	1568	0.8	23.4	> 8									HP
8-4_a	1164	0.3	22	> 4									HP
8-4_b	1176	0.6	24	> 2									RT
8-4_c	1192	0.5	18	> 4									F2
9-1_a	118	0.14	6	> 0									F5
9-3_a	351	0.16	18	> 2									F2
9-6_a	987	0.45	11	> 0									V
9-11_a	1342	0.44	11	> 0									F4

AUT height readings for elevated temperature scans, used to establish height sizing error:

Weld ID	Macro		AUT	Channel
	Height	Depth	Height	
8-1	10.4	22.3	13	V (Cu)
8-2	2.04	2	2.7	CN
8-3	1.08	25	2.1	RT
8-4	0.98	25	3.2	RT
8-7	0.58	25	1.2	RT
9-1	4.45	19	4.3	F2
9-2	3.34	18.9	3.6	F2
9-3	4.12	13.5	4.9	F3
9-4	1.95	6.9	1.3	F5
9-4_2	6.33	10.9	5.9	F5
9-5	0.6	7	1	F5
9-5_2	3.62	11.4	4.4	F5
9-6	4	16.7	4.3	F3
9-7	3.85	13.4	4.2	F4
9-8	4.42	13.5	5.2	F4
9-11	3.13	10.3	3.4	F4