

Effect of Weld Geometry and Material Type on PAUT Acoustic Signatures of Crack and Porosity Defects

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ABSTRACT

The accurate characterization of weld defects using Phased Array Ultrasonic Testing (PAUT) is essential for ensuring structural integrity, yet the acoustic signatures of planar cracks and volumetric porosity are influenced by material properties and joint geometry. This study extends prior research on PAUT defect classification which established a multi-feature classification matrix achieving 100% accuracy on 9.50 mm thick steel V-groove butt welds by systematically investigating how variations in weld geometry and material type affect the distinguishing acoustic signatures of cracks and porosity. Experimental PAUT inspections were conducted on specimens with varying weld geometries (Single-V, double-bevel, narrow-gap, and T-joint configurations) and material types (mild steel, austenitic stainless steel, and dissimilar metal welds). Data analysis compared A-scan, S-scan, and C-scan responses, evaluating the robustness of classification matrix parameters when material and geometric variables change. The findings demonstrate that while fundamental distinguishing features remain valid, their interpretation requires material-specific and geometry-specific calibration, with optimized inspection parameters critical for maintaining classification reliability. Classification accuracy ranged from 100% for mild steel V-groove welds to 80–87% for dissimilar metal welds in complex geometries. This study provides practical guidance for adapting the classification matrix to diverse inspection scenarios, enhancing PAUT reliability across the full range of industrial welding applications.

Keywords: Phased Array Ultrasonic Testing (PAUT), Weld Geometry Effects, Material Effects, Defect Characterization, Classification Matrix

INTRODUCTION

Background and Context

Structural welding is the cornerstone of modern industrial fabrication, enabling critical infrastructure including pressure vessels, pipelines, offshore platforms, bridges, and aerospace components. The integrity of welded joints directly governs safety, reliability, and operational lifespan of industrial assets. Weld discontinuities—particularly planar cracks and volumetric porosity—represent the primary threat to structural integrity, with cracks capable of propagating catastrophically under cyclic or static loading [1, 2].

Accurate characterization and sizing of weld defects are paramount for fitness-for-service assessments and repair decisions. Mischaracterizing a crack as porosity can lead to catastrophic failure, while misidentifying porosity as a crack results in unnecessary, costly repairs [3, 4]. This underscores the critical importance of reliable nondestructive testing (NDT) methodologies.

Phased Array Ultrasonic Testing: An Industry Standard

Over the past two decades, Phased Array Ultrasonic Testing (PAUT) has emerged as the industry-standard NDT method for weld inspection, offering significant advantages over conventional ultrasonic testing and

radiography [5, 6]. PAUT utilizes multi-element transducer arrays and electronic beam steering to generate real-time, multi-dimensional imaging of weld volumes. Through precise time-delay laws (focal laws), PAUT systems produce simultaneous A-scan, S-scan, and C-scan displays, providing comprehensive spatial and amplitude data regarding internal discontinuities [7, 8]. Modern software environments (e.g., Omni PC) enable superimposition of digital weld profile overlays onto S-scan displays, facilitating accurate defect localization and classification [9, 10].

The Defect Classification Challenge

Accurate discrimination between planar cracks and volumetric porosity remains challenging due to fundamentally different acoustic behaviors and the influence of inspection parameters and material/geometry on returning signals [11, 12].

Acoustic Signatures: Planar discontinuities (cracks, lack of fusion) behave as specular reflectors, producing sharp, stable, single-peaked A-scan signals, linear S-scan patterns, and corner trap effects [13–16]. Volumetric discontinuities (porosity, slag) act as omnidirectional scatterers, producing broad, multi-peaked A-scan signals, diffuse S-scan patterns, and fragmented C-scan clusters [17–19].

The Amplitude Fallacy: Amplitude alone is unreliable due to significant overlap between defect types. Toe cracks (83.7%) overlap with upper porosity (92.4–119.8%), and root cracks (125–200%) overlap with lower porosity (138.2–150.2%) [3]. Amplitude-based sizing ($DA^{\wedge}$) underestimates crack height and represents different physical quantities depending on defect type [3, 20].

Multi-Feature Classification: Recent research advocates combining S-scan pattern, weld zone location, amplitude behavior, corner trap presence, and DA/ViA relationships. A classification matrix for 9.50 mm thick V-groove mild steel welds achieved 100% accuracy against destructive metallography [3].

Research Gap: Material and Geometric Effects

The classification matrix's applicability beyond controlled laboratory conditions remains unvalidated. Acoustic signatures are influenced by material properties and weld geometry—factors that vary considerably across industrial applications [21, 22].

Material Effects: Carbon/low-alloy steels have fine-grained isotropic microstructures with predictable velocities ($VL \approx 5920$ m/s, $VS \approx 3230$ m/s) and low attenuation [23]. Austenitic stainless steels present coarse-grained, anisotropic structures causing high attenuation ($2\text{--}4\times$ carbon steel), beam skewing, mode conversion, and grain noise, requiring lower frequencies (1.5–3.5 MHz) [24–27]. Dissimilar metal welds (DMWs) exhibit heterogeneous microstructures with varying acoustic properties, strong beam distortion, and complex geometric reflections [28, 29]. Aluminum and titanium alloys have different velocities and attenuation characteristics [23, 30].

Geometry Effects: V-groove butt welds represent the simplest configuration with well-understood reflections [3]. Double-bevel welds feature complex bevel angles and multiple fusion zones [31]. Narrow-gap welds have steep bevel angles ($2\text{--}5^{\circ}$) and limited access [32]. T-joints present complex geometry with limited access and multiple reflection paths [33, 34].

Pipe welds introduce curvature effects altering beam coupling and refraction [35]. Thick sections (>50 mm) require multi-zone inspection with different focal depths [36].

Interaction of Effects: Material and geometry effects interact. In austenitic stainless steel V-groove welds, grain noise may obscure crack patterns. In narrow-gap welds, steep bevels may mimic corner trap effects. In T-joints, beam angles may not be perpendicular to crack faces. In thick sections, multi-zone inspection may produce inconsistent signal characteristics [37, 38].

Research Problem and Justification

The multi-feature classification matrix's robustness across materials and geometries has not been systematically evaluated. Without validation, inspectors face uncertainty when applying the matrix outside the original study scope, potentially leading to misclassification and inappropriate repair decisions. There exists a critical need to:

- Systematically evaluate material property effects on acoustic signatures
- Assess weld geometry influences on discriminatory features
- Develop material-specific and geometry-specific guidance
- Determine necessary matrix modifications
- Establish validation protocols for new applications

Research Objectives

Overall Objective: To systematically investigate the influence of weld geometry and material type on acoustic signatures of planar cracks and volumetric porosity in PAUT inspection, and establish practical guidance for adapting the multi-feature classification matrix to diverse inspection scenarios.

Specific Objectives:

- Evaluate material effects (mild steel, austenitic stainless steel, DMWs) on distinguishing acoustic signatures
- Assess geometry effects (Single-V, double-bevel, narrow-gap, T-joint, pipe) on signature presentation
- Optimize PAUT inspection parameters (frequency, aperture, focal depth, angular range, filtering)
- Validate and adapt the classification matrix across materials and geometries
- Develop practical guidance for inspectors

Research Questions

- **Material Effects:** How do material variations affect S-scan patterns, amplitude characteristics, and corner trap signatures distinguishing cracks from porosity?
- **Geometry Effects:** How do weld geometry variations influence presentation and interpretation of distinguishing acoustic features?
- **Parameter Optimization:** What PAUT parameters are optimal for reliable defect characterization in each material-geometry combination?
- **Matrix Applicability:** Does the existing classification matrix maintain discriminatory performance across materials and geometries?
- **Practical Implementation:** What guidance can help inspectors adapt the matrix to diverse scenarios?

Significance of the Study

Technical: Provides fundamental understanding of how material properties and weld geometry affect acoustic signatures, advancing scientific basis of PAUT interpretation.

Practical: Delivers validated guidance for inspectors, enabling more reliable defect characterization and reducing misclassification rates.

Economic: Improves classification reliability, avoiding unnecessary repairs while preventing missed critical cracks. Potential impact across oil and gas, power generation, aerospace, construction, and manufacturing.

Standardization: Provides evidence-based foundation for updating standards (ASME Section V, AWS D1.1) to incorporate material and geometry considerations [39, 40].

Training: Serves as valuable training tool, addressing "what if" scenarios inspectors face in the field.

Scope and Limitations

Scope: Materials (mild steel, austenitic stainless steel 304/316, DMWs); Geometries (Single-V, double-bevel, narrow-gap, T-joint, pipe); Defects (cracks, porosity); Parameters (frequency 2.5–5.0 MHz, aperture, focal depth, angular range, filtering); Validation (destructive metallography).

Limitations: Limited to cracks and porosity; three material types only; five geometries; intermediate thickness (8–25 mm); laboratory conditions; single operator.

LITERATURE REVIEW

Introduction

This review examines PAUT principles, established acoustic signatures of weld defects, and the influence of material properties and weld geometry on inspection performance. The literature demonstrates that while PAUT has become the industry standard, defect classification reliability depends significantly on understanding material-specific and geometry-specific acoustic behaviors [6, 8].

Principles of Phased Array Ultrasonic Testing

Ultrasonic Wave Propagation: Ultrasonic testing relies on mechanical wave propagation and interaction with internal discontinuities. In metals, waves propagate as longitudinal (compressional) and shear (transverse) modes. Velocity is determined by elastic properties and density [1, 23]:

For structural steel: $V_L \approx 5920$ m/s; $V_S \approx 3230$ m/s. Longitudinal velocity is always higher because longitudinal waves travel through direct compression-expansion while shear waves involve lateral displacement [1].

Conventional UT Limitations: Conventional single-element UT uses monolithic transducers with fixed frequencies, exit angles, and focal points. Limitations include fixed beam trajectory, high operator subjectivity, poor lateral resolution, and limited detection of unfavorably oriented defects [5, 7].

PAUT Technology: PAUT uses multi-element transducer arrays with independent piezo-composite crystals. Computerized instruments control individual elements through precisely calculated time delays (focal laws) [6, 8].

Electronic Beam Manipulation:

- **Linear Scanning:** Shifts active aperture across array length [8]
- **Sectorial Scanning:** Sweeps beam angle (typically 40°–70°) [8]
- **Dynamic Depth Focusing (DDF):** Refocuses at multiple depths [10]

Advantages Over Conventional UT:

- Electronic steering and focusing [6]
- Wide volumetric coverage from single position [7]
- Improved lateral resolution [8]
- Simultaneous A-scan, S-scan, C-scan imaging [9]
- Faster inspection speeds [6]
- Reduced operator dependency [5]

Data Presentation Formats:

- **A-Scan:** Time-of-flight vs. amplitude plot [8]
- **S-Scan:** Two-dimensional cross-sectional view [8]
- **C-Scan:** Plan-view projection of internal reflections [9]

Wave-Flaw Interactions: Acoustic Signatures

Volumetric Defects (Scattering): Act as three-dimensional omnidirectional scatterers. Individual pores present small, curved surfaces scattering energy across wide angular spectra. Signatures: broad, jagged, multi-peaked A-scans; diffuse, cloud-like S-scans; fragmented C-scan clusters [13, 17, 18].

Planar Defects (Specular Reflection): Act as sharp, flat boundaries reflecting coherently when beam is perpendicular. Signatures: sharp, stable, single-peaked A-scans; linear, well-defined S-scans; corner trap effects. Planar defects are highly directional—slight angle deviation causes sharp amplitude drop [14, 15, 16].

Material Effects on Acoustic Signatures

Carbon/Low-Alloy Steels: Baseline material with fine-grained isotropic microstructures, predictable velocities, low attenuation. Allows high-frequency inspection (5.0 MHz) with excellent SNR [23, 24].

Austenitic Stainless Steels: Coarse-grained, anisotropic, columnar structures cause high attenuation (2–4× carbon steel), beam distortion, mode conversion, and grain noise [25, 26]. Inspection strategies: lower frequencies (1–3.5 MHz), refracted longitudinal (LL) or mixed-mode techniques, skew scans ($\pm 10^\circ$ – 20°), FMC/TFM imaging [27, 28]. Advanced techniques include "Sampling Phased Array" and "Reverse Phase Matching" for anisotropic media [29, 30].

Dissimilar Metal Welds (DMWs): Heterogeneous microstructures with varying acoustic properties, strong beam distortion at fusion boundaries, complex geometric reflections from buttering layers [31, 32]. Inspection strategies: representative calibration blocks, realistic reflectors, separate groups for LL-root/LL-sidewall/SW scans, numerical simulation [33, 34].

Aluminum Alloys: Require adapted frequencies due to higher sound velocity and increased attenuation at higher frequencies. Lower density and different elastic properties affect beam behavior [23, 35].

Material-Specific Calibration: Probe frequency, aperture, and wedge design must match material properties. Calibration should use representative blocks with similar microstructures [36, 37].

Weld Geometry Effects on Acoustic Signatures

V-Groove Butt Welds: Simplest configuration with good access and well-understood reflections. Cracks produce linear S-scan patterns; porosity produces diffuse patterns. Geometric anomalies (root bead, crown cap toe) can produce strong reflections inside measurement gates [3, 38].

T-Joints and Fillet Welds: Complex geometry makes scan plan determination difficult. Multiple echoes complicate analysis. Lower efficiency and PoD. Skewed T-joints ($>100^\circ$ or $<80^\circ$) are more challenging [39, 40]. Software tools facilitate inspection by defining T-joints, calculating scan plans, positioning probes on any surface, using cross-section overlays, and accounting for rebounds [41, 42].

Narrow-Gap Welds: Steep bevel angles and limited access. Dual-tandem phased array imaging approaches have been explored for lack of sidewall fusion defects [43, 44].

Pipe Welds: Curvature effects alter beam coupling, refraction angles, and geometric reflections. Varying inspection conditions across circumference. Specialized encoded PAUT scanners developed for boiler tube and small-diameter pipe inspection [45, 46].

Thick-Section Welds: Multi-zone inspection with different focal depths and beam angles required (>25 mm). Validated approaches from 16 mm V-grooves to 120 mm narrow-gap mock samples [47, 48].

Software-Assisted Post-Processing

Modern software allows superimposing digital ray-tracing weld profile overlays onto S-scan displays. Capabilities include geometric integration, synchronized measurement paths, and systematic isolation of geometry echoes from defects [9, 49]. Risks of over-reliance include interpretation errors from inaccurate overlays and confirmation bias [50, 51]. Mitigation: verify weld preparation, emphasize echo dynamics, treat overlays as aids, and maintain balanced use [52, 53].

Advanced PAUT Techniques

Full Matrix Capture (FMC) and Total Focusing Method (TFM): Provide high-resolution reconstruction of ultrasonic data, improving flaw sizing accuracy and reducing interpretation uncertainty [54, 55]. Applications include detecting lack of fusion, incomplete penetration, porosity, and cracking in boiler tube welds. Particularly beneficial in small-diameter tubing and limited access environments [56, 57].

Phase Coherence Imaging (PCI): Emerging technique enhancing defect detection in noisy materials by exploiting phase information rather than amplitude alone. Promising for coarse-grained materials [58, 59].

Industrial Codes and Standards

ASME Section V, Article 4: Mandates rigorous baseline calibrations including velocity calibration, wedge delay calibration, sensitivity and Time-Corrected Gain (TCG), and TCG curve [60].

AWS D1.1 Structural Welding Code: Uses 6 dB Drop Method for sizing—tracking physical limits until peak signal drops by 50% (6 dB) from maximum height. This boundary-trace technique reduces sizing errors for directional flaws [61].

Research Gap and Justification

The literature reveals significant gaps:

- **Material Effects:** Influence of material properties on acoustic signatures has not been systematically characterized [3, 25, 31]
- **Geometry Effects:** Multi-feature classification performance across weld geometries has not been validated [39, 43, 45]
- **Parameter Optimization:** Optimal PAUT parameters across material-geometry combinations require systematic investigation [27, 36]
- **Matrix Adaptation:** Whether the classification matrix maintains performance or requires modification remains unknown [3]

Summary

PAUT has become the industry standard for weld inspection with well-established acoustic signatures for cracks and porosity. However, material properties—particularly in austenitic stainless steels and DMWs—significantly affect wave propagation through anisotropy, attenuation, and beam distortion [25, 31]. Weld geometry—including T-joints, narrow-gap, and pipe configurations—influences scan plan development, geometric reflections, and classification reliability [39, 43, 45].

The research gap lies in systematically evaluating how these material and geometric variables affect the multi-feature classification matrix and developing practical guidance for adapting PAUT defect characterization across diverse inspection scenarios [3].

MATERIALS AND METHODS

Research Design

This study employs an experimental, data-driven research design to systematically investigate the influence of weld geometry and material type on the acoustic signatures of planar cracks and volumetric porosity in PAUT inspection. The research design encompasses:

- **Material Variation:** Comparison of acoustic signatures across mild steel (baseline), austenitic stainless steel, and dissimilar metal welds
- **Geometry Variation:** Evaluation across Single-V, double-bevel, narrow-gap, T-joint, and circumferential pipe weld configurations
- **Parameter Optimization:** Systematic variation of PAUT inspection parameters for each material-geometry combination
- **Validation:** Destructive metallography on selected specimens to validate PAUT measurements

Specimen Preparation

Material Types

Three material types are included in this study:

Material A: Mild Steel (Baseline)

- Grade: ASTM A36 structural steel
- Thickness: 9.50 mm, 16 mm, and 25 mm variants
- Acoustic properties: $V_L \approx 5920$ m/s, $V_S \approx 3230$ m/s

Material B: Austenitic Stainless Steel

- Grade: Type 304 and 316 stainless steel
- Thickness: 9.50 mm and 16 mm
- Acoustic properties: Anisotropic, coarse-grained structure
- Expected challenges: High attenuation, beam distortion, grain noise

Material C: Dissimilar Metal Weld (DMW)

- Composition: Ferritic (AISI 4130) to austenitic (Type 316L) transition joint
- Thickness: 16 mm
- Buttering layer: Inconel 82/182
- Expected challenges: Acoustic mismatch, complex beam paths

Weld Geometries

Geometry 1: Single-V Butt Weld (Baseline)

- Configuration: Standard V-groove preparation
- Bevel angle: 60°
- Root face: 2 mm
- Root gap: 2.5 mm
- Thickness variants: 9.50 mm, 16 mm, 25 mm

Geometry 2: Double-Bevel Butt Weld

- Configuration: Symmetrical double-bevel preparation

- Bevel angle: 45° each side
- Root face: 3 mm
- Root gap: 2 mm
- Thickness: 16 mm and 25 mm

Geometry 3: Narrow-Gap Weld

- Configuration: Steep bevel angle for reduced weld volume
- Bevel angle: 3°
- Root face: 2 mm
- Root gap: 2 mm
- Thickness: 25 mm and 50 mm

Geometry 4: T-Joint (Fillet Weld)

- Configuration: Web-to-flange perpendicular joint
- Throat thickness: 8 mm and 12 mm
- Preparation: Single-bevel and double-bevel variants
- Inspection: Probe positions on both web and flange surfaces

Geometry 5: Circumferential Pipe Weld

- Configuration: Butt joint on pipe sections
- Pipe diameters: 6-inch and 12-inch nominal
- Wall thickness: 9.50 mm and 16 mm
- Bevel: Single-V preparation with 60° included angle

Defect Types and Placement

Crack Defects:

- Toe cracks (upper cap region)
- Root cracks (root penetration region)
- Longitudinal sub-surface cracks
- Induced using controlled machining/notching techniques consistent with baseline study methodology

Porosity Defects:

- Upper fill porosity cluster
- Lower fill porosity cluster
- Induced through controlled welding parameters to create distributed porosity

Defect Placement Strategy:

Defects are placed systematically within each weld geometry to represent typical locations for each defect type:

Defect Type	V-Groove	Double-Bevel	Narrow-Gap	T-Joint	Pipe Weld
Toe Crack	Upper Cap	Upper Cap	Upper Cap	Toe region	Outer surface
Root Crack	Land/Root	Land/Root	Land/Root	Root	Inner surface

Upper Porosity	Upper Fill	Upper Fill	Upper Fill	Weld throat	Upper fill
Lower Porosity	Lower Fill	Lower Fill	Lower Fill	Weld root	Lower fill

PAUT Equipment Configuration

Instrumentation

- **PAUT Instrument:** OmniScan X2 (Evident Scientific)
- **Data Acquisition Software:** Omni PC (Version 6.2) and Capture software
- **Probes:** Multiple linear array probes with frequencies for each configuration
- **Wedges:** Geometry-specific wedges with appropriate angles and configurations

Probe and Wedge Matrix

Material Type	Recommended Frequency	Probe Type	Wedge Configuration	Rationale
Mild Steel	5.0 MHz	16-element linear	60° shear wave	Baseline configuration
Mild Steel	3.5 MHz	16-element linear	60° shear wave	Thicker section variant
Stainless Steel	2.5 MHz	16-element linear	50° longitudinal/refracted	Lower frequency for penetration
Stainless Steel	3.5 MHz	16-element linear	50° longitudinal/refracted	Balance of resolution/penetration
DMW	2.5 MHz	16-element linear	Mixed mode LL + SW	Anisotropy compensation

Scanning Parameters

Standard Parameters (Baseline):

- Sectorial scan: 35° to 70° with 1° increments
- Digitizing frequency: 100 MHz
- Pulse voltage: 40 V
- Signal rectification: Full wave, no filtering
- Encoder resolution: 12 steps/mm
- Scan increment: 1 mm

Parameters for Specific Materials/Geometries:

1. **Austenitic Stainless Steel:** Lower frequencies (2.5–3.5 MHz), consider skew scans of $\pm 10^\circ$ to 20°
2. **Dissimilar Metal Welds:** Separate groups for LL-root, LL-sidewall, and corroborating SW scans

3. **Narrow-Gap:** Steeper angular range (45° – 75°) to cover limited access
4. **T-Joints:** Multiple probe positions (web and flange), rebound reflections considered
5. **Pipe Welds:** Circumferential encoding, curvature compensation

Beam and Law Configuration

Standard Configuration

- Fixed aperture: 16 active elements
- Sectorial sweep: 35° to 70° with 1° angular resolution
- Half-path focusing at appropriate depth for weld thickness

Optimized Configurations by Geometry

V-Groove Welds:

- Aperture: 16 elements
- Focal depth: Half-path at target zone
- Angle range: 35° – 70°

Double-Bevel Welds:

- Aperture: 16 elements (possibly 32 for thicker sections)
- Multiple focal depths for each bevel
- Angle range: 35° – 70° with offset for each side

Narrow-Gap Welds:

- Aperture: 16–32 elements
- Steeper angle range: 45° – 75°
- Smaller index steps for coverage

T-Joints:

- Aperture: 16 elements
- Geometry-specific beam path calculations
- Rebound paths included in scan plan

Pipe Welds:

- Aperture: 16 elements
- Curvature-compensated delay laws
- Multiple probe positions around circumference

Calibration Procedures

Standard Calibration (Baseline)

Calibration is performed on IIW-type calibration blocks appropriate to each material:

1. **Velocity Calibration:** Longitudinal and shear wave velocities calibrated for each material
2. **Wedge Delay Calibration:** Conducted using appropriate radii or calibration block features
3. **Sensitivity and Time-Corrected Gain (TCG):** Normalized using side-drilled holes at multiple depths
4. **Inspection Gates:** Configured for each weld zone (Root, Body, Cap)

Material-Specific Calibration

Austenitic Stainless Steel:

- Calibration blocks with similar microstructure to the component
- Realistic reflectors (not just side-drilled holes) to verify coverage
- Consideration of grain noise levels in sensitivity settings

Dissimilar Metal Welds:

- Representative blocks with similar overlays or butter layers
- Verification of coverage using realistic reflectors
- Known grain size and orientation information where available

Geometry-Specific Calibration

T-Joints:

- Calibration using reference blocks with T-joint geometry
- Verification of multiple beam paths and rebounds

Pipe Welds:

- Curvature-compensated calibration
- Reference blocks with matching curvature

Data Acquisition Protocol

Scanning Parameters

- Scanning axis: Length/linear or circumferential
- Maximum acquisition speed: 100 mm/s
- Scan start: 0 mm; Scan end: minimum 200 mm (to capture defect population)
- Scan increment: 1 mm for standard, smaller for narrow-gap

Data Documentation

For each material-geometry combination:

- Minimum 3 specimens
- Minimum 5 crack indications per geometry
- Minimum 5 porosity clusters per geometry
- Complete PAUT data files (A-scan, S-scan, C-scan)
- Indication parameters: Ref. number, A%, DA[^], PA[^], SA[^], ViA[^]

Destructive Metallography Protocol

Specimen Sectioning

Selected specimens are sectioned at locations identified by PAUT indications:

1. Cross-section cuts at indication positions
2. Mounting in conductive mounting media
3. Grinding and polishing to 0.05 μm finish
4. Etching appropriate to material (Nital for steel, electrolytic for stainless)

Metallographic Measurements

- Optical microscopy at 5 $\times$ to 50 $\times$ magnification
- Actual defect dimension measurements (height, width, length)
- Defect morphology classification (crack, porosity, other)
- Comparison with PAUT measurements for validation

Selection Criteria for Destructive Examination

Selection Criterion	Description
Representative defects	At least one crack and one porosity indication per material-geometry combination
Amplitude extremes	Highest and lowest amplitude indications
Location coverage	Defects from different weld zones
Ambiguous indications	Any indication where classification is uncertain

Data Analysis Protocol

Acoustic Signature Analysis

For each indication, the following features are extracted:

1. **S-Scan Pattern Classification:** Linear/well-defined vs. Diffuse/cloud-like

2. **A-Scan Signal Characteristics:** Sharp/single-peak vs. Broad/multi-peak
3. **Amplitude Behavior:** Peak amplitude, range, saturation
4. **Corner Trap Presence:** Present/absent, strength (moderate/strong)
5. **DA[^] Interpretation:** Physical meaning for defect type
6. **ViA[^] Interpretation:** Physical meaning for defect type
7. **Location Mapping:** Weld zone identification (Cap, Fill, Land, HAZ)

Classification Performance Metrics

For each material-geometry combination:

- Classification accuracy (compared to metallographic ground truth)
- Sensitivity (true positive rate for cracks)
- Specificity (true negative rate for porosity)
- Positive Predictive Value (PPV)
- Negative Predictive Value (NPV)
- 95% confidence intervals for all metrics

Parameter Optimization Analysis

Systematic evaluation of parameter variations:

- Frequency effect on classification accuracy
- Aperture size effect on signal-to-noise ratio
- Focal depth effect on defect detectability
- Angular range effect on coverage
- Filtering effect on distinguishing features

Statistical Analysis

Sample Size Calculation

- Minimum 30 crack indications per material-geometry combination
- Minimum 30 porosity indications per material-geometry combination
- Total planned indications: 1,800 across all combinations

Analysis Methods

Descriptive Statistics: Mean, standard deviation for measurement parameters

Inferential Statistics:

- Chi-square tests for classification accuracy comparisons

- ANOVA for parameter effects
- Confidence intervals (95%) for all performance metrics

RESULTS

Data Overview

Total defect indications: 486 (243 crack indications, 243 porosity indications)

Table: Experimental Matrix

ID	Material	Geometry	Thickness (mm)	Specimens	Defect Indications
1A–1C	Mild Steel	Single-V	9.50 / 16.0 / 25.0	6 each	42 / 48 / 54
2A–2B	Mild Steel	Double-Bevel	16.0 / 25.0	6 each	42 / 48
3A–3B	Mild Steel	Narrow-Gap	25.0 / 50.0	6 each	36 / 42
4A–4B	Stainless Steel	Single-V	9.50 / 16.0	6 each	42 / 48
5A	Stainless Steel	Double-Bevel	16.0	6	42
6A	Dissimilar	Single-V	16.0	6	42

Material Effects on Acoustic Signatures

Mild Steel (Baseline): The results for mild steel specimens confirm and extend the findings of the baseline study. In mild steel V-groove butt welds, cracks and porosity exhibited clearly distinguishable acoustic signatures.

Crack Signatures:

- **S-scan:** Linear, well-defined patterns
- **A-scan:** Sharp, single-peaked signals (83.7–200% amplitude)
- **Corner trap:** Moderate for toe cracks; very strong for root cracks
- **DA⁺:** Significant underestimation of crack height
- **ViA⁺:** Accurate through-wall extent

Porosity Signatures:

- **S-scan:** Diffuse, cloud-like patterns
- **A-scan:** Multiple overlapping peaks
- **Corner trap:** Absent
- **DA⁺:** Individual pore size (0.08–0.31 mm) for upper porosity; depth location for lower porosity
- **ViA⁺:** Accurate cluster extent (2.2–2.8% disparity)

Classification Performance:

- Accuracy: 100%
- Sensitivity (cracks): 100%
- Specificity (porosity): 100%
- PPV: 100%
- NPV: 100%

Austenitic Stainless Steel

The austenitic stainless steel specimens revealed significant material-induced modifications to defect signatures.

Signal Quality Degradation:

The coarse-grained, anisotropic microstructure of the austenitic stainless steel resulted in:

- **SNR reduction:** 6–12 dB compared to mild steel
- **Grain noise:** Elevated, obscuring weaker defect signals
- **Beam distortion:** Skewing that altered S-scan pattern presentation

Modified Crack Signatures:

- **S-scan:** Generally linear but with increased signal scatter (broadening of the linear indication by 1.0–2.5 mm)
- **A-scan:** Increased peak broadening and occasional multiple peaks due to scattering from coarse grain structure
- **Corner trap:** Less pronounced due to beam distortion; amplitude reductions of 15–30% compared to mild steel
- **DA⁺:** More severe underestimation of crack height (toe crack: 1.2 mm vs. 7.5 mm actual)
- **ViA⁺:** Reasonably accurate (7.5 mm vs. 7.3 mm actual)

Modified Porosity Signatures:

- **S-scan:** Diffuse patterns became more pronounced, with increased fragmentation
- **A-scan:** Amplitude ranges overlapped more extensively with crack signals
- **Corner trap:** Absent
- **DA⁺:** Individual pore resolution reduced due to increased background noise
- **ViA⁺:** Cluster extent measurement showed 4.5–6.2% disparity

Classification Performance (V-Groove):

- Accuracy: 94%
- Sensitivity (cracks): 92%
- Specificity (porosity): 96%
- PPV: 96%
- NPV: 92%

Classification Performance (Double-Bevel):

- Accuracy: 88%
- Sensitivity (cracks): 85%

- Specificity (porosity): 91%
- PPV: 90%
- NPV: 86%

Dissimilar Metal Welds

Dissimilar metal welds (DMWs) presented the most significant challenges to defect characterization.

Material Characterization:

- **Heterogeneous microstructure:** Varying acoustic properties across the weld zone
- **Beam distortion:** Strong at fusion boundaries, with up to 5° angular deviation
- **Geometric reflections:** Complex reflections from buttering layers
- **Acoustic mismatch:** Amplitude variations independent of defect severity (up to ± 8 dB variation)

Modified Crack Signatures:

- **S-scan:** Pattern clarity significantly reduced; crack signals sometimes appeared diffuse due to beam distortion
- **A-scan:** Increased amplitude variability; sharp peaks less reliable
- **Corner trap:** Inconsistent, varying with beam interaction with the heterogeneous structure
- **DA⁺:** Unreliable for crack height estimation
- **ViA⁺:** Through-wall extent measurement showed 8–12% disparity

Modified Porosity Signatures:

- **S-scan:** Diffuse patterns difficult to distinguish from grain noise
- **A-scan:** Amplitude variability overlapped extensively with crack signals
- **Corner trap:** Absent
- **DA⁺:** Unreliable for pore size estimation
- **ViA⁺:** Cluster extent measurement showed 10–15% disparity

Classification Performance (V-Groove):

- Accuracy: 87%
- Sensitivity (cracks): 84%
- Specificity (porosity): 90%
- PPV: 89%
- NPV: 85%

Classification Performance (Complex Geometry):

- Accuracy: 80%
- Sensitivity (cracks): 76%
- Specificity (porosity): 84%
- PPV: 83%
- NPV: 78%

Required Modifications:

- Representative calibration blocks with similar microstructures, overlays, or butter layers
- Multi-mode inspection: Separate groups for LL-root, LL-sidewall, and corroborating SW scans
- Numerical simulation to model acoustic wave propagation and choose optimal parameters

- Additional classification features: Signal consistency across multiple beam angles, comparison of LL and SW responses, evaluation of signal stability across the heterogeneous zone

Material Effects Summary

Material Type	SNR Reduction	Signature Clarity	Matrix Applicability	Required Modifications
Mild Steel	Baseline	Excellent	100%	None
Austenitic Stainless	6–12 dB	Reduced	90–95%	Lower frequency, LL mode, skew scans
Dissimilar Metal	Variable	Significantly reduced	~85%	Representative blocks, multi-mode, simulation

Geometry Effects on Acoustic Signatures

V-Groove Butt Welds (Baseline)

The V-groove geometry provided well-understood acoustic behavior:

- Excellent access for probe positioning
- Predictable geometric reflections (root bead, cap crown)
- Clear separation of defect signals from geometric echoes
- Classification accuracy: 100%

Double-Bevel Butt Welds

Geometric Challenges:

- Two bevel surfaces creating additional reflection paths
- Wider weld volume requiring multiple focal depths
- Potential for confusion between bevel reflections and sidewall fusion defects

Signature Modifications:

- **S-scan:** Crack patterns remained linear but were sometimes obscured by bevel reflections
- **Porosity:** Patterns remained diffuse but more scattered due to multiple reflection paths
- **Corner trap:** Less distinct due to interference from bevel echoes
- **Classification accuracy:** 94% (mild steel), 88% (stainless steel)

Required Modifications:

- Multi-zone inspection: Separate focal laws for each bevel and root region
- Weld overlay accuracy: Precise bevel angle input critical
- Signal dynamics emphasis: Greater emphasis on echo dynamics and signal stability

Narrow-Gap Welds

Geometric Challenges:

- Steep bevel angles (3°) creating limited angular window
- Limited probe positioning options
- Increased geometric reflections from steep surfaces

Signature Modifications:

- **Angular range:** Reduced (45° – 75° needed versus 35° – 70° for V-groove)
- **S-scan:** Crack patterns often appeared compressed in the angular dimension
- **Porosity:** Patterns showed less dispersion due to limited beam angles
- **Classification accuracy:** 90% (mild steel)

Required Modifications:

- **Optimized angle range:** Shifted angular range to optimize coverage
- **Smaller index steps:** More detailed spatial sampling required
- **Enhanced imaging:** FMC/TFM techniques for resolving defects in narrow volume
- **Filtering:** Aggressive filtering sometimes required to reduce geometric noise

T-Joints

Geometric Challenges:

- Multiple probe positions required (web and flange surfaces)
- Complex beam paths including rebounds
- Limited access for some orientations
- Geometric echoes from multiple surfaces

Signature Modifications:

- **S-scan:** Significant variability depending on probe position
- **Corner trap:** Varied with beam path
- **Porosity:** Difficult to distinguish from geometric noise
- **Classification accuracy:** 70–80% (single position), 95% (combined positions)

Required Modifications:

- **Multi-position scanning:** Combination of web and flange scans essential
- **Rebound path consideration:** Classification features must be evaluated considering beam path used
- **Location-specific features:** Different distinguishing features for different inspection positions
- **Software-assisted positioning:** Implementation of scan plans to guarantee complete coverage

Pipe Welds

Geometric Challenges:

- Curvature altering beam coupling and refraction angles
- Varying inspection conditions across the circumference
- Access limitations for large-diameter pipes

Signature Modifications:

- **S-scan:** Curvature-related distortion
- **Corner trap:** Varied with beam orientation relative to curvature
- **Classification accuracy:** 92% with curvature-compensated parameters

Required Modifications:

- **Curvature compensation:** Delay laws adjusted for pipe curvature

- Multiple circumferential positions: Adequate sampling around circumference
- Specialized scanners: Encoded PAUT scanners for pipe inspection

Geometry Effects Summary

Geometry	Access	Geometric Echoes	Matrix Applicability	Required Modifications
V-Groove	Good	Minimal	100%	None
Double-Bevel	Moderate	Moderate	94%	Multi-zone, precise overlay
Narrow-Gap	Limited	High	90%	Optimized angles, FMC/TFM
T-Joint	Limited	High	70–80% (single) / 95% (combined)	Multi-position, rebound analysis
Pipe	Moderate	Moderate (curvature)	92%	Curvature compensation

Classification Performance

The classification performance of the multi-feature matrix was evaluated across all material-geometry combinations using destructive metallography as ground truth. Table 4.4.3 presents the accuracy, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) for each condition. The results demonstrate a clear degradation in classification performance as material complexity and geometric difficulty increase. Mild steel V-groove welds achieved perfect classification (100% across all metrics), establishing the baseline. Performance declined progressively through double-bevel (94%), narrow-gap (90%), and T-joint configurations (70–80% single position; 95% combined). Austenitic stainless steel showed reduced performance (94% V-groove; 88% double-bevel) due to grain noise and beam distortion, while dissimilar metal welds exhibited the lowest accuracy (87% V-groove; 80% complex geometry) owing to heterogeneous microstructure and acoustic mismatch. These results confirm that while the fundamental distinguishing features remain valid, their reliability is significantly influenced by material type and weld geometry.

Classification Performance Summary

Condition	Accuracy	Sensitivity	Specificity	PPV	NPV
Mild Steel, V-Groove	100%	100%	100%	100%	100%
Mild Steel, Double-Bevel	94%	92%	96%	96%	92%
Mild Steel, Narrow-Gap	90%	88%	92%	92%	88%
Mild Steel, T-Joint (single)	70–80%	68–78%	72–82%	72–82%	68–78%
Mild Steel, T-Joint (combined)	95%	94%	96%	96%	94%

Condition	Accuracy	Sensitivity	Specificity	PPV	NPV
Mild Steel, Pipe	92%	90%	94%	94%	90%
Stainless Steel, V-Groove	94%	92%	96%	96%	92%
Stainless Steel, Double-Bevel	88%	85%	91%	90%	86%
DMW, V-Groove	87%	84%	90%	89%	85%
DMW, Complex	80%	76%	84%	83%	78%

Note: All accuracy, sensitivity, specificity, PPV, and NPV values are reported with 95% confidence intervals (not shown in table for brevity). The confidence intervals were calculated using the Wilson score method for binomial proportions.

Parameter Optimization

Frequency Effects

The systematic variation of inspection frequency revealed significant effects on defect characterization:

Mild Steel:

- 5.0 MHz: Best resolution, excellent SNR, optimal for V-groove ≤ 25 mm
- 3.5 MHz: Adequate for thicker sections (>25 mm) with some resolution loss
- Classification accuracy maintained $>98\%$ across both frequencies

Austenitic Stainless Steel:

- 2.5 MHz: Essential for adequate penetration, acceptable SNR, best classification performance (94%)
- 3.5 MHz: Marginal for some specimens, reduced SNR, classification accuracy 88%
- 5.0 MHz: Unusable due to excessive grain noise

Dissimilar Metal Welds:

- 2.5 MHz: Best performance for the heterogeneous structure (87% accuracy)
- Multi-frequency techniques: Sequential inspection at 2.5 and 3.5 MHz provided complementary information

Aperture Effects

Aperture size influenced resolution and penetration:

- 16-element aperture: Standard, adequate for most configurations

- 32-element aperture: Improved resolution for deeper zones, better lateral resolution in thin sections
- Classification accuracy improved by 3–5% with larger aperture for complex geometries

Focal Depth Effects

Focal depth optimization proved critical for defect detection:

- Half-path focusing at target zone: Optimal for most configurations
- Multi-zone focusing: Essential for thick sections (>25 mm) and complex geometries
- Defects outside focal zone showed reduced detectability and pattern clarity

Angular Range Effects

Angular range significantly influenced classification performance:

- V-groove: 35°–70° optimal
- Double-bevel: 35°–70° with offset for each side
- Narrow-gap: 45°–75° necessary for coverage
- T-joint: Position-dependent, typically 40°–75°
- Pipe: Curvature-compensated angle range

Filtering Effects

Filtering effects on classification performance:

- **No filtering:** Best for preserving signal morphology, essential for classification
- **Video filtering:** Useful for display smoothing but may obscure some features
- **Aggressive filtering:** Can eliminate corner trap indicators, reducing classification accuracy

Recommendation: Maintain raw signal capture (no filtering) for classification data, apply display filtering only for visualization.

Optimized Parameter Matrix

Based on the systematic evaluation, the following optimized parameter matrix is recommended:

Material	Geometry	Frequency	Aperture	Focal Depth	Angular Range	Filtering
Mild Steel	V-Groove (<16mm)	5.0 MHz	16	Half-path	35–70°	None
Mild Steel	V-Groove (>16mm)	3.5 MHz	16	Half-path	35–70°	None
Mild Steel	Double-Bevel	5.0 MHz	16–32	Multi-zone	35–70°	None
Mild Steel	Narrow-Gap	3.5 MHz	32	Multi-zone	45–75°	Video

Stainless Steel	Any	2.5–3.5 MHz	16–32	Half-path	40–70°	Video
DMW	Any	2.5 MHz	16	Multi-mode	35–70°	Video
Mild Steel	T-Joint	5.0 MHz	16	Position-specific	40–75°	None
Mild Steel	Pipe	5.0 MHz	16	Curvature-compensated	35–70°	None

Classification Matrix Applicability and Adaptation (Research Question 4)

Matrix Performance Across Conditions

The baseline classification matrix was evaluated across all material-geometry combinations:

Condition	Matrix Performance	Required Modifications
Mild Steel, V-Groove	100%	None
Mild Steel, Double-Bevel	94%	Multi-zone considerations
Mild Steel, Narrow-Gap	90%	Angle range adjustment, FMC/TFM
Mild Steel, T-Joint (single)	70–80%	Multi-position combination required
Mild Steel, T-Joint (combined)	95%	Position-specific interpretation
Mild Steel, Pipe	92%	Curvature compensation
Stainless Steel, V-Groove	94%	Material-specific parameters
Stainless Steel, Double-Bevel	88%	Material + geometry adaptation
DMW, V-Groove	87%	Significant adaptation required
DMW, Complex	80%	Multi-mode + representative blocks

Matrix Adaptation Framework

Based on the result, a systematic framework for adapting the classification matrix is proposed:

Step 1: Material Assessment

- Determine material type and acoustic properties
- Assess grain structure (fine vs. coarse, isotropic vs. anisotropic)
- Evaluate need for frequency reduction, mode selection, skew scans

Step 2: Geometry Assessment

- Identify weld geometry and access conditions
- Assess geometric reflections and beam path complexity
- Determine probe positions and scan plan requirements

Step 3: Parameter Optimization

- Select frequency, aperture, focal depth, angular range based on material-geometry assessment
- Calibrate using representative specimens
- Validate on known reference reflectors

Step 4: Feature Evaluation

- For each indication, evaluate S-scan pattern (linear vs. diffuse)
- Determine weld zone location (Cap, Fill, Land, HAZ)
- Assess amplitude behavior and corner trap presence
- Analyze DA/ViA relationship

Step 5: Contextual Interpretation

- Apply material-specific and geometry-specific interpretation criteria
- Document confidence levels
- Consider additional features for complex cases

Step 6: Validation

- Cross-reference with additional PAUT views
- Consider complementary NDT methods if ambiguous
- Document classification reasoning

Additional Features for Complex Conditions

For materials and geometries where the baseline matrix shows reduced performance, additional features are resulted:

Austenitic Stainless Steel:

- Signal stability across multiple beam angles
- Comparison of LL and SW responses
- Consistency of signal with material microstructure

Dissimilar Metal Welds:

- Signal consistency across the heterogeneous zone
- Comparison with numerical simulation predictions
- Multi-mode (LL + SW) correlation

T-Joints:

- Consistency across probe positions
- Analysis of rebounded beam paths
- Correlation with geometric overlay considering multiple surfaces

Narrow-Gap Welds:

- FMC/TFM image quality
- Phase coherence imaging (PCI) results
- Comparison with modeled beam coverage

DISCUSSION

This section interprets the findings of the experimental investigation, addressing each research question in turn. The discussion synthesizes results across material types and weld geometries, compares findings with established literature, and explores the practical implications for PAUT inspection practice. The section concludes with a discussion of study limitations and recommendations for future research.

Material Effects on Acoustic Signatures (Research Question 1)

Mild Steel

These findings are consistent with established PAUT literature. Planar cracks act as specular reflectors producing distinct, well-defined echoes when the beam is oriented perpendicular to the crack face. The corner trap effect, particularly strong for root cracks, produces extremely high amplitude signals (up to 200% saturation) due to reflection from both the crack face and root geometry. The diffuse scattering behavior of porosity is consistent with the physical nature of volumetric defects: multiple small, rounded reflectors produce independent reflections that overlap to create the characteristic complex A-scan waveform. The classification matrix developed from the baseline study achieved 100% accuracy in distinguishing cracks from porosity based on S-scan pattern, weld zone location, amplitude behavior, and DA/ViA relationships. This provides a validated benchmark against which material and geometric effects can be assessed.

Austenitic Stainless Steel

These findings are consistent with the literature on ultrasonic inspection of austenitic stainless steels. The coarse, directional grains scatter shear waves and distort sound paths, while anisotropy bends angles unpredictably. The results confirm the need for specific inspection strategies:

- **Frequency Selection:** Lower frequencies (2.5–3.5 MHz) proved essential for adequate penetration and signal-to-noise ratio, consistent with literature recommendations. While 5.0 MHz provided better resolution in mild steel, it produced unacceptable grain noise in stainless steel.
- **Beam Mode Selection:** Refracted longitudinal (LL) and mixed-mode techniques significantly outperformed shear wave techniques in coarse-grained material, consistent with the literature. LL waves are less affected by grain scattering than shear waves.
- **Skew Scans:** Adding skew scans of $\pm 10^\circ$ to 20° improved detection by exposing indications hidden by grain orientation, confirming literature findings.
- **Classification Matrix Adaptation:** The classification matrix maintained its discriminatory power when applied with material-appropriate parameters, but confidence levels were reduced for borderline indications. The linear vs. diffuse S-scan pattern distinction remained valid, though pattern clarity was reduced.

Dissimilar Metal Welds

The findings support the literature recommendations for dissimilar metal welds inspection:

1. **Representative Calibration Blocks:** Blocks with similar microstructures, overlays, or butter layers are essential for reliable calibration.
2. **Multi-Mode Inspection:** Separate groups for LL-root, LL-sidewall, and corroborating SW scans are necessary for comprehensive coverage.
3. **Numerical Simulation:** Modeling acoustic wave propagation to observe effects of test circumstances and choose optimal parameters.
4. **Classification Matrix Adaptation:** Additional features are required for dissimilar metal welds classification, including:
 - Consistency of signal across multiple beam angles
 - Comparison of Longitudinal and Shear waves responses
 - Evaluation of signal stability across the heterogeneous zone

Geometry Effects on Acoustic Signatures (Research Question 2)

The second research question investigated how weld geometry influences the presentation and interpretation of distinguishing acoustic features between cracks and porosity. The results demonstrate that while fundamental distinguishing features remain valid across geometries, their application requires geometry-specific scan plans and interpretation approaches. Geometry primarily affects the presentation and detectability of features rather than the features themselves.

V-Groove Butt Welds (Baseline)

The V-groove geometry provided well-understood acoustic behavior with excellent probe access, predictable geometric reflections, and clear separation of defect signals from geometric echoes. Classification accuracy reached 100%, confirming the validity of the baseline study and providing a benchmark for evaluating more complex geometries.

Double-Bevel Butt Welds

The double-bevel geometry introduced additional complexity, reducing classification accuracy to 94%. Two bevel surfaces created additional reflection paths, while the wider weld volume required multiple focal depths. S-scan patterns for cracks remained linear but were sometimes obscured by bevel reflections, and corner trap effects were less distinct due to interference from bevel echoes. Required modifications included multi-zone inspection with separate focal laws, precise bevel angle input for accurate overlays, and greater emphasis on echo dynamics rather than overlay-based interpretation.

Narrow-Gap Welds

Narrow-gap welds presented unique challenges due to limited access and steep bevel angles, reducing classification accuracy to 90%. The steep bevel angles (3°) created a limited angular window, restricted probe positioning, and increased geometric reflections. Required modifications included optimized angular range (45° – 75°), smaller index steps for detailed spatial sampling, FMC/TFM techniques for resolving defects in the narrow volume, and aggressive filtering to reduce geometric noise.

T-Joints

T-joints presented the most significant geometry-related challenges, with classification accuracy dropping to 70–80% for single-position inspection but recovering to 95% when combined positions were used. The complex geometry required multiple probe positions, created complex beam paths including rebounds, and produced geometric echoes from multiple surfaces. Required modifications included multi-position scanning

combining web and flange scans, rebound path consideration, location-specific features, and software-assisted positioning. These findings confirm the literature that T-joints "have always presented a challenge for ultrasonic testing" due to their "complex geometry [making] scan plan determination difficult."

Pipe Welds

Circumferential pipe welds introduced curvature effects that reduced classification accuracy to 92% with curvature-compensated parameters. Curvature altered beam coupling and refraction angles, created varying inspection conditions across the circumference, and imposed access limitations. Required modifications included curvature compensation through adjusted delay laws, multiple circumferential positions for adequate sampling, and specialized encoded PAUT scanners.

Summary of Geometry Effects

The geometry effects can be summarized as follows: V-groove provides 100% matrix applicability requiring no modifications; double-bevel provides 94% requiring multi-zone inspection and precise overlay; narrow-gap provides 90% requiring optimized angles and FMC/TFM; T-joint provides 70–80% (single) and 95% (combined) requiring multi-position scanning and rebound analysis; and pipe provides 92% requiring curvature compensation. The fundamental distinguishing features remain valid across geometries, but their application requires geometry-specific scan plans and interpretation approaches. Inspectors must adapt their scan plans and interpretation criteria to the specific geometry being inspected, rather than applying a one-size-fits-all approach.

Parameter Optimization (Research Question 3)

The third research question investigated optimal PAUT inspection parameters for reliable defect characterization across different material-geometry combinations. The systematic variation of frequency, aperture, focal depth, angular range, and filtering revealed significant effects on classification performance.

Frequency selection proved critical, with optimal values varying by material. For mild steel, 5.0 MHz provided the best resolution and signal-to-noise ratio for sections up to 25 mm, while 3.5 MHz was adequate for thicker sections with classification accuracy maintained above 98%. For austenitic stainless steel, 2.5 MHz was essential for adequate penetration and achieved the best classification performance (94%), while 3.5 MHz was marginal (88%) and 5.0 MHz was unusable due to excessive grain noise. For dissimilar metal welds, 2.5 MHz provided the best performance (87% accuracy), with sequential multi-frequency inspection at 2.5 and 3.5 MHz providing complementary information.

Aperture size influenced resolution and penetration, with 16-element apertures adequate for most configurations and 32-element apertures improving resolution for deeper zones and complex geometries by 3–5%. Focal depth optimization proved critical, with half-path focusing at the target zone optimal for most configurations and multi-zone focusing essential for thick sections and complex geometries. Angular range significantly influenced classification performance, with 35°–70° optimal for V-groove, 45°–75° necessary for narrow-gap, and position-dependent ranges for T-joints. Filtering effects showed that no filtering best preserved signal morphology essential for classification, while aggressive filtering could eliminate corner trap indicators and reduce accuracy.

Based on these findings, an optimized parameter matrix was developed. For mild steel V-groove welds under 16 mm, 5.0 MHz with 16-element aperture, half-path focusing, and 35°–70° angular range without filtering is recommended. For thicker sections, 3.5 MHz is preferred. Double-bevel welds require 5.0 MHz with 16–32 element aperture and multi-zone focusing. Narrow-gap welds require 3.5 MHz with 32-element aperture, multi-zone focusing, 45°–75° angular range, and video filtering. Austenitic stainless steel requires 2.5–3.5 MHz with 16–32 element aperture and video filtering. Dissimilar metal welds require 2.5 MHz with 16-element aperture, multi-mode inspection, and video filtering. T-joints require position-specific focusing with 40°–75° angular range, while pipe welds require curvature-compensated focusing. This optimized parameter

matrix provides practical guidance for inspectors, enabling reliable defect characterization across diverse material-geometry combinations.

Classification Matrix Applicability and Adaptation (Research Question 4)

The fourth research question evaluated whether the multi-feature classification matrix maintains its discriminatory performance across materials and geometries. Results showed progressive degradation: mild steel V-groove achieved 100%, declining through double-bevel (94%), narrow-gap (90%), T-joint (70–80% single; 95% combined), stainless steel (94% V-groove; 88% double-bevel), DMW (87% V-groove; 80% complex), and pipe (92%). Based on these findings, a six-step adaptation framework was developed: material assessment, geometry assessment, parameter optimization, feature evaluation, contextual interpretation, and validation.

For challenging conditions, additional features are recommended—signal stability across beam angles for stainless steel, multi-mode correlation for DMWs, position consistency for T-joints, and FMC/TFM imaging for narrow-gap welds. The key finding is that the matrix maintains discriminatory power but requires material-specific and geometry-specific adaptation, transforming it from a fixed laboratory tool into a flexible, field-adaptable methodology.

Comparison with Literature

The findings of this study are broadly consistent with established literature on PAUT defect characterization. The observation that austenitic stainless steels require lower frequencies (2.5–3.5 MHz) and exhibit 6–12 dB lower SNR than carbon steels aligns with extensive research, including Silk (1984) and Williams (1985). The finding that shear wave techniques are compromised in coarse-grained materials, and that LL or mixed-mode techniques are superior, is well supported. The challenges observed with DMWs—heterogeneous microstructure, beam distortion, and acoustic mismatch—confirm literature recommendations for representative calibration blocks, multi-mode inspection, and numerical simulation.

Geometry effects also align with prior research: T-joint challenges requiring multi-position scanning and rebound path consideration, narrow-gap welds requiring optimized angular ranges and FMC/TFM imaging, and pipe welds requiring curvature compensation are all consistent with published findings.

Novel Contributions

- **Systematic Characterization:** First systematic evaluation of material effects on the multi-feature classification matrix across multiple materials and geometries.
- **Quantitative Performance Metrics:** Provision of accuracy, sensitivity, and specificity across conditions.
- **Adaptation Framework:** Development of a systematic six-step framework for adapting the classification matrix.
- **Optimized Parameter Matrix:** Provision of parameter guidance for different material-geometry combinations.
- **Practical Guidance:** Development of field-usable guidance for inspectors working with challenging materials and geometries.

Practical Implications for Industry

For Inspection Service Providers

- **Material-Specific Qualification:** Inspectors should be qualified on material-specific specimens, understanding attenuation, SNR characteristics, and frequency/mode selection.
- **Geometry-Specific Procedures:** Inspection procedures should include geometry-specific scan plans, calibration settings, and classification criteria.

- **Parameter Selection:** The optimized parameter matrix (Table 5.3.6) provides guidance for frequency, aperture, focal depth, angular range, and filtering.
- **Documentation and Uncertainty:** Classification decisions should document confidence levels, supporting features, ambiguity, and recommendations for further investigation.

For Standards and Code Development

- **Material-Specific Guidance:** Standards should provide specific guidance for austenitic stainless steels and DMWs.
- **Geometry-Specific Procedures:** Standards should acknowledge geometry effects and provide scan plan and calibration requirements.
- **Classification Framework:** Standards should incorporate the multi-feature classification approach with documentation and confidence level assignment.

For Training Programs

- **Material Effects Module:** Hands-on inspection of different materials.
- **Geometry Effects Module:** Practical experience with T-joints, narrow-gap, and pipe configurations.
- **Classification Matrix Training:** Systematic training on the multi-feature approach and adaptation framework.
- **Case Studies:** Real-world examples of classification challenges.

For Quality Assurance

- **Performance Demonstration:** Regular demonstration on material-geometry-specific test blocks.
- **Inter-Observer Comparison:** Periodic comparison of classification decisions.
- **Statistical Process Control:** Monitoring of accuracy, false positive, and false negative rates.

LIMITATIONS

Material Limitations

- Limited to mild steel, austenitic stainless steel, and DMWs; other materials not investigated.
- Controlled laboratory defects may differ from service-induced defects.
- Single grade per material type investigated.
- Homogeneity assumed within each specimen.

Geometry Limitations

- Limited to five geometries; many variations not covered.
- Idealized laboratory geometries may differ from field welds.
- Simplified access conditions may not represent field constraints.

Experimental Limitations

- Limited sample sizes for some material-geometry combinations.
- Single operator used; inter-operator reliability not assessed.
- Parameters optimized but not exhaustively varied.

Generalizability Limitations

- Results depend on proper calibration.
- Equipment-specific (OmniScan X2).
- Software-specific (Omni PC).

Recommendations for Future Research

Extended Material Investigation

- Additional materials (aluminum, titanium, composites).
- Natural/service-induced defects.
- Material grade effects
- Heat treatment effects.

Extended Geometry Investigation

- Additional geometries (skewed T-joints, branch connections).
- Thick sections (>50 mm).
- Repair welds.

Advanced Techniques

- FMC/TFM systematic evaluation.
- Phase Coherence Imaging (PCI).
- Machine learning for automated classification.
- Numerical simulation correlation.

Field Validation

- Field studies under realistic conditions.
- Multi-operator reliability studies.
- Longitudinal tracking of classification outcomes.

Standardization

- Standardized procedures for PAUT defect classification.
- Comprehensive training materials.
- Validated reference specimens.

Summary

The discussion has addressed the five research questions through systematic analysis of experimental results:

- **Material Effects:** Material type significantly affects acoustic signatures. Mild steel provides baseline performance (100%). Austenitic stainless steel requires frequency reduction (2.5–3.5 MHz) and mode selection (~94%). DMWs require significant adaptation (~87%).
- **Geometry Effects:** Weld geometry significantly influences classification reliability. V-groove provides baseline (100%). Double-bevel (94%), narrow-gap (90%), T-joint (70–80% single; 95% combined), and pipe (92%) require geometry-specific considerations.
- **Parameter Optimization:** An optimized parameter matrix has been developed for each material-geometry combination.
- **Matrix Applicability:** The classification matrix requires material-specific and geometry-specific adaptation; a six-step framework has been developed.
- **Practical Implementation:** Practical guidance for inspectors, including procedures, training, and quality assurance considerations.

The study confirms that fundamental distinguishing features (S-scan pattern, weld zone location, amplitude behavior, corner trap presence, DA/ViA relationship) remain valid across materials and geometries.

However, their interpretation requires material-specific and geometry-specific calibration, with optimized parameters and consideration of additional features for complex conditions. The adaptation framework provides a systematic approach for extending the classification matrix to new applications, enhancing PAUT reliability across the full range of industrial welding applications.

CONCLUSION

This study systematically investigated the influence of weld geometry and material type on the acoustic signatures of planar cracks and volumetric porosity in PAUT inspection. The following conclusions are drawn:

- **Material Effects:** Mild steel provides baseline performance (100%). Austenitic stainless steel requires frequency reduction (2.5–3.5 MHz) and mode selection (~94%). DMWs require significant adaptation (~87%).
- **Geometry Effects:** V-groove provides baseline (100%). Double-bevel (94%), narrow-gap (90%), T-joint (70–80% single; 95% combined), and pipe (92%) require geometry-specific considerations.
- **Parameter Optimization:** An optimized parameter matrix has been developed for each material-geometry combination.
- **Matrix Applicability:** The classification matrix requires material-specific and geometry-specific adaptation; a six-step framework has been developed.
- **Practical Implementation:** Practical guidance for inspectors, including procedures, training, and quality assurance considerations.

The study confirms that fundamental distinguishing features remain valid across materials and geometries. However, their interpretation requires material-specific and geometry-specific calibration, with optimized parameters and consideration of additional features for complex conditions.

The adaptation framework provides a systematic approach for extending the classification matrix to new applications, enhancing PAUT reliability across the full range of industrial welding applications.

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Author Contributions

Surafel Yemane conceived and designed the study, conducted the experimental inspections, analyzed the data, and wrote the manuscript. The author has read and approved the final manuscript.

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Ethics Statement

This study involved analysis of existing inspection data and did not involve human subjects or animal studies. All data analysis was conducted in accordance with established research ethics guidelines. Institutional data access policies were followed for data sharing.

- All inspections conducted in controlled laboratory environment

- No human subjects or animal studies involved
- Data analysis conducted in accordance with established research ethics guidelines
- Institutional data access policies for data sharing

Data Availability Statement

The Omni PC scan files generated during this study are not publicly available due to the proprietary nature of the software data formats and specific industrial sample configurations. However, the author (Surafel Yemane) can provide access to the raw data in a standardized format upon reasonable request from qualified researchers, subject to institutional data access policies. All processed data presented in this manuscript are included in the tables.

Conflict of Interest

The author declares no conflict of interest.

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