CASE STUDY ON THE USE OF ADVANCED PHASED ARRAY ULTRASONIC TESTING METHOD ON LIMITED ACCESS T-JOINT WELDS MADE OF P91 STEEL

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Abstract: *This paper evaluates the performance of ultrasonic testing using the advanced Phased Array Technique (PAUT) applied to T-branch welded joints with unilateral access. The base material of the components forming the welded assembly is the thermally resistant martensitic steel grade P91 (9Cr1MoVNbN). The welding processes used to fabricate the assembly were TIG (Tungsten Inert Gas) for root pass deposition, and SMAW (Shielded Metal Arc Welding) for filling the joint.*
The quality assessment aimed to analyze the welding-induced imperfections, considering the known susceptibility of this material to creep failure during prolonged service at temperatures of 300–500°C, which can lead to aging effects, diffusion of chemical elements, and microstructural degradation. Due to geometrical constraints and limited accessibility imposed by the pipe system configuration containing the examined welded joint, a single-direction Phased Array Ultrasonic Testing (PAUT) inspection (unilateral scan) was selected. Consequently, the inspection represents a deviation from the ideal application conditions specified in ASME Boiler and Pressure Vessel Code, Section V, Article 23 (SE-213).

Keywords: Phased Array Ultrasonic Testing (PAUT), ultrasonic testing (UT), single-sided scanning, P91 steel, limited access inspection

1. INTRODUCTION

As today's combined cycle power plants operate under more demanding steam conditions and duty cycles than plants built in the last decade, designers are choosing now high-performance materials, such as ferritic steels with improved creep resistance properties, such as 9Cr-1Mo-V, for the manufacture of critical sections of steam boilers and the steam generator of heat recovery units [1-2].

X10CrMoVNb9-1 (or 9Cr-1Mo-V) is a martensitic steel, known as Grade 91, containing a minimum of 9% Cr and 1% Mo, microalloyed with Nb and V, with a controlled N content. It is suitable for applications operating at high temperatures (not more than 650 °C) and pressure of 250 bar - 300 bar. Its mechanical performance (yield strength ranging from 550MPa-860MPa, good resistance to stress corrosion cracking and sensitization) allows a significant reduction in the thickness of manufactured components compared to other heat-resistant steel grades, such as Grade 22 [3-4]. This steel is normalized at 1050 °C, followed by air cooling to 200 °C and then tempered at 760 °C, to obtain their mechanical properties.

Welding techniques like shielded metal arc welding (SMAW), tungsten inert gas argon arc welding (GTAW), and submerged arc welding (SAW) are frequently used to join related components. Post weld heat treatments (PWHT) are used to improve the joint's creep strength and toughness, to reduce residual stress and hardness, and to guarantee that the joint can withstand elevated temperatures and high pressures for an extended period [5].

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High-quality P91 welds require right filler metal that assures the correct chemical composition in the weld metal, i.e. that provides a typical X-factor designation for the product. The formula for X-factor that evaluates the weldment's resistance to temper embrittlement is calculated considering the effects of critical contaminants in this steel: phosphorous (P), antimony (Sb), tin (Sn), and arsenic (As):

$$X = (10P + 5Sb + 4Sn + As)/100 \quad (1)$$

The X-factor of a filler metal must be lower than 15 to be suitable for P91 applications [6]. Also, many measures can be taken for controlling diffusible hydrogen amounts in the weld, to prevent hydrogen-induced cracking, such as preheating procedures, good cleaning of metallic surfaces, and low humidity level [7-8]. The creep damage of P91 steel in long-term service is one of the prime causes of structural aging, chemical element diffusion, and microstructural degradation, which can lead to premature failure [9-10].

From non-destructive inspections, it has been found that in pressurized structures made of P91 steel that have been in long-term service, failures have occurred either in the weld or in the thermo-mechanically affected zone (HAZ) [11]. The thermal shock generated by the welding process favors reaching critical loading conditions at which micro-defects existing in the material are produced or developed, which cannot usually be detected by conventional means [12].

Studies conducted on the welding of P91 alloy have found that crack propagation occurs in the early stage of cooling. By increasing the value of heat input, the length and critical distance of crack propagation increase. Therefore, to avoid the appearance of cracks in the HAZ, the values of heat input during welding must be kept as low as possible [13].

If access to the joint area is limited to only one weld side, its examination is difficult. Therefore, guided-wave ultrasonic inspection is an option that can more accurately identify the location of defects, as the waves propagate along the structure, scanning the material over the entire thickness [14-15].

The paper presents the research carried out to improve the accuracy of identifying defects occurring during welding of a T-joint made of P91 steel, with access from only one side. For this purpose, to calibrate the non-destructive inspection device using Phased Array Ultrasonic Testing method (PAUT), a reference block made of P91 steel was designed and manufactured, in which holes of different diameters were drilled, placed at different distances from the surface. To validate the PAUT examination method, additional liquid penetrant testing (PT) was performed, after excavating the deposited metal where the presence of the defect was observed. It was found that the use of the experimental reference block facilitated the defect identification process and shortened the required examination time.

2. EXPERIMENTAL PROCEDURE

2.1. General considerations

Creep strength of welded joints, such as similar and dissimilar metal welds, is a key to confirming structural reliability in long-term operation. Both Type IV creep failure in similar metal welds and interface failure in dissimilar metal welds of P91/Inconel are considered in the design stage and residual life prediction at high temperatures. Since creep strength reduction in similar metal welds of mod.9Cr-1Mo steel was experimentally confirmed in long-term creep tests, residual life predictions for Type IV creep failure have also been an important issue in

USC plants during long-term service. The susceptibility of the material to creep-related degradation necessitates the use of a reliable volumetric nondestructive examination technique. Consequently, Phased Array Ultrasonic Testing (PAUT) was conducted in compliance with the provisions of the ASME Boiler and Pressure Vessel Code, Section V [16-17].

2.2. Welded joint overview

The examined joint is a branch-type welded connection (T-joint) between two pipes, classified as a set-on branch connection, with the branch pipe welded onto the external surface of the main pipe, as seen in Fig. 1.

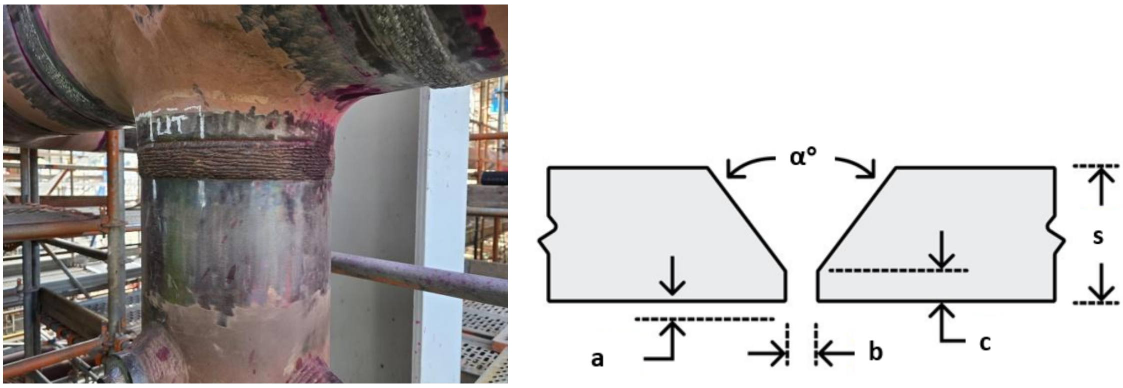


Figure 1. Set on branch connection and the single V groove
(α = 60°, s = 47 mm, a = 13 mm, b = 3 mm, c = 10 mm)

The component examined is a pipe with an outside diameter of 323.8 mm and a wall thickness of 47 mm. The material used for fabrication is SA 355 Grade P91, a creep-resistant martensitic steel widely employed in high-temperature service applications. The welded joint was prepared using a single, symmetric V-groove configuration. Welding was performed by combining Gas Tungsten Arc Welding (GTAW) for the root pass with Manual Metal Arc Welding (MMAW) for subsequent filling and capping passes. The branch connection itself is a hot-forged, normalized, tempered and fully machined T-piece.

2.3. Nondestructive testing requirements

Due to geometric and accessibility limitations imposed by the configuration of the piping system to which the examined welded joint belongs (branch-type joint in the form of a set-on branch connection), the PAUT examination was performed from a single scanning direction only (unilateral scanning). Accordingly, the examination was conducted as a deviation from the ideal application conditions specified in ASME BPVC.V, ARTICLE 23, SE-213, which states that to ensure detection of discontinuities that may not provide a favorable response from one side, scanning shall be performed in both circumferential directions for longitudinal discontinuities and when an axial scan is specified by the using party or parties, in both axial directions for transverse discontinuities. The study aims to demonstrate the effectiveness of unilateral PAUT examination, in accordance with the requirements of ASME Boiler and Pressure Vessel Code, Section V.

2.3.1. Examination conditions

As the connection to the main pipe is established through a cast fitting, the welded joint is considered to fall under the category of butt welds. In ASME BPVC.V, ARTICLE 23, SE-2700 – is stated that Phased array scanning procedures for welds shall be established using scan plans that indicate the required stand-off positions for the probe to ensure volume coverage required and appropriate beam angles. Volume coverage required may include the full volume of weld plus a specified region either side (such as the heat affected zone). Welds shall be inspected from both sides, where possible. But welds should be examined from both sides of the weld and preferably from the bevel opening side (when access permits). For thick wall sections, multiple probe stand-offs or multiple focal law stand-offs will be required for linear scanning to ensure full volume coverage.

2.3.2. Equipment and setup used

The equipment used for this application is listed in Table 1 and the setup information is provided in Table 2.

Table 1. Equipment used for examining the set on branch connection

Equipment used for the application	
Flaw detector	Olympus OmniScan X3
Scanner	Olympus HSMT Compact
Probe model	5L32-A31
Probe frequency	5 MHz
Probe aperture	32
Wedge model	SA31-N55S AOD16
Wedge angle	36.10°

Table 2. Setup description

Parameter	**Value**
Gain	38.8 dB
Velocity	3240 m/s
Examination Mode	PE (Pulse-Echo)
First element used	1
Last element used	16
Probe skew	90°

2.3.3. Calibration blocks

According to ASME Boiler and Pressure Vessel Code Section V, and in particular Article 4 and Article 23 (SE-213) governing phased array ultrasonic testing (PAUT), reference blocks are essential elements for calibration and procedure validation. In practice, two distinct categories are commonly employed: dynamic (calibration) blocks and qualification (demonstration) blocks. Although terminology may vary in industry usage, their functions are clearly differentiated by purpose and application.

The dynamic block is primarily intended for instrument calibration and system performance verification under scanning conditions. It is used prior to and, when required, during examination to ensure that the ultrasonic system operates within specified parameters. For PAUT applications, the dynamic block serves to establish reference sensitivity (gain setting), verify beam steering angles and focal depths generated by each focal law and ensure adequate coverage of the intended examination volume during probe movement.

Because PAUT involves electronic beam steering and dynamic data acquisition, the calibration process must demonstrate that each programmed focal law produces the intended sound field characteristics. Therefore, the dynamic block is fundamentally associated with equipment setup, parameter verification, and repeatability control.

Section V of the ASME BPCV requires that dynamic calibration blocks (reference blocks) be manufactured from the same product specification and material or equivalent P (grade) numbers (Fig. 2). The qualification block shall be within ±25% of the thickness to be examined. The contact surface of the calibration block shall have the same curvature or be within the range of 0,9-1,5 times the diameter.

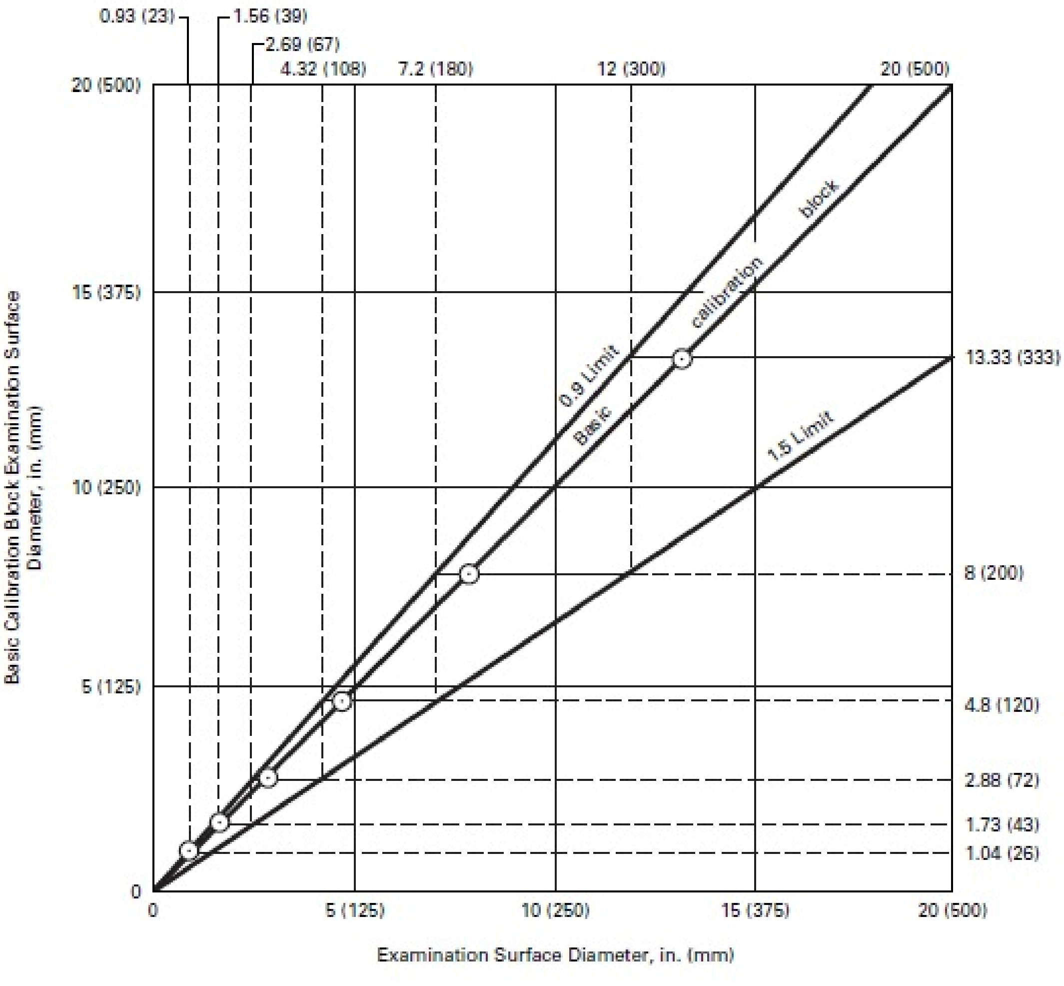
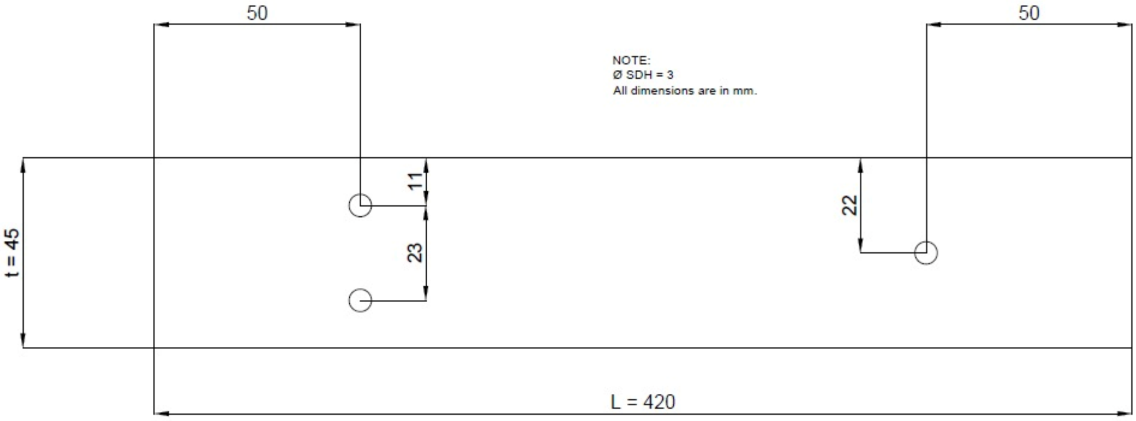


Figure 2. Ratio limits for curved surfaces

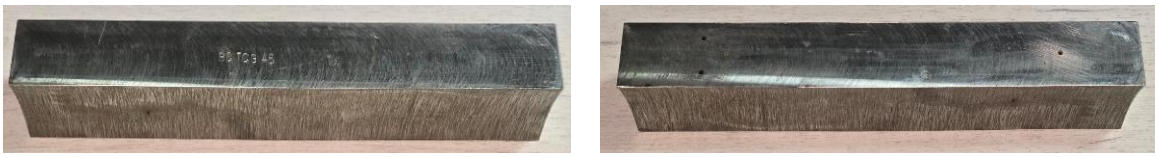
Table 3 presents the specified dimension and actual measurements for the reference block. The graphical representation of the block is depicted in Fig. 3a, and the designed reference block is shown in Fig. 3b.

Table 3. Specified dimensions and actual measurements for the reference block

Surface	Type	Length [mm]		Width [mm]		Depth [mm]		Angle		Distance		Flat Bottom
		Speci fied	Actual	Speci fied	Actual	Speci fied	Actual	Spec i fied	Actual	Speci fied	Actual	
REF01	SDH 1	20	20.02	3	3.00	11	11	0	0	50	50	YES
REF02	SDH 2	20	20.02	3	3.00	34	34	0	0	50	50	YES
REF03	SDH 3	20	20.04	3	3.00	22	22	0	0	50	50	YES



a) Graphical representation of the reference block



b) (PA)UT reference block

Figure 3. Reference block designed and manufactured.

The qualification block is used to validate the examination procedure itself, rather than merely the equipment settings. Its purpose is to demonstrate that the proposed inspection technique can detect relevant discontinuities under representative conditions. This block replicates, as closely as practicable, the essential variables of the production weld, including base material and metallurgical condition, surface condition and access limitations, scanning direction and probe positioning constraints, etc.

The qualification block shall contain a minimum of three flaws parallel to the production welded axis as follows:

- One surface flaw on the OD surface (notch depth 10-20% of the thickness).
- One surface flaw on the ID surface (notch depth 10-20% of the thickness).
- One drilled hole flaw (diameter of 1.3 mm).

If the weld examination can only be performed on one side of the weldment axis, the reference block shall contain two sets of defects, one on each side of the weldment axis. The maximum size shall be based on the thickness of the reference block and shall not exceed the value specified in the reference code section. For the present study, the qualification block was made of P91 steel and had a diameter of 406.4 mm with a nominal thickness of 45 mm.

Table 4 presents the required reflectors for a single-sided examination, including their theoretical dimensions and the actual dimensions achieved after mechanical preparation, Figure 4 shows the actual reference block, and Figure 5 shows the positioning of the reflectors on the qualification block, referenced to the imaginary weld central axis.

Table 4. Specified dimensions and actual measurements for the qualification block

Surface	Type	Length [mm]		Width [mm]		Depth [mm]		Angle		Distance		Flat Bottom
		Speci-fied	Actual	Specified	Actual	Speci-fied	Actual	Speci-fied	Ac-tual	Speci-fied	Actual	
REF01	SDH 1	50	50.03	3	3.00	50	50	90	90	1.5	1.5	YES
REF02	NOTCH 3	15	15	1	1.00	2	2.01	-	-	0.5	0.5	YES
REF03	NOTCH 4	15	15	1	1.00	2	2.01	-	-	0.5	0.5	YES
REF04	OD NOTCH 5	15	15	1	1.00	2	2.01	-	-	37	37	YES
REF05	OD NOTCH 6	15	15	1	1.00	2	2.01	-	-	37	37	YES
REF06	OD NOTCH 7	15	15	1	1.00	2	2.01	-	-	7.5	7.5	YES
REF07	ID NOTCH 8	15	15	1	1.00	2	2.01	-	-	7.5	7.5	YES
REF08	SDH 2	50	50.04	3	3.00	50	50	90	90	1.5	1.5	YES

Figure 4. PAUT qualification block

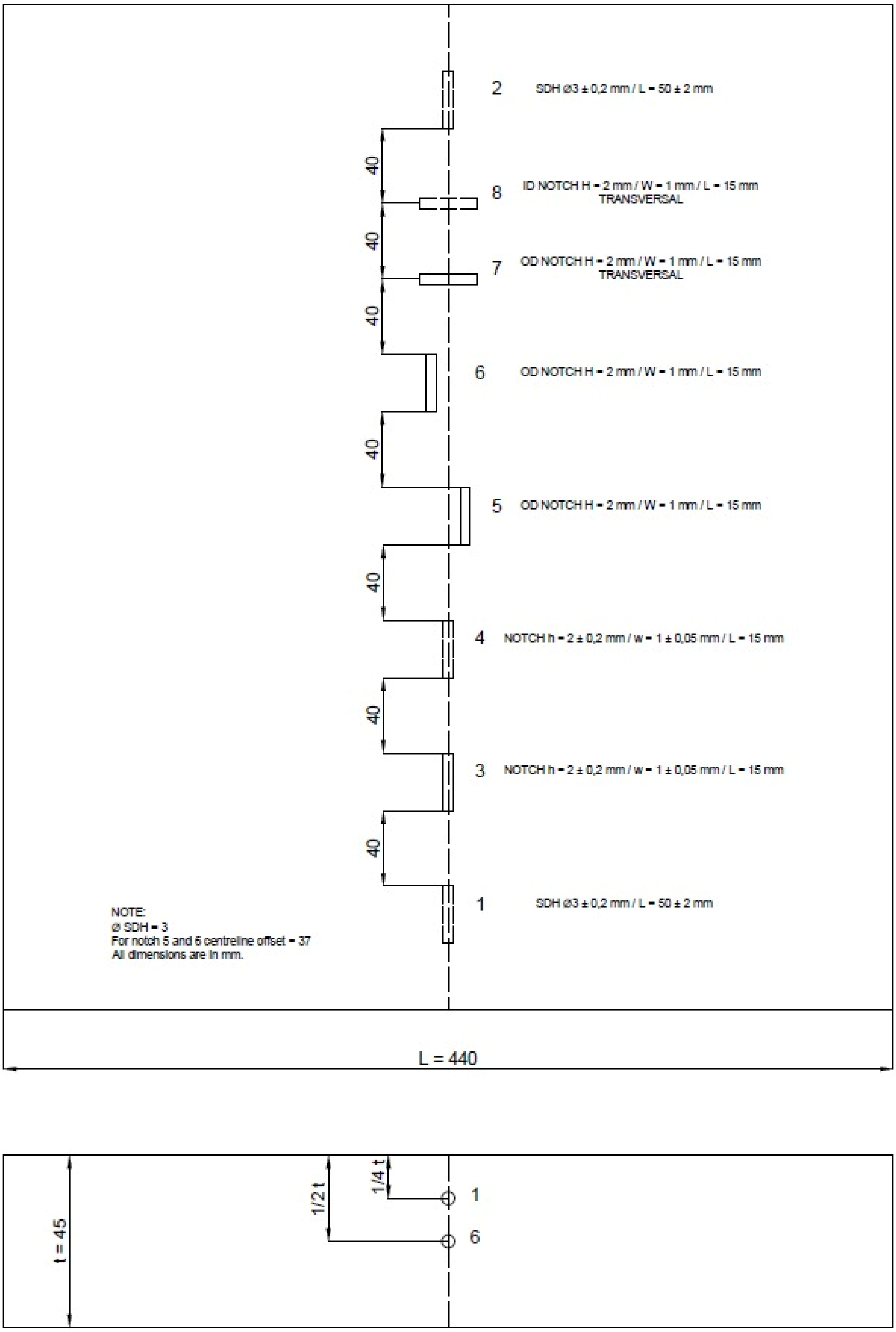


Figure 5. Graphical representation of the qualification block

2.3.4. Nondestructive examination

It is known that ultrasonic beams must traverse through complex geometry with only one-sided access, often missing features on the far side of the weld. This can especially compromise the detection of lack of fusion (LOF) and similar planar defects on the opposite bevel. The present examination aims to highlight the use of single-sided PAUT examination in accordance with the requirements and guidelines imposed by ASME Boiler and Pressure Vessel Code, Section V.

Prior to the actual examination, the ultrasonic flaw detector was calibrated using a dynamic calibration block. Subsequently, a setup was generated to ensure full coverage of the entire weld inspection volume (Fig. 6). The inspection was then validated using a qualification block, which highlighted discontinuities present both at the surface and within the volumetric section.

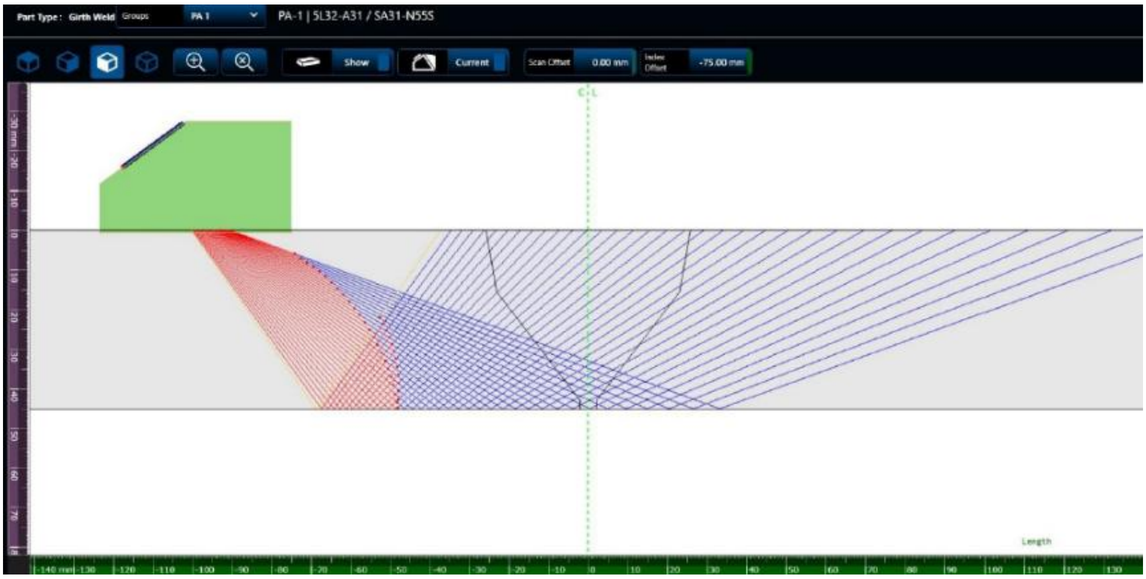


Figure 6. The setup used for single-sided scanning

The examination identified a lack of sidewall fusion (LOSF) imperfection located on the far side of the weld, opposite to the probe position. Based on the evaluation of the defect response and in accordance with the acceptance criteria of ASME B31.1, the indication exceeded the permissible limits and was consequently classified as a defect, exhibiting the characteristics listed in Table 5. Figure 7 presents the examination software image of the defect.

Table 5. Defect characteristics

Characteristic	Value
Amplitude	68.3%
Depth Absolute	31.62 mm
Path Length	67.63 mm
Surface distance/Sound Path Projection	111.55 mm
Vertical Indication Amplitude	7.64 mm

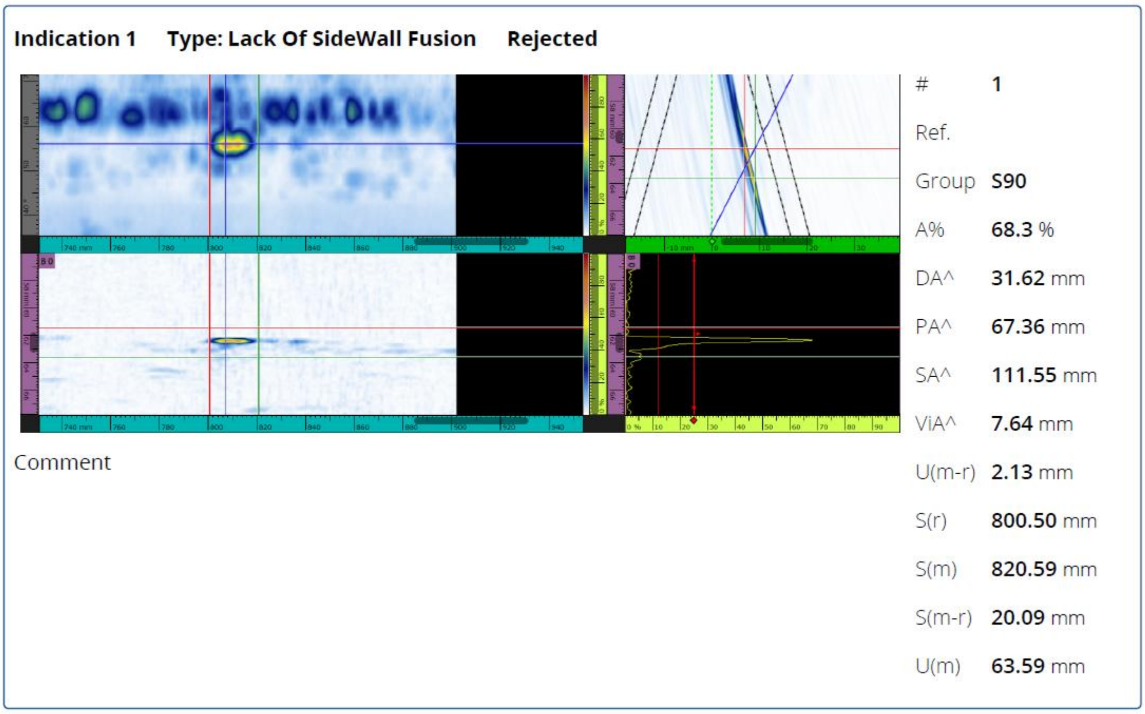


Figure 7. Examination software image of the defect

Based on the values presented in Table 5, the indication identified during the single-sided Phased Array ultrasonic examination exhibits dimensional and response characteristics relevant for evaluation in accordance with the applicable acceptance criteria.

The maximum recorded amplitude of 68.3% indicates a significant ultrasonic response, suggesting the presence of a discontinuity with high reflectivity, consistent with a lack of sidewall fusion (LOSF) imperfection. The absolute depth value of 31.62 mm confirms that the defect is located approximately in the mid-thickness region, on the far side of the weld relative to the probe position, which is typical for limited-access configurations with single-sided scanning.

The sound path length of 67.63 mm and the surface distance/sound path projection of 111.55 mm are consistent with the calculated beam trajectory for the refracted angle used in the Phased Array setup, validating the spatial positioning of the indication with respect to the T-joint geometry. Correlation of these parameters enables precise localization of the defect in both the cross-sectional and longitudinal planes.

The vertical indication amplitude of 7.64 mm reflects the estimated through-thickness extent of the discontinuity, indicating a pronounced development along the weld sidewall. This value, together with the relatively high signal amplitude, supports the classification of the indication as a rejectable defect according to the applicable acceptance criteria.

Overall, the parameters obtained from the examination confirm the presence of a structurally significant imperfection located on the far side of the joint relative to the probe position, demonstrating the effectiveness of the method in detecting and characterizing defects in limited-access T-joint weld configurations. To confirm the existence of the identified defect and validate the PAUT examination, penetrant testing (PT) was performed after excavation reached the indicated location, confirming the defect, as shown in Figure 8.

Figure 8. Penetrant testing examination

An initial excavation of the welded area was performed by controlled grinding using an abrasive grinding disc, in order to progressively remove material and expose the suspected discontinuity.

The excavation was carried out locally in the area indicated in Fig. 7 to a partial depth sufficient to visually expose the discontinuity without removing the entire ligament. The grinding profile was smooth and properly blended to avoid introducing artificial indications, in accordance with surface preparation requirements of ASME Section V, Article 6. This first excavation was intended solely to expose and confirm the presence of the defect.

Following surface preparation, a Liquid Penetrant Examination (PT) was performed in accordance with ASME Section V, Article 6. The procedure consisted of:

1) Surface Cleaning

The excavated surface and at least 25 mm of adjacent material were cleaned and degreased using the cleaner/remover supplied in the SONDA penetrant testing kit. The surface was thoroughly dried prior to penetrant application.

2) Penetrant Application

A dye penetrant, Type II – Method C (solvent removable) from the SONDA kit was uniformly applied. A dwell time of 10 minutes was observed.

3) Excess Penetrant Removal

Excess penetrant was removed using lint-free cloths lightly moistened with cleaner/remover, avoiding over-cleaning.

4) Drying

Drying was performed using clean, dry compressed air.

5) Developer Application

A non-aqueous wet developer (Form d) from the SONDA kit was applied in a thin, uniform layer. A minimum development time of 10 minutes was allowed prior to interpretation.

6) Examination

Examination was performed under natural white light with a minimum intensity of 1000 lux. The examination confirmed the presence of a relevant linear indication corresponding to a defect depth of 31.62 mm.

After confirmation of the defect by PT examination, a second excavation was performed. Material was removed by controlled grinding with an abrasive disc to a depth of approximately 42 mm from the original surface. This corresponds to the confirmed defect depth (31.62 mm) plus additional material to ensure complete removal of the discontinuity and any affected base material. This corresponds to the confirmed defect depth (31.62 mm) plus additional material to ensure complete removal of the discontinuity and any affected base material.

After completion of the second excavation and final surface preparation, a repeat Liquid Penetrant Examination was performed. No rejectable indications were detected. Evaluation was performed in accordance with the acceptance criteria applied in accordance with ASME B31.1.

3. CONCLUSIONS

This study demonstrated the application of single-sided phased array ultrasonic testing (PAUT) on a branch-type welded connection (T-joint) classified as a set-on branch, fabricated from P91 steel. The examination was motivated by the known susceptibility of P91 steel to creep damage during long-term service, which represents a critical factor in the structural aging and degradation of power piping systems and can potentially lead to premature failures.

The inspection was conducted in accordance with the requirements of the ASME Boiler and Pressure Vessel Code, Section V, and the acceptance criteria for identified imperfections were based on ASME B31.1 – Power Piping. Despite the inherent limitations associated with single-sided access, the study confirmed that such examinations can reliably detect defects with low probability of identification, if scanning techniques and validation procedures adhere strictly to ASME recommendations.

The defect identified by PAUT was further verified using local penetrant testing (PT) following excavation, confirming both its presence and position. This combined approach underscores the capability of single-sided PAUT to reveal one of the most critical and frequently encountered defects in branch-type welded connections, specifically lack of sidewall fusion (LOSF), which is widely recognized in literature as a high-risk flaw for P91 welds in high-temperature, high-pressure applications.

Overall, the study demonstrates that, with proper calibration, setup, and validation, single-sided PAUT constitutes a reliable inspection method for detecting critical volumetric and planar defects in complex welded geometries, offering a practical solution when access is limited while maintaining compliance with relevant ASME codes. The findings support the use of complementary NDT techniques, such as PT, to strengthen defect characterization and provide confidence in structural integrity assessments.

4. REFERENCES

[1]. **Junak, G. et al.,** *Mechanical Properties of P91 Steel (X10CrMoVNb9-1) during Simulated Operation in a Hydrogen-Containing Environment*, Materials 2024, 17(17), 4398. https://doi.org/10.3390/ma17174398

[2]. **Kopec, M.; Kukla, D.; Brodecki, A.; Kowalewski, Z.L.,** *Effect of high temperature exposure on the fatigue damage development of X10CrMoVNb9-1 steel for power plant pipes*. Int. J. Press. Vessel. Pip. 2021, 189, 104282.

[3]. **Hald, J.,** *Microstructure and long-term creep properties of 9-12%Cr steels*. Int. J. Press. Vessel. Pip. 2008, 85, 30–37.

[4]. **C. Yang and M. Sun.,** *Study on Mechanical Properties of P91 Steel Testing by Self-made Microindenter*. MEMAT 2022; 2nd International Conference on Mechanical Engineering, Intelligent Manufacturing and Automation Technology, Guilin, China, 2022, p. 1-4.
[5]. **Sunhare, K.C.; Patle, S.D.; Narang, H.K.,** *An Overview of Welding Processes Influence on P91 Steel's Mechanical Properties*, Mater Sci Eng J. 2025; 3(1): 1011.
[6]. **Hernandez, D.; Benson, D.,** *Advanced GMAW processes help in welding P91*, The tube and pipe journal, May 26, 2016.
[7]. **Jeffrey F. Henry,** *Growing experience with P91/T91 forcing essential code changes*, Alstom Power Inc and ASME Task Group. Retrieved from https://www.ccj-online.com/growing-experience-with-p91-t91-forcing-essential-code-changes/
[8]. **Denghui Wang, Fei Gao, Fulai Yang, Kai Yan, Zheng Zhang**, *Effect of creep fracture mode transition of P91 steel welded joints on long-term creep fracture life*, Journal of Materials Research and Technology, Volume 33, 2024, Pages 6374-6388, ISSN 2238-7854. https://doi.org/10.1016/j.jmrt.2024.10.214
[9]. **Silva F.J.G., Pinho A.P., Pereira A.B., Coutinho Paiva O.**, *Evaluation of Welded Joints in P91 Steel under Different Heat-Treatment Conditions*. Metals 2020, 10, 99. https://doi.org/10.3390/met10010099
[10]. **Takashi Honda, Takuya Fukahori, Takumi Tokiyoshi, Yasuharu Chuman, Toshihide Igari, Alan CF. Cocks**., *Creep damage analysis of mod.9Cr-1Mo steel welds considering void mechanics modeling*, International Journal of Pressure Vessels and Piping, Volume 189, 2021, 104251, ISSN 0308-0161. https://doi.org/10.1016/j.ijpvp.2020.104251
[11]. **Kai Yang, K.; Zhang, Y.; Zhao, J.,** *Elastoplastic Fracture Analysis of the P91 Steel Welded Joint under Repair Welding Thermal Shock Based on XFEM*, Metals, 2020, 10(10), 1285. https://doi.org/10.3390/met10101285
[12]. **Ravichandran, D., Mohuiddin, S., & Ismail, M**., (2016). *Single sided weld inspection using advanced ultrasonic methods*. Malaysia International NDT Conference and Exhibition 2015, Nov 22–24, Kuala Lumpur, Malaysia. e-Journal of Nondestructive Testing Vol. 21(1). https://www.ndt.net/?id=18677
[13]. **Abson, D.J.; Rothwell, J.S.**, *Review of type IV cracking of weldments in 9–12%Cr creep strength enhanced ferritic steels*. Int. Mater. Rev. 2013, 58, 437–473.
[14]. **Keyi, Y.; Zandong, H.; Chen, Y.; Zhong, Y.,** *Ultrasonic Inspection for Creep in P91 Steel Weldments Based on Non-creep Feature Space Projection*, Journal of Mechanical Engineering, 2016, 52(8):51-57. DOI: 10.3901/JME.2016.08.051
[15]. **Dhayalan, R.K.; Rajkumar, V.; Kumar, A.,** *Ultrasonic high frequency guided waves for testing of dissimilar metal welds,* Materials today: Proceedings, Vol. 44, Part 2, 2021, p.2978-2984.
[16]. **American Society of Mechanical Engineers,** *ASME Boiler and Pressure Vessel Code, Section V: Nondestructive Examination* (New York: ASME, 2023).
[17]. **American Society of Mechanical Engineers**, *ASME B31.1 – Power Piping* (New York: ASME, 2022).