Inspection for High Temperature Hydrogen Attack

(Draft7.1 for resolved March 2021 comment ballot and March-September 2021 meetings actions)

API RECOMMENDED PRACTICE 586, Section 2

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Contents

Introduction

The form of hydrogen damage called high temperature hydrogen attack (HTHA) is discussed in API RP 571, API RP 941, and API 941 TR-A.

The purpose of this recommended practice (RP) is to describe the wide variety of inspection methods and techniques applicable for reliable detection and assessment of service-induced HTHA damage in the refinery equipment.

This document includes information assembled from the refining industry experience and is anticipated to be balanced with applicable API and other related industry standards and practices.

This RP is intended to provide guidance for the use of optimized inspection techniques but should not be considered the final technical basis for HTHA detection and analysis. The inspection techniques descriptions in this RP are not intended to present an absolute guideline for every possible situation that may be confronted. The reader may need to consult with an inspection engineer or NDE SEM for specific circumstances.

1 Scope

This recommended practice (RP) applies to inspection of equipment in refineries, petrochemical facilities, and chemical facilities in which hydrogen or hydrogen-containing fluids are processed at elevated temperature and pressure. The guidelines in this RP can also be applied to hydrogenation plants such as those that manufacture ammonia, methanol, edible oils, and higher alcohols.

This RP summarizes inspection methods and techniques applicable for reliable detection and assessment of service-induced HTHA damage. This RP is reference document for the new and early inspection approaches. The techniques discussed and recommended in this RP are optimized for inspection of HTHA.

Non-destructive Evaluation (NDE) characterization, categorization, and sizing related to HTHA manifestation is intended to be used for reporting and conducting Fitness-For-Service (FFS) assessments.

Presented in this document considerations when planning an HTHA inspection should be utilized as a reference to other integrity related documents.

Presented in the annex (s) examples of optimized setups, results of experimental tests and actual data acquired from operating plants are foreseen to improve HTHA inspection.

2 Normative References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For undated references, the latest edition of the referenced document (including any addenda) applies.

API Recommended Practice 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry.
API Recommended Practice 941, Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants", Eighth Edition, Adendum 1.
API 941 TR-A, The Technical Basis Document for API RP 941.
API, Recommended Practice 579-1 / ASME FFS-1, Fitness-For-Service, TBD Edition, Part 16, (Draft).
ASME *Boiler and Pressure Vessel Code* (*BPVC*) [1], *Section V: Pressure Vessels; Division 1.*

[1] *ASME International, 2 ParkAvenue, New York, New York 10016-5990, www.asme.org.*

3 Abbreviations

3.1 Acoustic Emission Testing (AET)

3.2 Advanced Ultrasonic Backscatter Technique (AUBT)

3.3 Blister (B)

3.4 Crack-like (C)

3.5 Combination of Volumetric, Blister, and Crack-like (CVBC)

3.6 Field Metallography and Replication (FMR)

3.7 Fitness-For-Service (FFS)

3.8 Full Matrix Capture/Total Focusing Method (FMC/TFM)

3.9 Heat Affected Zone (HAZ)

3.10 High Sensitivity Wet Fluorescent Magnetic Testing (HS WFMT)

3.11 High Temperature Hydrogen Attack (HTHA)

3.12 Inclusions (I)

3.13 Inside Diameter (ID)

3.14 Non-destructive Evaluation (NDE)

3.15 Optical Light Microscopy (OLM)

3.16 Outside Diameter (OD)

3.17 Lack of Fusion (LOF)

3.18 Lack of Penetration (LOP)

3.19 Laminations (L)

3.20 Localized Thin Area (LTA)

3.21 Penetrant Testing (PT)

3.22 Phased Array Ultrasonic Testing (PAUT

3.23 Positive Materials Identification (PMI)

3.24 Post Weld Heat Treatment (PWHT)

3.25 Radiographic Testing (RT)

3.26 Scanning Electron Microscopy (SEM)

3.27 Subject Matter Expert (SME)

3.28 Submerged Arc Welding (SAW)

3.29 Shielded Metal Arc Welding (SMAW)

3.30 Time of Flight Diffraction (TOFD)

3.31 Ultrasonic Testing (UT)

3.32 Visual Testing (VT)

3.33 Volumetric (V)

3.34 Weld Overlay (WOL)

3.35 Wet Fluorescent Magnetic Particle Testing (WFMT)

4 Summary of Inspection Methods

4.1 General

4.1.1 The selection of optimum inspection methods and intervals for HTHA in specific equipment or applications is the responsibility of the owner/user.

4.1.2 HTHA damage may occur in welds, weld Heat Affected Zones (HAZs), or in the base metal. Even within these specific areas, the degree of damage may vary widely. if damage is suspected, then a thorough inspection of representative samples of these areas shall be conducted. The susceptibility to HTHA and inspection scope should be determined by owner's -operators subject matter experts (SMEs).

4.1.3 HTHA inspection relies on specialized techniques. These techniques, procedures, and operator proficiency should be demonstrated on a broad spectrum of HTHA-damaged samples (including both damage degree and damage areas, i.e., welds and base metal).

4.1.4 Tables 1, 2 and 4 provide a summary of available methods of inspection for HTHA damage and include a discussion of the advantages and limitations of each.

4.2 Recommended Inspection Approach

While early backscattered UT approach may be appropriate for complementary HTHA inspection, Time of Flight Diffraction (TOFD), Phased Array Ultrasonic Testing (PAUT), Full Matrix Capture/Total Focusing Method (FMC/TFM) and High Sensitivity Wet Fluorescent Magnetic Testing (HS WFMT) are now the recommended NDE techniques for HTHA inspection—see Table 1a and Table 2 (second column). More details about the Ultrasonic Testing (UT) techniques and essential variables can be found in ASME BPV Code Section V, Articles 1 and 4 and related Appendixes and other publications focused on in-service inspections [2–10].

Encoded UT techniques as described in Table 1a are effective for detecting HTHA damage, and two or more recommended UT techniques are often used in combination to overcome the limitations of any single technique.

The use of the highest practical frequency (e.g., 7.5 MHz to 10.0 MHz) is recommended to achieve maximum detection sensitivity for the detection of microdamage. Selection of frequency of equivalent wavelength for the purpose of discriminating HTHA from metallurgical imperfections is recommended. For example, use of 10 MHz 0-degree longitudinal wave to be compared with 5 MHz transverse wave angle beam in order to determine orientation of imperfection. The use of "typical" shear wave frequency in the 3.5 MHz to 5.0 MHz range may also be included to enhance characterization of coalesced or macrocracking associated with adjacent microdamage.

4.2.1 Time of Flight Diffraction (TOFD)

— TOFD involves a pair of angled longitudinal wave probes with discrete transmitter and receiver facing towards each other on the same surface of the material being inspected.

— The transmitter emits a broad beam of energy that insonifies the area of interest. Responses from the direct path between the probes (lateral wave), reflected and diffracted energy from features within the material, and reflected energy from the far surface are detected by the receiver.

— The probe pair is scanned with a fixed separation while ultrasonic waveforms are digitized at predetermined intervals. These are used to create real-time B or D-scans typically with grayscale imaging.

4.2.2 Phased Array Ultrasonic Testing (PAUT)

- In ASME *BPVC* Section V, *Nonmandatory Appendix E*, E-474, "the UT-phased array technique is a process wherein UT data are generated by controlled incremental variation of the ultrasonic beam angle in the azimuthal or lateral direction while scanning the object under examination."

- PAUT offers an advantage over processes using conventional search units with fixed beam angles, as it acquires considerably more information by covering a large range of angles (sweep).

4.2.3 Full Matrix Capture/Total Focusing Method (FMC/TFM)

- In ASME *BPVC* Section V: Article 1, *Mandatory Appendix I, Glossary of Terms for Nondestructive Examination,* FMC/TFM is an industry term for an examination technique involving the combination of classic FMC data acquisition and TFM data reconstruction.

- FMC/TFM process offers improved detection because all reflected, diffracted, and scattered signals are stored in the FMC matrix and are used for TFM reconstruction; characterization is better because of enhanced spatial resolution; sizing is more accurate because all points or pixels defined by high resolution grid within the Region of Interest (ROI) can be focused during the imaging process.

4.2.4 High Sensitivity Wet Fluorescent Magnetic Testing (HS WFMT)

- High Sensitivity Wet Florescent Magnetic Testing (HS WFMT) is a combination of surface metal removal, macro etching and continuous Wet Florescent Magnetic Particle Inspection technique.
- HS WFMT can detect early stages of HTHA damage. HTHA damage detection using HSWFMT is limited to the depth of removed material and highly dependent surface preparation.
- Metal sample removal and metallurgical analysis is the most effective method for characterization and improving NDE interpretation.

4.3 Early Inspection Approach

"Conventional" backscattered UT has been a primary technique in the past [1]. Backscattered UT includes several "sub-techniques" and are listed in this section. These techniques for detection and characterization of HTHA are considered less effective than the new techniques listed in section 4.2.

4.3.1 Amplitude-based

- High-frequency ultrasonic waves backscattered from within the metal are measured. HTHA can increase backscatter signal amplitude.

- Has been shown to detect HTHA fissures in base metal, away from weldments.

- Original manufacturing flaws/material inclusions can cause false positives.

4.3.2 Pattern Recognition

- High-frequency ultrasonic waves backscattered from within the metal are analyzed. HTHA causes a rise and fall in backscatter pattern.

- Has been shown to detect HTHA fissures in base metal, away from weldments.

4.3.3 Spatial Averaging

— Backscatter data are collected over an area scanned. The signal is averaged to negate grain noise.

— Has been shown to detect HTHA fissures in base metal, away from weldments.

4.3.4 Directional Dependence

— Compares backscatter signal as taken from inside diameter (ID) and outside diameter (OD) directions. HTHA- damaged materials will show a shift in indicated damage towards the exposed surface (ID).

— Has been shown to detect HTHA fissures in base metal, away from weldments.

— Orientation of damage affected by stress planes and grain structure.

— Evidence of more than one directional plane has been observed opposing this principle.

4.3.5 Frequency Dependence

— Compares backscatter of two different frequency transducers. HTHA-damaged material will show a shift and spread of backscatter in time.

— Has been shown to detect HTHA fissures in base metal, away from weldments.

4.3.6 Velocity Ratio

— Velocity ratio is a technique for indication characterization by measuring the ratio of shear wave velocity versus longitudinal wave velocity of straight beam on base metal. Based on empirical data, velocity ratio increases when there is HTHA damage in the base metal. The threshold value commonly used in the past is 0.555.

— Velocity ratio is more effective when the depth percentage of damage is relatively large, usually when it is more than 20 %. The measurement locations of shear wave and L-wave need to match very well to reduce measurement error. There are also some recent cases demonstrated that the characterization result did not match metallurgical analysis.

5 HTHA Manifestation, NDE Characterization/Categorization and Reporting

In API 579-1, draft section on assessment of HTHA damage, HTHA damage is categorized as (1) volumetric, (2) blister, (3) crack-like flaw, and (4) combination of volumetric, blister, and crack-like flaw damage. An example for damage reporting is shown in Table 3.

1. HTHA Volumetric Damage—Typically occurs in base metal and is widespread on the component. An exception is for local hot spots on high temperature components where accelerated HTHA damage may occur locally because of the high temperature. This damage is characterized by submicron intergranular voids and fissuring (see Figure 1). Proposed NDE characterization/categorization/reporting acronym—(V).

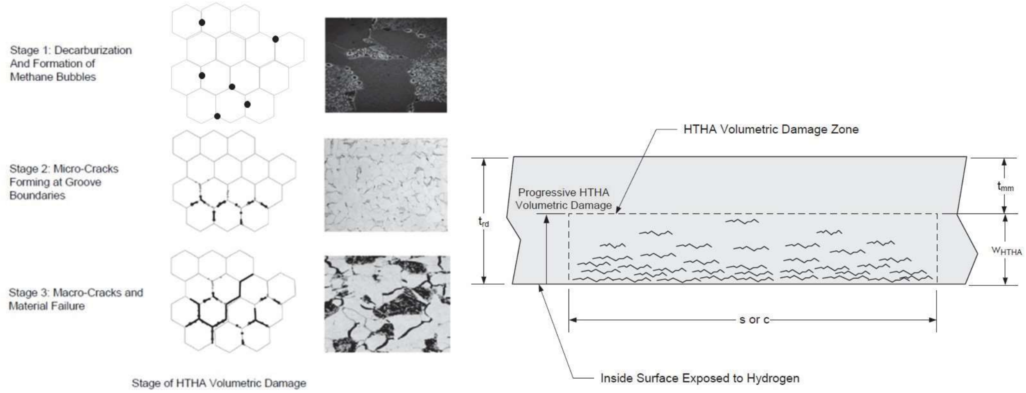

Figure 1—HTHA Volumetric Damage Manifestation (left) and Sketch (right)

2. HTHA Blisters—An advanced form of volumetric damage, where the methane pressure results in macro-scale fissuring in the form of blisters on the inside surface of a component (see Figure 2). Proposed NDE characterization/categorization/reporting acronym—(B).

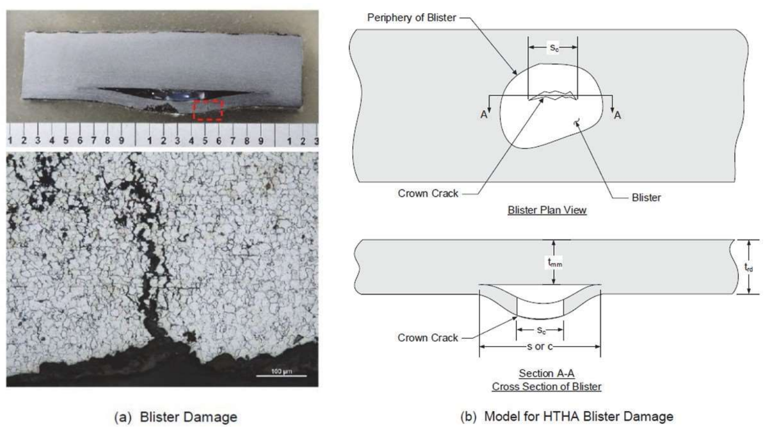

Figure 2—HTHA Blister Damage Manifestation (left) and Sketch (right)

3. HTHA Crack-like Flaw Damage—Typically associated with the HAZ of welds. This crack-like flaw is planar for this damage mechanism. It is characterized by cracking in the heat affected zones or fusion boundary of welds (see Figure 3). Proposed UT characterization/categorization/reporting acronym—(C). Although this macro image highlights the crack-like flaw, less advanced HTHA damage (Stage 1 or Stage 2 damage) may be present elsewhere in the sample, as it is likely that HTHA damage extends beyond crack-like flaws.

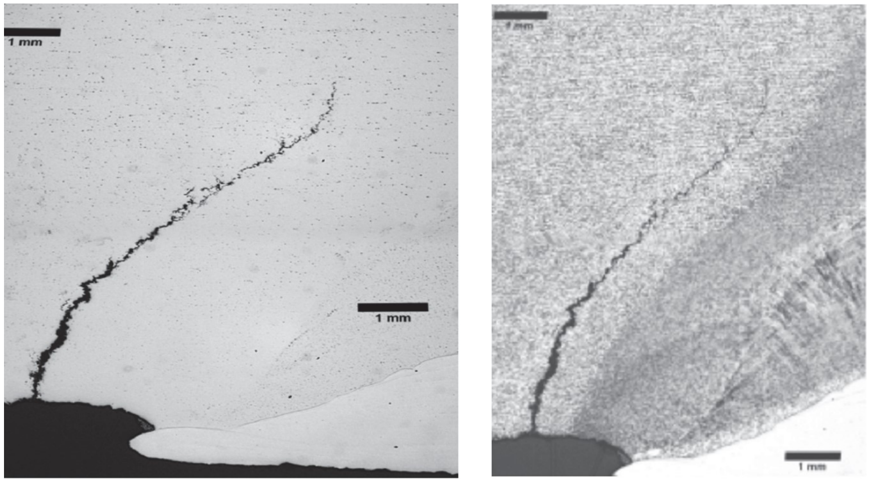

Figure 3—HTHA Crack-like Flaw Damage Manifestation

4. HTHA Combination of Volumetric, Blister, and Crack-like Flaw Damage—Volumetric damage can occur to the base metal while crack-like flaws are occurring within the HAZ of welds (See Figure 4). Volumetric damage that occurs ahead of the crack tip can weaken the nearby material, leading to even faster crack growth rates. Proposed UT characterization/categorization/reporting acronym—(CVBC). Note that it is also possible to have volumetric and crack-like flaws without necessarily having blisters. In advance of the cracking, it is possible to have Stage 2 damage, which is usually detectable by NDE, and Stage 1 damage, which is usually not detectable by NDE.

NOTE Metallurgical imperfections such as inclusions (I) and laminations (L) will probably be detected and may act as HTHA damage nucleation points. Welding imperfections such as lack of fusion (LOF) and lack of penetration (LOP) will probably be detected also. Additional NDE characterization is required to avoid miscategorization and false positive indications.

Figure 4—HTHA Combination of Volumetric, Blister, and Crack-like Flaw Damage Manifestation.

Table 1a – Recommended Ultrasonic Techniques

	TOFD	PAUT	FMC/TFM
Description	Diffraction and time-based. Longitudinal-longitudinal diffraction mode setup of pair transducers. B- and D-grayscale 2D image of the digitized A-scan. Higher frequencies increase capability for detection of HTHA at weldments.	Reflective and diffraction-based. Longitudinal and shear waves. Linear, 2-D matrix and annular arrays. A-, B-, C-, D-, S- scan 2D imaging. Pulse-echo scheme (using higher frequency sound) increases capability for detection of HTHA in base material and weldments/HAZ.	Reflective, diffraction and scatter-based. Longitudinal and waves. Linear and 2-D matrix arrays. A-, B-, C-, D- scan 2/3D imaging. FMC data acquisition scheme that involves the collection of all possible combinations of sources and receivers in an array, and TFM imaging scheme that involves computation of a focused image on every point of an imaged region (using high-frequency sound) to increase the capability for better detection and sizing of HTHA in base material and weldments/HAZ.
Detection Capability Effectiveness [a]	Usually Effective: Can detect Stage 2 HTHA in base metal, weld HAZ, and at weldments.	Usually Effective: Can detect Stage 2 HTHA in base metal, weld HAZ, and at weldments.	Usually effective: Can detect Stage 2 HTHA: in base metal, weld HAZ, and at weldments.
Sizing Effectiveness	Usually effective for length and depth (location) and height sizing. Not effective for precise location and sizing (width) perpendicular to the scanning direction.	Usually effective for length and depth (location), height and width sizing when appropriate inspection setup is used.	Usually effective for length and depth (location), height and width sizing. When appropriate inspection setup is used, better effectiveness can be achieved than PAUT.
Characterization Capability	— With a combination of these techniques, proper characterization between HTHA damage and large fabrication flaws (e.g. lamination in base metal, LOP, LOF, slag, isolated porosity, and inclusion) can be effective through indication location, advanced imaging and pattern recognition. — Difficult to distinguish early-stage HTHA from inclusions/impurities. — Difficult to distinguish HTHA-induced cracking versus cracks induced with potentially other damage mechanisms from one inspection data set. — Encoded data storage makes it possible to perform more reliable monitoring of indication from multiple inspections than conventional methods. — The fundamental principles of early characterization techniques (backscatter signal pattern recognition, frequency spectrum analysis, and velocity ratio) are still applicable to further assist in indication characterization. These techniques can be applied on data collected from new techniques (TOFD, PAUT, and TFM) to improve capability and confidence for characterization between HTHA and other damage mechanisms.		
Comments	— Higher inspection speed for a parallel scan and lower inspection speed for combined parallel and nonparallel scans. — Consideration is to be given to the blind zone created by the leading edge of the ID response masking low amplitude responses from adjacent flaws and/or flaws located in the shadow zone caused by the ID geometry. Similarly, inspections from the ID will create a near-surface blind zone due to the lateral wave. Supplemental techniques such as PAUT or FMC/TFM should be considered where damage within the blind zones is a concern.	Greatest effectiveness achieved in near field of the transducer used. (Typ. minimum of 32 elements for thickness ≤1 in./25mm and 64 for > 1 in./25mm). Lower but practical inspection speed.	Greatest effectiveness achieved in near field of the transducer used and using high-density reconstruction grid. (Typ. minimum of 64 elements for a typical 10 MHz transducer and 65,000-1,000,000 grid points). Lower but practical inspection speed.

NOTE 1 Techniques must be developed/assessed/applied according to case-specific applications (e.g. thickness, geometry, material of construction, access, etc.)

NOTE 2 Optimized and validated procedures to include well-tuned application specific setups for TOFD, PAUT, and FMC/TFM.

NOTE 3 Operators should have HTHA-specific training and qualifications.

NOTE 4 Validation or progressive qualification may be conducted using scoop or boat sampling or destructive testing.

NOTE 5 Readers should reference Annex A-E for additional detailed guidance.

NOTE 6 Early-stage HTHA damage may not be ID surface connected.

[a] Effectiveness is based upon Stage 2 volumetric damage. Full inspection effectiveness (versus detection capability) will be covered in future effort to address 581 inspection effectiveness guidance.

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Table 1b—Early Ultrasonic Techniques

For Detection and Sizing	Single Element A Scan Straight Beam Manual Scanning	Single Element A Scan Angle Beam Manual Scanning
Description	Use single element straight beam probe in initial scanning targeted to detect indications equivalent to the size of HTHA fissures.	Use high-frequency single element angle beam probe (flat or contour focused) in initial scanning targeted to detect indications equivalent to the size of HTHA fissures and microcracking in the heat affected zone.
Effectiveness	— Performance of manual scanning without data recording is very dependent on technician capability and condition during inspection. Therefore, the effectiveness of manual scan for detection is considered less effective than new techniques with data recording capability. — These techniques can be used as supplemental techniques in situations where initial scanning techniques with encoded data recording is not practical.	

For Characterization	Velocity Ratio	Attenuation	Longitudinal Spectral Analysis	Angle-beam Spectrum Analysis	Conventional Single Element A-scan Backscatter Pattern Recognition
Description	Ratio of shear and longitudinal wave velocity is measured. HTHA changes the ratio.	Dispersion of ultrasonic longitudinal wave is measured by recording drop in amplitude of multiple echoes. HTHA increases attenuation.	The first backwall signal is analyzed in terms of amplitude versus frequency. HTHA will attenuate high-frequency response more than low frequencies.	The spectrum of any suspect signal from pulse-echo inspection of weld/HAZ is compared with a reference spectrum taken in the pitch-catch mode from the base metal. HTHA causes the pulse-echo spectrum to increase amplitude with increase of frequency.	— Amplitude-based — Pattern Recognition — Spatial Averaging — Directional Dependence — Frequency Dependence
Capability	— A combination of these techniques is historically used to assist in characterizing an indication of HTHA from other flaws. — Reliability and repeatability of angle beam spectrum analysis are very dependent on subjective judgement of personnel during inspection. — Very limited data is collected for monitoring purposes, and the data collection process is time consuming.				

Table 2—Non-ultrasonic NDT Methods for HTHA [a]

	Wet Fluorescent Magnetic Particle Testing (WFMT)	High Sensitivity Wet Fluorescent Magnetic Particle Testing (HS WFMT)	Radiographic Testing (RT)	Visual Testing (VT)	Acoustic Emission Testing (AET)
Description	Ferrous particles with fluorescent coatings suspended in liquid gather at interruptions in magnetic flux lines at the surface creating an indication. Magnetic flux should be generated by alternating current (ac). Surfaces are prepared via wire wheel or sand blasting.	See description of HS WFMT in 4.1.4 Additionally, detailed surface preparations (grinding, material removal, and macro-etching) are used along with detailed application work processes and the specific work processes are discussed in more detail in Annex D.	Radiation energy is used to create an image on film or an electronic detector. Radiography is commonly used for weld quality evaluation and wall thickness measurement.	Internal VT of pressure vessels for surface blistering. White light applied parallel to the internal surface can aid in revealing blisters protruding beyond the surface plane.	Low-frequency sound waves are generated either when crack-like flaws propagate (microscopically), or during crack-tip blunting. AET for HTHA is usually executed during monitoring of thermal gradients associated with temperatures of interest so actual process-induced stresses are used. Detects and locates sound wave origins.
Detection Capability	Can detect HTHA only after cracks have formed. Cannot detect fissures or voids.	Capable of detecting randomly oriented incipient, early-stage, and late-stage HTHA damage at the inspection surface.	Can detect late-stage HTHA damage in the form of cracks. Cannot detect early-stage HTHA damage.	Surface blisters are readily apparent. HTHA damage has been detected below blistered or damaged cladding.	Capable of detecting discontinuities with high-stress concentration factors and has a higher probability of detection for late-stage HTHA damage. [6,11]
Damage Sizing	Provides high confidence in indication length dimensions along with location and orientation. Cannot nondestructively determine depth.	Provides high confidence in indication width and length dimensions along with location and orientation. Cannot nondestructively determine depth.	Provides indication width and length dimensions along with location and orientation. Cannot size depth.	Can only size the perimeter of the deformed blister immediately adjacent to the surface.	AET cannot size the detected indications.
Advantages	Crack indications can be seen visually, and little interpretation is required. Large surface areas and complex geometries (including nozzles) can be inspected.	Can detect HTHA early-stage at the prepared surface. Large surface areas and complex geometries (including nozzles) can be inspected.	RT provides a visual image and can be used as a permanent record.	No special inspection tools are needed. Blister interpretation is clear.	AET is capable of inspecting several vessels and piping sections simultaneously. No practical limitation on material temperature. Often used prior to T/A to guide shutdown inspection efforts.
Limitations	Cannot detect HTHA fissures or voids. Detects only the advanced stages after surface cracks have formed. Cannot determine the depth of HTHA damage.	Only detects surface-breaking HTHA damage. Requires highly skilled technician and significant interpretation. Cannot determine the depth of HTHA damage. Only effective on the prepared surfaces.	May miss cracks, depending upon the orientation of the crack plane. RT of equipment with external coverings will reduce inspection detection sensitivity.	HTHA frequently occurs without the formation of surface blisters. Blisters, when present, are likely to be an indication of advanced HTHA. Cracking is not always visible.	Needs adequate applied stresses to create release of sound waves from the stress risers, e.g., HTHA cracks, being sought. Consequently, it is imperative that all stresses are well understood, especially during the monitoring of thermal changes, such as a planned cooldown, in order to generate a valid AET inspection.
Recommendations	Recommended for internal inspection of pressure vessels to detect surface-breaking cracks.	Recommended for internal inspection of pressure vessels to detect surface-breaking cracks and randomly oriented incipient, early-stage HTHA damage.	Not recommended as a primary HTHA inspection method.	Not recommended for general HTHA detection but may detected base metal or cladding blisters.	Recommended as a layer of protection for high risk equipment or as a global screening method. In both cases, additional more focused follow-up inspections using alternative methods are recommended.

[a] The effectiveness of all these inspection methods are dependent on highly skilled and trained NDT personnel.

Table 3—Example for FMC/PAUT/TOFD Reporting Table

EXAMPLE: FMC or PAUT or TOFD HTHA Data Reporting Table for Hotspot # or Plate Area # or T-Junction # or Weld # of Vessel # or Piping Circuit #

L_{msd} (X/Y) = ...in./mm (X or Y coordinate spacing of the reference point to the nearest major structural discontinuity

L_W (X/Y) = ... in./mm (X or Y coordinate spacing of the reference point to the Nearest Weld Joint)

Scan/ File	t_{rd} in./mm (Wall Thickness reading)	Indication #	Isolated SIngle (Is)/ Group (G) Indication	Indication Character-ization	X-position to Reference Point (in./mm)		Y-position to Reference Point (in./mm)		Δ X, in./mm (s/longitudinal or c/circumferential extend)	Δ Y, in./mm (s/longitudinal or c/circumferential extend)	t_{mm-ID} in./mm (Minimum measured undamaged wall thickness at ID)	t_{mm-OD} in./mm (Minimum measured undamaged wall thickness at OD)	W_{HTHA} in./mm (Wall thickness with HTHA damage/ a-Depth per FFS which is equal to UT vertial height reading)	Comments
					From	To	From	To						

NOTE 1 Fitness For Service (FFS) nomenclature used in API 579-1, draft section on assessment of HTHA damage, is expanded for the proposed UT reporting table.

NOTE 2 No FFS Interaction rules are currently available.

L_{msd} X or Y coordinate spacing to the nearest major structural discontinuity, example nozzle.

L_W X or Y coordinate spacing to the nearest weld joint.

t_{rd} Thickness reading at the time of the FFS assessment (wall thickness).

s Longitudinal extent of HTHA volumetric or other damage in a cylinder or pipe, meridional and circumferential extent of HTHA damage in a sphere (can be Δ X and Δ Y).

c Circumferential extent of HTHA volumetric or other damage, as applicable (can be Δ X and Δ Y).

$t_{mm-ID/OD}$ Minimum measured undamaged wall thickness at ID/OD.

W_{HTHA} Wall thickness with HTHA damage.

a Depth of the crack-like flaw per FFS assessment which is equal to the vertical measured by UT.

6 General Inspection Plan

The following are considerations when planning an HTHA inspection:

- Operational-based screening of equipment to estimate damage state, extent, and location with owner's-operator's mechanical integrity and operation personnel. Finite element modeling, infrared surveys (for hot spots), and review of repair/inspection history (including PWHT history) may assist in identifying most susceptible locations. Operational history should also be reviewed, especially with regarding services with different degradation mechanisms. Fitness For Service (FFS) analysis can be performed to support inspection planning and evaluation of NDE results.

- Examples of locations where HTHA has been identified (also see general considerations at the first paragraph of Section 5) include, but limited to:
  - See Chemical Safety Board report [12] on failure of heat exchanger equipment (zoned metallurgy)
  - Dissimilar metal welds
  - Thick section components (e.g., heavy wall nozzles)
  - Non PWHT'ed piping welds and vessels
  - See API RP 941 list for cross check list
  - Prior weld repair locations
  - Internal attachment welds (and damage extending into pressure containing boundary)
  - Pipe-to-fitting welds

- PMI: Consider PMI (and alloy composition analysis) of weld filler metal on all welds and base metal to confirm uniform HTHA susceptibility.

- UT techniques should be applied from outside to the maximum extent possible. If performed from internal surface, NDE sensitivity will be reduced for near ID surface damage.

- Surface preparation is a critical parameter influencing effectiveness of all ultrasonic techniques, especially for frequencies above 5 MHz.

  - In some situations, there is incentive for the removal of weld reinforcement (cap) to enable specialized UT techniques across the weld cap.

- The most recent HTHA inspection approach is a combination of time of flight diffraction (TOFD), phased array UT (PAUT), and/or full matrix capture/total focusing method (FMC/TFM). The new combined approach is considered to be more effective than the previous approach (i.e. advanced ultrasonic backscatter technique [AUBT] contained in the prior edition of API RP 941). AUBT has limited data recording capability.

- If the inspection screening is based on TOFD (to extent possible due to productivity and tolerance of flaw tilt), consider complimentary FMC or/and PAUT techniques to confirm.

- If the inspection is based on FMC or/and PAUT techniques, consider complementary TOFD (to extent possible) to confirm and assist with interpretation of indications.

- Consider inspection based on simultaneous TOFD, FMC, PAUT data collection and recording the un-rectified waveforms (A-scans) for more reliable data analysis of complimentary images including backscattering.

- The detection capability for early stages of HTHA will diminish with increasing thickness (and grain size) due to ultrasonic attenuation. Due to the attenuation, lower frequencies are generally required for thicker materials, and this results in the reduced sensitivity/resolution, and characterization. For example, PAUT focusing is limited to the near field and may not be readily achievable for thick materials or working on second leg for nozzle weld inspection. Similarly, TOFD will require multiple set-ups to assure adequate coverage.

- UT Limitations: The use of highly sensitive UT techniques (e.g., high-frequency TOFD, PAUT, FMC and backscatter) are susceptible to false positive calls and challenging signal interpretation depending on circumstances. Some factors that led to these challenges include:

- dirty steels with significant inclusions;
- poor surface condition (scanning or non-scanning sides);
- welds with significant fabrication flaws, and weld repair with associated changes in grain structure (e.g., SMAW repair of SAW)
- single-sided weld access (e.g., nozzles);
- internal cladding (e.g., weld overlay) will compromise UT performance (when beam is reflected off base metal/overlay interface)
- NDE analysis by examiners with limited HTHA experience;
- temperature will influence performance and degrade sensitivity as temperature increases (e.g., above 140°F, 60°C)

- Data encoding is recommended to the extent possible since it assures full coverage, enables secondary data review and correlation among multiple techniques).
- Manual scanning techniques (without data recording) should only be considered as a supplement for HTHA detection when encoded data recording is not possible.
- Single element UT transducer may be useful for limited access locations when current techniques (e.g., TOFD/ PAUT/FMC are not possible).
- Of all the inspection methods for base metal examination, UT techniques and HSWFMT are the most sensitive techniques and have the best chance of detecting HTHA damage
- When the internal surface is accessible, HS WFMT can be used to detect subsurface damage while still in the fissuring stage, prior to the onset of significant cracking. HS WFMT has significant surface preparation requirements that are reviewed in Annex D of this RP.
- When the internal surface is accessible, WFMT can detect small surface-breaking cracks.
- When the internal surface is accessible, close visual inspection can detect small, coin-sized surface blisters, which can be an indication of the presence of internal HTHA. Visual inspection for HTHA damage requires a very close examination using light sources capable of being directed at oblique angles on to the surface being examined, permitting observation of shadows created by blistering. The absence of surface blisters does not provide assurance that internal HTHA is not occurring, since HTHA frequently occurs without the formation of surface blisters.
- Due to limitations of individual inspection technique, higher effectiveness is achieved using combinations of nonintrusive and intrusive technologies. Nonintrusive examples are TOFD, PAUT, and FMC. Intrusive technology examples are internal visual, HS WFMT, and metal extraction using scoop or boat sampling. The aforementioned NDT techniques are used to identify location(s) for metal extraction. Metal samples are then analyzed using metallurgical techniques for final verification.

- Recommend consulting NDE subject matter expert (SME) for review and approval for all proposed HTHA inspection plans, techniques procedures and reports.

— Operator Qualification and Training: All HTHA NDE techniques are highly dependent upon technician training and usage of the proper procedure. HTHA NDT examiner should have damage mechanism-specific training using a broad spectrum of samples (damage extent and type), and sample geometries (e.g., girth welds and nozzle welds). Recommend that HTHA-specific UT method training should be a minimum of 40 hours for currently qualified and certified UT examiners. HS WFMT examiners should have similar training requirements and a minimum of 24 hours of HTHA specific training.

7 Cladding/WOL and Bimetallic Welds

The following are considerations for inspection of clad or weld overlaid equipment subject to HTHA:

— Integrity and inspection of cladding/WOL should be considered to determine HTHA susceptibly due to cladding damage.

— Cracks in cladding/WOL will decrease its effectiveness as a hydrogen barrier. A method to determine the effective hydrogen partial pressure in clad or overlaid steel is discussed in RP 941, Annex D.

— Inspection of cladding/WOL itself should also be considered typically using VT, PT, and UT for cladding/WOL interface integrity.

— Consider inspection of bimetallic butt welds from the ferritic side when using UT techniques to reduce the influence of the austenitic coarse-grain weld structure on the reliability. The presence of any buttering between the ferritic parent and the weld could present both difficulties for penetration through the weld and problems for interpretation of the signals.

8 Intrusive Inspection-narrative on When/How to Use Complementary Tools

The following are considerations when planning an intrusive inspection to look for HTHA damage:

— Planning: Review the history of the equipment item to be inspected. Search for history of indications noted, removed, repaired etc. Also, modifications made such as nozzle installation or removal, corrosion repair, crack repairs etc. Include all such items on the list for visual, PMI, and HSWFMT.

— Visual Inspection:

 — It is recommended to abrasive-blast the inside surface of the equipment being inspected.

 — White light positioned oblique to the inside surface is needed to search for blisters.

— HS WFMT may be applied to locations such as:

 — representative sample of circumferential, axial, nozzle, and attachment welds;

 — weld repaired areas;

 — those with complex geometry;

 — in areas of incorrect materials of construction;

 — high-stress areas; and

- poor workmanship areas that indicate locations of high stress common to weld repairs and modifications.

- Metal Extraction: Prioritization of areas selected for metal extraction should include the following:
  - locations where UT examinations revealed indications;
  - where HWFMTs revealed indications;
  - where visual inspection detected blistering; and
  - where PMI detected incorrect materials of construction.
- Metal extraction locations should not be selected at random. Locations should be selected and prioritized based on evidence of anomalies.
- Localized thin area (LTA) calculations should be conducted prior to the start of an internal inspection. Hemispherical scoop-type extractions are most favorable. Hemispherical-shaped material removal does not require weld repair if diameter and depth do not exceed LTA calculations per ASME FFS-1/API 579-1.
- Boat samples are most common for metal extractions. Weld repair is needed in most cases. Weld repair on material with HTHA damage can be difficult. Boat sample extraction configuration can be changed to hemispherical shape by grinding techniques.

9 Use of FMR, Metallography and SEM for Metallurgical Validation of HTHA

Field metallography and replication (FMR), also called in-situ metallography, can be effective in detecting the early stages of HTHA (decarburization and fissuring) at the surface of the steel as well as differentiating between HTHA and other forms of cracking and naturally occurring inclusions in the steel. Skill and experience are required for the surface polishing, etching, replication, and microstructural interpretation. A triple etch/polish procedure is recommended (similar to creep evaluations) to reveal the fine details of HTHA damage so that accurate identification of HTHA can be made. After the final polish step, the surface should be lightly etched so that individual fissures and voids are not obscured by the grain boundaries. Because in situ metallography only examines one surface at a time, in order to evaluate a cross section of damage, either multiple replicas need to be taken at different depths of grinding or the depth can be varied by tapering the grinding so that the replica can extend from shallow to deeper locations of the prepared location. Metallurgical sampling (e.g., “scoop” or “boat” sampling) has the advantage of capturing a cross section and some length of material that can be examined in a metallurgical lab. Metallographic examination should be used to better interpret NDE results and damage classification. One note of caution is that HTHA may be subsurface, so using a surface inspection technique, such as replication or WFMT, may not detect damage. Since HTHA fissuring begins subsurface, it is recommended to remove 0.020 in. to 0.120 in. (0.5 mm to 3 mm) of material during the preparation for FMR examination. If desired, more material can be removed to reveal damage further subsurface or to confirm the depth of damage that was indicated by NDE techniques.

In some cases, even when using advanced inspection techniques, it may not be possible to interpret the results without additional metallographic examination. The use of a scanning electron microscope (SEM) at magnifications greater than 1000x is recommended for the metallurgical validation process. HTHA damage (fine methane bubbles or tight cracks) near or below optical light microscopy (OLM) resolution limits has been documented in ex-service components and laboratory generated samples [13–14]. The resolution limit of OLM makes distinguishing critical differences between voids versus polishing and etching pits challenging. Both appear as dots at 1000x with OLM or very tight fissures versus heavily etched grain boundaries (both appear as dark grain boundaries at 1000x with OLM). As the NDT technologies continue to advance, it has become apparent that even early-stage HTHA damage may be detected. Use of SEM allows for more clear and definitive analysis that will help prevent false positive and false negative metallurgical validations. Metallurgical validation methods for HTHA are provided in Table 4.

API 941 TR-A provides several examples of non-PWHT’d carbon steel equipment items in which crack-like HTHA damage has been metallurgically validated without observable decarburization [14]. Additionally, there are calculations to support this finding, which indicate the required amount of decarburization associated with crack-like HTHA formation that may be below the resolution capabilities of OLM. Thus, HTHA cracks viewed by OLM may look similar to cracks resulting from other damage mechanisms: e.g., reheat cracking, weld metal cracking, hydrogen-induced cracking , stress corrosion cracking, and creep cracking. Guidance on HTHA manifestation and appearance is also provided in Section 5 of this RP as well as the API 941 TR-A. Careful examination of the equipment operating conditions and use of SEM is critical for proper diagnosis.

Table 4—Metallurgical Validation Methods for HTHA

	Field Metallography and Replication (FMR)	Scoop Sampling and Metallurgical Examination	Boat Sampling and Metallurgical Examination	Full Thickness Sample Removal and Metallurgical Examination
Description	Field metallography uses a microscope to directly observe the prepared surface's microstructure, and replication produces a negative film of the surface that is examined in a laboratory. In both cases, three rounds of polishing and etching are recommended for detection of HTHA damage.	Removal of metal using a spherical-shaped cutter to produce a lens of metal. Metallurgical specimens are then extracted and examined in a laboratory setting using optical microscopy, scanning electron microscopy (SEM), and limited mechanical testing.	Requires a common angle grinder. Recommend using thin wafer cut off blades to remove samples. Metallurgical specimens are then extracted and examined in a laboratory setting using OLM, SEM, and limited mechanical testing.	Hot or cold cutting of a geometric shape and remove the full wall thickness of material. Metallurgical specimens are then extracted and examined in a laboratory setting using optical microscopy, SEM, and mechanical testing.
Detection Capability	On the prepared surface, it can detect cracks, fissures, changes in microstructure, i.e., decarburization, and possibly voids. FMR is the most limited of the validation methods.	High magnification optical or electron microscopy can be used for confirmation of early-stage damage.	High magnification optical or electron microscopy can be used for confirmation of early-stage damage.	Specimens extracted from the removed material can be evaluated using high magnification optical microscopy or electron microscopy to confirm early-stage HTHA damage.
Damage Sizing	Very accurate width and length. Depth may be determined through controlled grinding and follow-up FMR. The typical area of inspection is small (less than 1 $in.^2$), so it is commonly used for surface area damage sizing.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.
Advantages	Can be carried out at weld metal, heat affected zone, and base metal. May confirm damage mechanism and may validate indications detected by inspection methods, e.g., UT or AET. FMR is a nondestructive method and a negative result enables the section tested to remain in service. Its biggest advantage is that results can often be found quickly while on-site.	In addition to the FMR advantages: laboratory examination results in higher sensitivity. Repair may not be necessary per results of API 579-1 FFS (Part 5) assessment.	In addition to the FMR advantages: laboratory examination results in higher sensitivity. If the boat sample divot is blend ground, repair may not be necessary per results of an API 579-1 FFS (Part 5) assessment.	Provides the most material for metallurgical examination and testing.
Limitations	Cladding must be removed. Best if 0.02 in. to 0.125 in. (0.5 mm to 3 mm) of base material is removed to reveal subsurface damage. Only surface-breaking damage on the prepared surface is detectable.	Access space is required for equipment. Specialized equipment and training is required and can be arranged to be on-site proactively or contracted once the need is identified.	Access space is required for equipment but may be less than what is required for scoop cutting equipment. Location may require repair. Welding on HTHA damage material can be challenging. Skilled technicians are required to avoid unnecessary damage to equipment.	Location must be repaired. Welding on HTHA damage material can be challenging. Consider using a nozzle or pipe cap welded so that weld metal contacts the external surface where there is rarely any HTHA damage. Typically takes the most time to analyze the metallurgical samples.
Additional Considerations	Recommended as an informative inspection only and will be supported by the other validation methods listed in this table. May be used to trigger additional inspections.	Recommended as a high confidence follow-up inspection to the limited inspection area.	Recommended as a high confidence follow-up inspection due to limited inspection area.	Recommended as a high confidence follow-up inspection due to limited inspection area.

NOTE 1 Evidence of decarburization at the ID surface may or may not be associated with HTHA damage and should not be used as a primary detection approach for HTHA. Surface decarburization can be associated with the manufacturing process and may be present on both inner and outer surfaces.

NOTE 2 Regardless of metallurgical validation technique, three rounds of light etching followed by polishing are recommended to remove plastic deformation that may obscure voids and fissures.

NOTE 3 If cleaning between polishing steps is needed, cotton balls, or lint free wipes are recommended.

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Annex A (informative)

Ultrasonic Array Techniques

A.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of Ultrasonic array techniques (PAUT and FMC/TFM) for HTHA inspection.

A.2 Basics

Figure A1 is showing the principles of PAUT beamforming (BF) and FMC/TFM non-beamforming techniques, Sectorial (S) scan and a scanning plan with typical C-, B-, D- views. Both PAUT and FMC/TFM use an array transducer with multiple piezo-composite elements in a common housing. The aperture is chosen such that the inspection volume is placed in the near field of the sound beam.

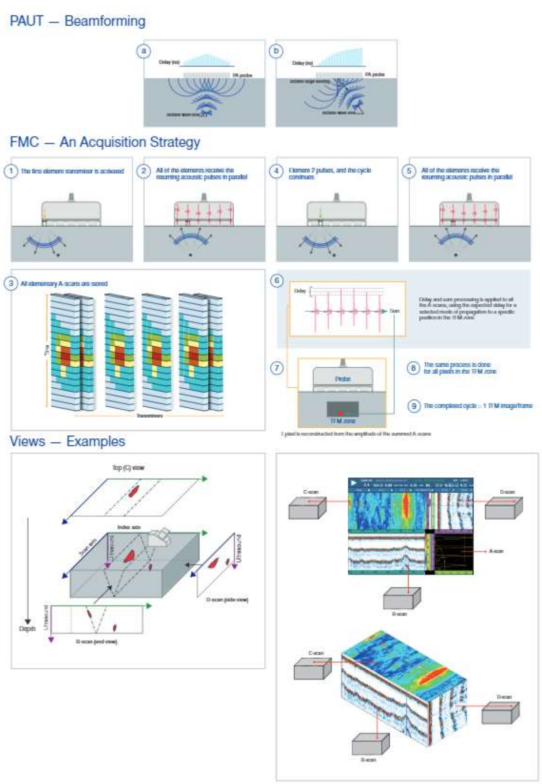


Figure A1. PAUT and FMC/TFM principals and views. Reprinted with permission from Olympus.

A.3 Equipment and Setups

32-128 channel, ultrasonic instruments with parallel architecture and PAUT/FMC/TFM/ATFM software capabilities can be used. The instrument can be integrated with fully and semi-automated scanners and array probe(s) attached to solid wedges (Rexolite and Thermoplastic) and/or conformable (flexible) elastomer wedges filled with water. Normal beam L-wave array probes can be used for inspection and damage verification on base material with solid wedges, and on welds without removing the reinforcement (crown) with flexible wedges. Angle beam shear wave (SW) array probes can be used for weld inspection and base material damage verification. The distance calibration, sensitivity, and amplitude fidelity check with and without Time-Corrected Gain (TCG) can be completed on standard PAUT blocks, and SDHs fabricated in the test components. Amplitude fidelity check should demonstrate a prevention of signal loss due to incorrect FMC/TFM properties, specifically grid density setting. Integrated tools in the software can be used for the amplitude fidelity check.

A.4 Array Probes Selection

The key parameters for selection candidates array probes for HTHA inspection are the frequency, aperture, pitch and elevation. These parameters are selected to have specific near field position (a.k.a. focalization range) and focal spot size. The information in array probes specifications should be reviewed and can assist operators to select the right probe for performing HTHA inspection in the near field and to improve detection, characterization and sizing capabilities using probes with the highest practical frequency and the smallest beam spot.

Examples for the central frequency, aperture, and near field for a set of linear and matrix probes that can be used for optimized HTHA inspections are shown in Table A1. The near field represents the maximum thickness for PAUT and FMC/TFM inspections in carbon and low alloyed steels. For example, the near field of the 10MHz -64 elements linear probe in Table A1 with thin thermoplastic wedge is 198mm (8") for L-wave, and 109mm (4") for 55° S-wave. The achievable sensitivity at certain depth needs verified with a calibration block per ASME Section V, Article 4 requirements.

Table 1. Example specifications for linear array probes: central frequency, aperture and near field. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Probe central frequency (MHz)	Aperture (mm^2)		Normal beam L-wave, no wedge/ thermoplastic 1 mm wedge (near field, mm)		Normal beam L-wave, 23/20 mm height Rexolite wedge (near field, mm)		Normal beam L-wave, 23/20 mm height water wedge (near field, mm)		Angle beam S/T-wave, SW55° 45/29/14 mm height Rexolite wedge (near field/ depth, mm)		Angle beam S/T-wave, SW55° 45/29/14 mm height water wedge (near field/ depth, mm)	
	Linear (1 × 64 elements)	Matrix (4 × 16 elements)	Linear (1 × 64 elements)	Matrix (4 × 16 elements)	Linear (1 × 64 elements)	Matrix (4 × 16 elements)	Linear (1 × 64 elements)	Matrix (4 × 16 elements)	Linear (1 × 64 elements)	Matrix (4 × 16 elements)	Linear (1 × 64 elements)	Matrix (4 × 16 elements)
5	320	160	298	96	287	89	290	90	277/162	89/53	206/119	70/41
7.5	250	130	311	132	297	120	307	122	285/167	119/70	211/122	91/53
10	150	60	198	65	190	62	194	62	186/109	60/36	145/83	50/29

Dual Linear Array (DLA) or Dual Matrix Array (DMA) transducers are also often used for HTHA inspection. These probes use Longitudinal Waves (LW) that are designed to replicate the detection capability of TOFD method. The wedge design associated with the DLA and DMA probes includes a roof angle (and sometimes a squint angle) creating a mechanical beam focus that maximize the focusing ability at a selected position. When using angle beam DLA and DMA probes, the wedge isolates the transmitter from the receiver, eliminating the need for a tall wedge design and dampening material. DLA/DMA probe can often allow to have the probe sitting closer to the weld. The smaller wedges also permits for less energy to be lost in the wedge material allowing for more sound to penetrate the part to be inspected and also permitting a deeper near field. When compared to Shear Wave (SW), LW allows for greater angular range while keeping good sensitivity and resolution. This becomes especially useful in hard-to-reach area or when only one side of the weld is accessible.

A.5 Sensitivity and Resolution

PAUT sensitivity and resolution to detect and separate HTHA damage is limited to half wavelength (for Carbon Steel, 10 MHz SW: 0.16mm/160µm) and the focal spot size. Classical TFM sensitivity and resolution is limited to one-tenth of the wavelength and Region of Interest (RoI) grid's density (for Carbon Steel, 10 MHz SW, 497x497 grid points in 25x25mm RoI: 0.016mm/16µm). A wizard integrated in the software can be used for calculation the right RoI.

A.6 Inspection and Analysis

A surface preparation, typical for advanced UT inspections, is required (see B6). Line and/or raster scanning for data collection and typical C- (Top View), B- (T- or End View), D- (Side or Front View) scans can be used for localization and sizing of HTHA damage. In addition, PAUT S- scan (view) and single plane TFM view can be used for sizing verification. Data collection scans can be performed at multiple frequencies and 12dB above the reference gain. The time domain signals (Un-rectified waveforms or A-scans) can be collected for more detail post processing analysis to assist HTHA damage characterization periodic inspections. The analysis can be performed at the reference gain or with reduced 3-6dB gain.

Typically, HTHA micro damage is detectable only in the higher end of the practical 5-15 MHz frequency range. The same HTHA indications can be missing at the lower frequency range. For example, large macro HTHA damage may be detected and visualized using 5MHz techniques, but the number of indications will be limited. When a mix of metallurgical imperfections and micro/macro HTHA damage is present multiple UT techniques, 3D visualization and segmentation can be used to improve the characterization process and differentiate HTHA damage from metallurgical imperfections. The second step of the analysis can be sizing. Tip diffraction technique can be used for damage height sizing when the tip is detected and imaged. 6dB or 3dB drop techniques can be used for damage height sizing when the tip was not detected. The same techniques can be used for length sizing.

The best results of HTHA ultrasonic array inspection can be accomplished following these rules:

— Use the highest practical frequency for a specific base material, wall thickness and weld
— Work in the near field (aperture and frequency dependent)
— Use the smallest beam spot for PAUT (aperture and frequency dependent)
— Use the highest density grid in RoI for FMC/TFM/ATFM (RoI size and number of pixels dependent).

Reliable detection, characterization and sizing of in-service induced, localized and complex HTHA damage can be achieved when multiple, high frequency, FMC/TFM/ATFM LL and TT paths and PAUT sectorial scan techniques are utilized.

— Better than 0.2mm (200µm/0.008”) detection sensitivity can be reached for HTHA clustered volumetric damage, single blister and crack-like indications and/or a combination of all of them.
— Improved characterization as a result of enhanced spatial resolution e.g. ability to resolve two or several closely spaced indications can be accomplished. When spaced apart larger than the grid ROI resolution, HTHA damage will be imaged better (without large arcs) and can be resolved.
— Enhanced sizing resolution and more accurate sizing of HTHA clustered volumetric, blister and crack-like indications can be completed because all points or pixels defined by high resolution grid within the ROI can be focused during the imaging process using TFM/ATFM.

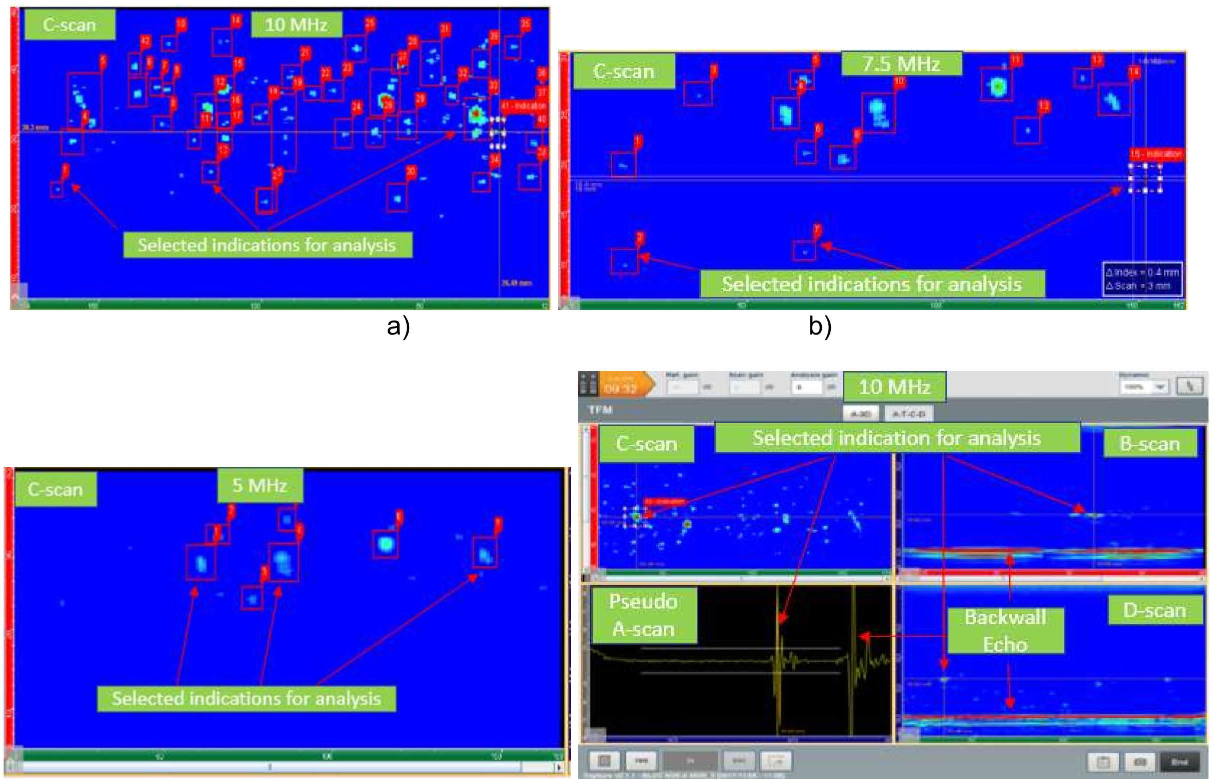
A7. Examples for Ultrasonics Array Techniques Capabilities

Example A1 - Samples with Synthetic HTHA Damage.

— Plates, pipes, and small vessels with synthetic (accelerated) HTHA damage can be used for training, procedure validation and examiner performance (practical) qualification.
— The inspection frequency is one of the most critical inspection parameters. Earlier stage damage can be potentially missed if probe frequency is too low, or over call if probe frequency is too high.
— This example demonstrates that 10 MHz FMC/TFM, LL path technique can detect and size better synthetic HTHA damage oriented parallel to ID comparing with lower frequency LL techniques and TT path technique.
— Figure A2a shows more than 100 micro and macro indications identified (boxed) in the projected C-scan of a block (plate) that contains synthetic HTHA damage. 10MHz linear and matrix probes and FMC/TFM technique in LL path/mode were used. Only 30% of the indications were observed

on projected C-scan created by using a lower frequency 7.5 MHz linear array probe (Figure A2c) and only 10% of the indications were detected when using 5 MHz linear array probe (Figure A2d).

— One relatively large micro indication of HTHA micro damage was selected for analysis and boxed in the projected top view image (C-scan) shown in the top-left corner of Figure A2d.
— The red color of the image indication is a sign of strong reflected and diffracted signals from the damage and was confirmed by pseudo A-scan (Figure A2d bottom-left).
— The same indication is marked with a crossing of x/y measuring cursors in the single plane B-scan- (Figure A2d top-right) and D-scan (Figure A2d bottom-right).
— The estimated length of the micro indication in TFM front view was ~0.7mm (~700µm). Multiple small indications of HTHA volumetric damage were observed in both B-and D-scans and are represented by light blue dots.

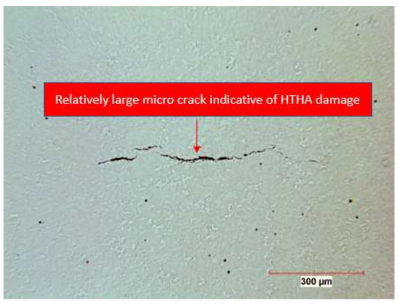


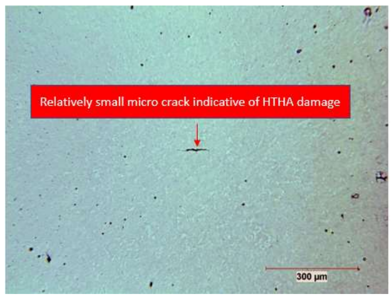
c) d)

Figure A2. FMC/TFM LL imaging: (a) 10MHz projected C-scan of damage block; (b) 7.5MHz projected C-scan of damage block; (c) (5MHz projected C-scan of damage block; d) 10MHz split screen imaging of selected indication: projected C-scan (left top), single plane B-scan (top right), single plane D-scan (bottom right), pseudo A-scan (bottom left). From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

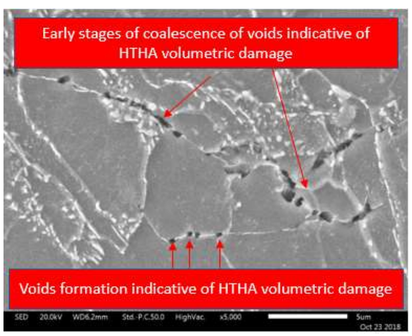
— The presence and the length of ~0.7mm (~700µm) micro indication analyzed in Figure A2d was validated at low magnification using optical microscopy – Figure A3a. Optical microscopy at lower magnification in Figure A3b displayed a smaller ~0.1mm (~100 µm) fissure forming isolated microcrack below to the larger microcrack. The separation between these microcrack is larger than the pixel size and allows to be visualized as isolated indications.
— SEM at higher magnification revealed damage features ~0.010mm (~10µm) showing grain boundary void formation and some early stages of coalescence of voids in the periphery of the main feature- Figure A3c.

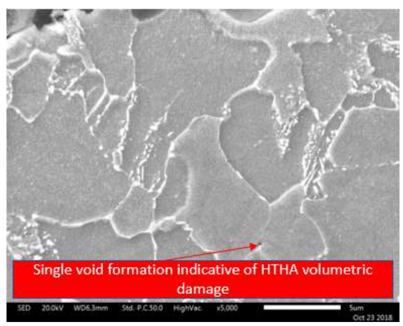
- — No evidence was obtained to verify that any of the array techniques is capable to detect linking voids at one grain boundary or clustered linking voids in a small volume. If limited fissures start forming small micro crack in the clustered linking voids along 5-10 damaged grain boundaries the detectability probably is enhanced. This type of early stages volumetric damage is possibly visualized as a blue haze and cloudy area around internal large microcracks and macrocracks or adjacent to the bar surface exposed to the hydrogen (Figure A2d right). This surface of the bar is acting as a backwall for ultrasound and is represented by the solid red line in the front and side view images.
- — A damage feature showing severe dissolution of grain boundaries and some early stage of single sub-micron void formation are presented in Figure A3d. Sub-micron void formations are not detectable by any of the current field applicable PAUT and FMC/TFM/Adaptive TFM (ATFM) techniques.





a) b)





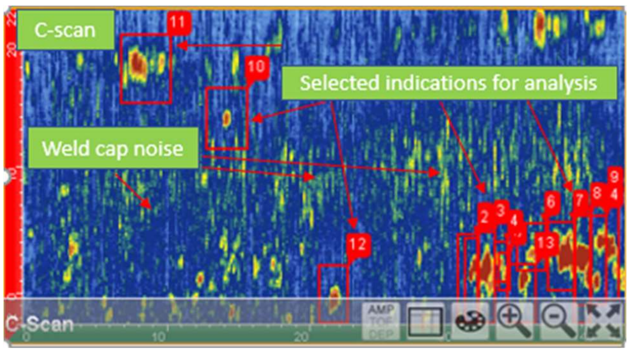
c) d)

Figure A3. Optical microscopy and SEM imaging of accelerated HTHA damage: (a) ~100X; as-polished; fissures forming relatively large micro crack; (b) ~100X; as-polished; fissures forming small micro crack; (c) ~5000X; Nital Etchant; SEM photograph of damage feature showing grain boundary void formation and some early stages of coalescence of voids in the periphery of the main feature; (d) ~5000X; Nital Etchant; SEM photograph of damage feature showing severe dissolution of grain boundaries and some early stage of single void formation. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Example A2 - Channel welds (Reboiler, C - 0.5 Mo material, 14mm wall thickness, 53 years in service).

- — Indications for potential HTHA blistering, micro and macro cracking were detected in the channel shell to head circumferential weld and HAZ using 10 MHz linear probe, FMC/TFM TT technique.
- — RoI width was extended to cover the HAZ of the weld at the head side. Similar micro and macro indications were observed on the head side, but the severity was lower compared to the shell side.
- — The largest indications selected on the C-scan for a detailed analysis are shown in Figure A4a. Boxed indications 1-9, 12 are on the shell side and indications 10-11 are on the head side.

- The analysis results for indication #2 (boxed in the right bottom corner of Figure A4a) are shown in the split screen views of Figure A4b. B-scan image (Figure A4b top-left) analysis displays a root crack with 5mm height representing 34% wall thickness (WT) damage. The intersections of the vertical and horizontal cursors on C-scan (Figure A4b bottom-left), D- cumulative scan (Figure A4b bottom-right) and D- scan single plane (Figure A4b top-right) are showing the location of the same crack-like indication. The elongated red areas on the right side of C-scan and D-scans represent potentially breaking macro cracking at the root.
- The clusters of blue dots in the single plane D-scan represents an early stage of HTHA damage.
- Indications of potential facets of HTHA damage was detected at skew -10° in the breaking areas using 10 MHz 4x16 elements matrix probe and S-scan - Figure A4c. The results in the second focalization plane indicate that the root crack is potentially continuous.



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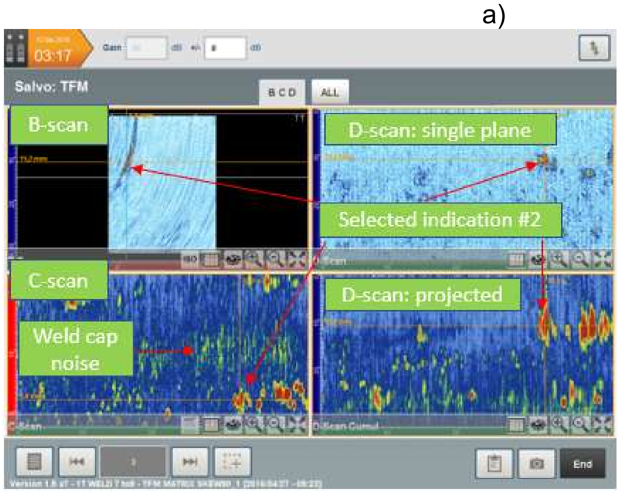

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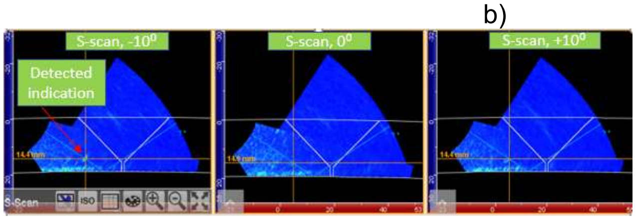

c)

Figure A4. 10 MHz TT FMC/TFM and PAUT techniques imaging of HTHA weld damage: (a) linear probe C-scan and identification of the indications; (b) linear probe split screen views of root crack-like indication #2; (c) indication of potential HTHA damage detected in the breaking areas using matrix probe and S-scan at skew -10°. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

— The metallographic investigation verified the presence of root cracking, step-wise cracking and blistering with cracking edges.
— A cross section image of the root crack is shown in Figure A5a. Optical metallography confirmed matrix probe findings that the crack in HAZ is a continuous macrocrack along the weld starting from indication #2 and finishing at the end of the scan.
— Macro stepwise cracking was observed in the base material adjacent to the root crack - Figure A5b. Microscopic and macro blistering with cracking edges was documented near to ID - Figure A5c.
— Voids and linked voids as an indication of volumetric HTHA damage were observed at the tips of the cracks and blisters at higher magnification - Figure A5d. Single sub-micron voids and sub-micron linking voids were not detected with any array techniques.
— Stress related micro cracks were observed at the same magnification (Figure A5e), but it was not possible to distinguish HTHA crack-like damage from stress related micro cracking with array ultrasonic techniques. The same limitation is valid for any ultrasonic techniques.

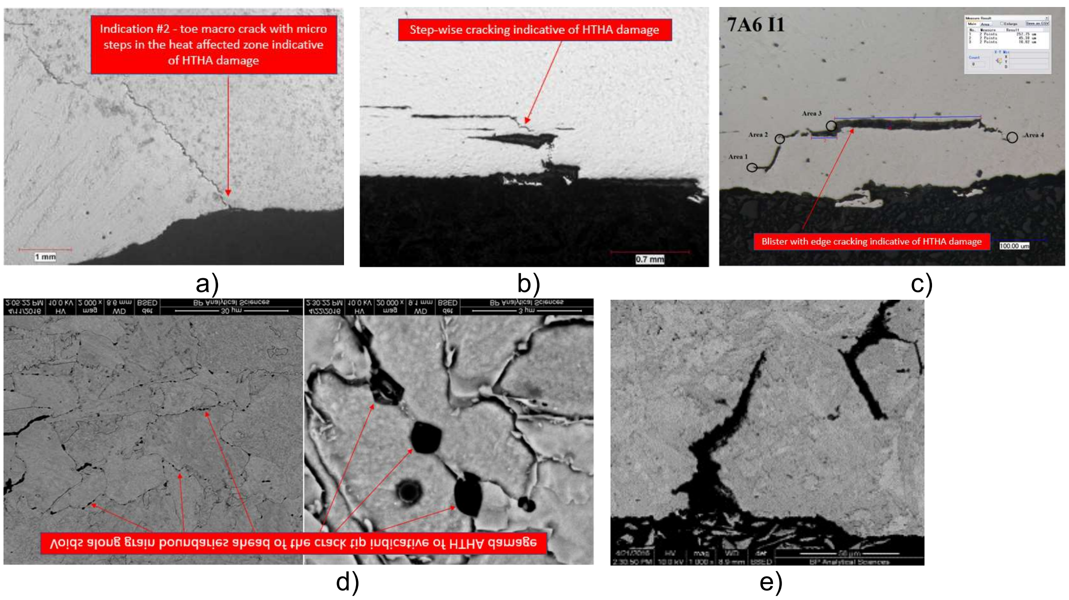

Figure A5. Weld damage validation using optical metallography and SEM: (a) root cracking (~20X, Nital etched); (b) stepwise macro cracking (~40X, Nital etched); (c) blisters (~40X, Nital etched); (d) voids along grain boundaries (~2,000X, Nital etched-left; ~20,000X, Nital etched-right); (e) stress-related micro cracking (~1,000X, Nital etched. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Example A3 - Channel base material (Reboiler, C - 0.5 Mo material, 14mm wall thickness, 53 years in service).

— Figure A6a is an illustration of identification (boxing) of a potential base material HTHA damage in C-scan projected views using PAUT 5-7.5-10 MHz straight beam techniques.
— Very small number of indications for a potential damage were identified on 5 MHz C-scan comparing to relatively higher number of indications on 7.5 and 10 MHz C-scans.
— Indications#10.1a.1 and 10.1a.2 were selected for detailed analysis and comparison using projected or single plain B-Scans.
— Figure A6b illustrates the comparison of single plane B-Scans. Top row consists of PAUT (called also Beam Forming -BF) B-scan, middle raw FMC/TFM and bottom row FMC/ATFM imaging; left column consists of 5MHz, middle column 7.5MHz and right column 10MHz techniques imaging.
— The best detection and image resolution for indications 10.1a.1 and 10.1a.2 was achieved using 10 MHz FMC/ATFM LL technique – see bottom/right image of Figure A6b. A cluster of smaller and weaker indications were detected above both indications using the same technique.
— 10 MHz PAUT SW, 7.5 MHz and 10 MHz FMC/TFM TT techniques confirmed the presence of

both indications. PAUT S-scan images using two focal laws (groups) are shown in the top of Figure A6c. The first group was focused on the mid wall (top-left) and the second group was focused on the bottom (top-right). The bottom raw of Figure A6c represents TFM TT technique images for both 7.5 MHz and 10 MHz transducers.

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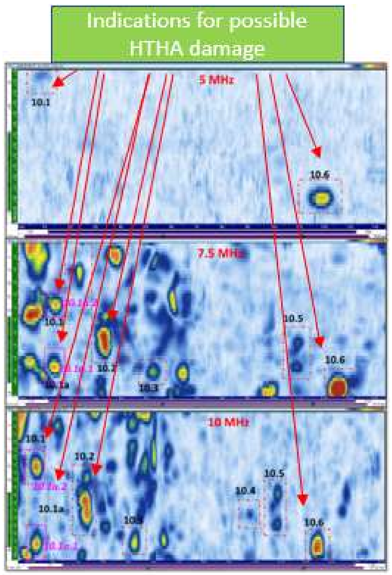
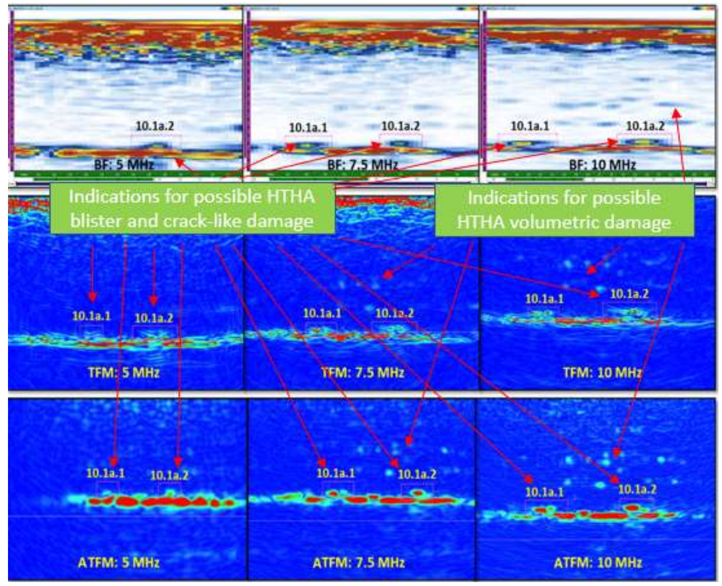


a)



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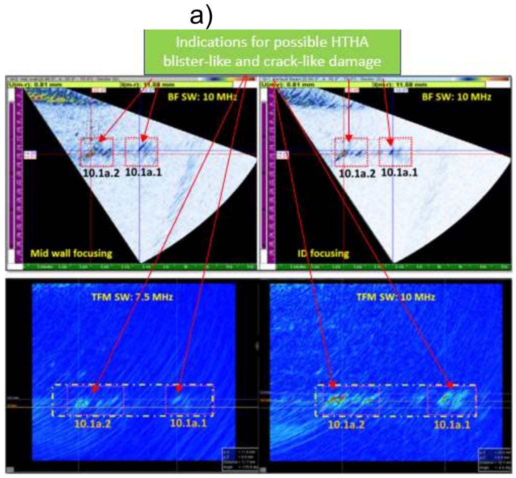
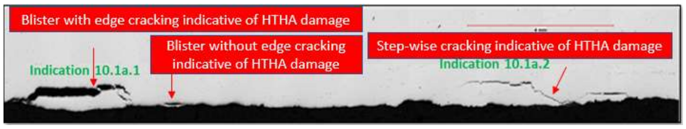


c)

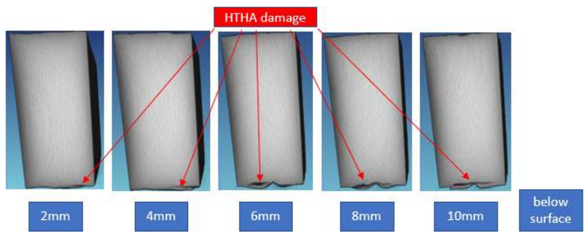
Figure A6. Imaging of Indication #10.1a.1 and #10.1a.2: (a) projected PAUT straight beam C-Scans comparison; (b) PAUT straight beam and FMC/TFM/ATFM LL B-Scans comparison; (c) comparison of PAUT S-Scans and FMC/TFM TT B-scans using shear wave techniques. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

— Enhanced detection and visualization capabilities of FMC/TFM and ATFM techniques at higher frequency were validated metallographically using progressive grinding.
— The metallographic images for both indications are shown in Figure A7a-c. Indications#10.1a.1 was classified as two micro blisters and 10.1a.2 as a stepwise micro crack.
— The complexity of the blistering morphology in the mount remnants was validated using Computed Tomography (CT). CT images of indication 10.1a.2 from 2 to 10mm below the front polished surface of the mount are shown in Figure A7b.
— The height and the width of the indications were measured from the metallographic images. A good agreement was achieved in the comparison of PAUT techniques results (longitudinal

straight beam and angle shear wave beam) with FMC/TFM LL, FMC/TFM TT, FMC/ATFM LL and metallographic measurements for Indication#10.1a.1. Better sizing results were demonstrated using high frequency FMC/TFM and FMC/ATFM techniques both complemented by post processing tool called segmentation.



a)



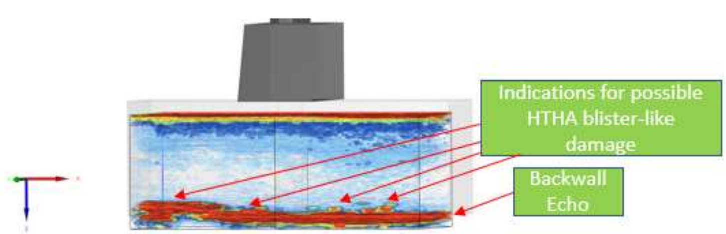
b)

Figure A7. Metallographic and CT Images for Indications 10.1a.1 and 10.1a.2: (a) x10, Indications 10.1a.1 and 10.1a.2; (b) CT images of Indication 10.1a.2 from 2 to 10mm below the polished surface of the mount. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Example A4 - Drum welds and base material (Zinc oxide drum, C - 0.5 Mo material, 34mm wall thickness, 45 years in service).

— No signs of HTHA damage in the drum was reported using AUBT and TOFD during the first inspection of selected areas at risk.
— An area of scattered blistering, approximately 0.5x0.5 m (20x20”), was detected visually during the following internal inspections – Figure A8a.
— 10 MHz, FMC/TFM LL and TT techniques were used during the second inspection of selected areas at risk.
— 3D TFM LL path visualization of the detected blister-like damage is shown in Figure A8d.
— C-scan data analysis revealed widely spread multiple indications of potential HTHA damage in the base material and HAZ on both side of the welds. The localized nature of HTHA damage in one area and through wall distribution is shown in Figure A8b.
— Through wall thickness (WT) imaging analysis determined that predominantly HTHA damage in plate S2 is clustered in less than 10% WT.
— Optical metallographic verification of micro and macro blistering is shown in Figure A8d.
— Figure A8e is showing SEM image of voids formation and coalescence at an early stage in the front of the blister tip.

a)



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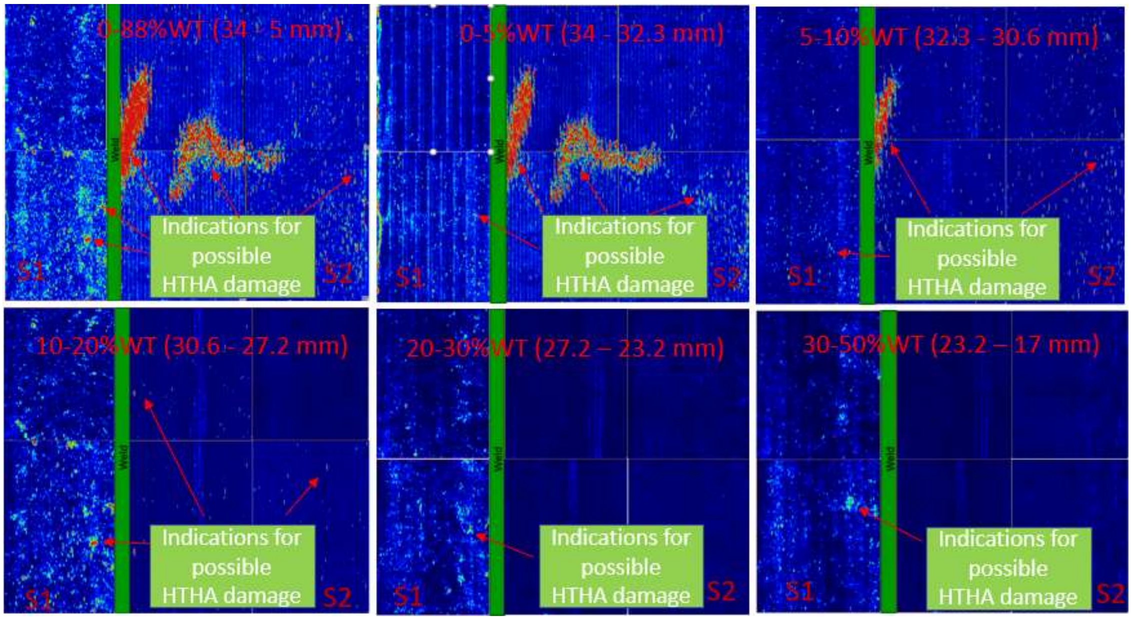

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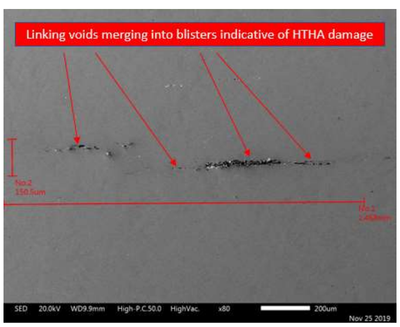

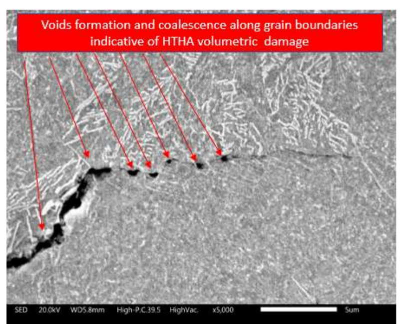

d) e)

Figure A8. Drum south section FMC/TFM imaging and HTHA validation: (a) visual validation of typical blister bulging; (b) 3D imaging of blister-like damage; (c) localized and through wall distribution; (d) optical metallography of linking voids merging into blisters, ~80X; As-Polished; (e) SEM validation of early stage HTHA volumetric damage, ~5,000X; Nital etched. From Materials Evaluation, Vol. 78, No.11. Copyright © 2020 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Annex B (informative)

TOFD Technique

B.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of TOFD technique for HTHA inspection.

B.2 Basics

Figure B1 shows TOFD principle and data presented in the form of grey scale images in either B or D scan views.

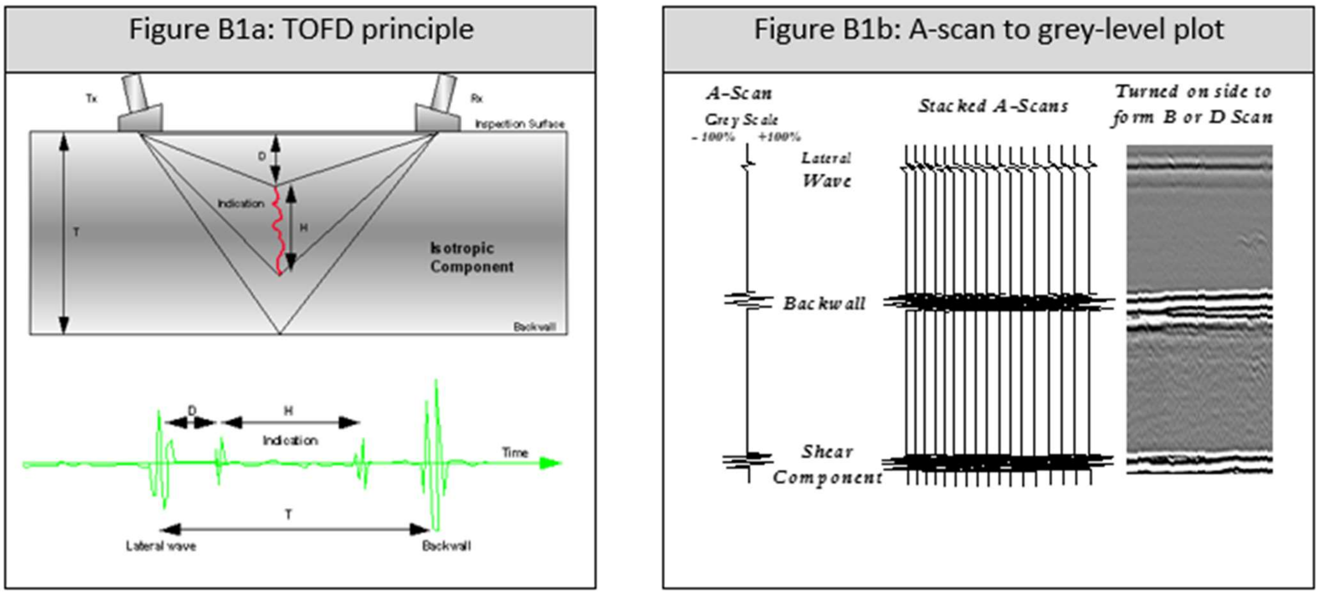

Figure B1. TOFD Principle and Presentation of Results. Reprinted with permission from Sonomatic.

B.3 Interaction of TOFD with HTHA

Damage levels are as described in Section 5 of API 541 and Section 5 of this RP, in accordance with API 579-1.

Stage 1 Volumetric (V) damage consisting of decarburization and methane bubble formation is below the threshold of detection for NDE methods.

Stage 2 Volumetric (V) and Blistering (B) micro-damage is not detectable at the individual flaw level, but where the size and concentration of micro-feature are of sufficient magnitude, effects can be observed in the received TOFD waveform. Experience has shown that flaws of a few microns and above can create increased levels of scatter providing the quantity and density of damage is sufficient to disrupt propagation of the ultrasonic beam. Clearly, higher ultrasonic frequencies are more likely to be affected than lower frequencies for a given level of damage.

The material itself will act as a natural filter for higher frequencies. As the objective of the inspection is to capture responses from Stage 2 (V) & (B) damage, and/or to detect coalesced micro-fissuring (C), which may be expected to occur within volumes of material affected by Stage 2 damage, it is therefore recommended to perform TOFD using the highest frequency the material will support. Background electrical noise, reverberations and standing signals should not interfere with interpretation.

Prior to inspection, the material should be scanned using broadband amplifier settings, analyze the frequency spectrum, and select probe frequency and amplifier settings that home in on the higher end of the received frequency spectrum. If frequency analysis is not available, the test item itself should be scanned using a range of amplifier filter settings until the desired sensitivity level has been achieved.

Damage in the size range of interest for Stage 2 damage may be one of two types:

1. **Micro-fissuring (V).** Individual fissures tend to be in the order of the grain size, and as the damage progresses, these link up in a three-dimensional matrix to form coalesced fissures that have a tendency for alignment with material stresses. When these coalesced fissures reach several millimeters in size, they become detectable as Stage 3 (C) damage and can be characterized using the pulse-echo ultrasonic techniques described in this recommended practice.
2. **Micro-blisters (B).** Microscopic non-metallic inclusions have been observed to be initiation sites for micro-fissuring through accumulation of hydrogen and/or methane. This increased internal pressure has a tendency to separate the material in the plane of the inclusions, which follow the grain flow of the material. As the damage progresses over time, individual micro-blisters may link up in the direction of the grain flow to form Stage 3 (C) macro-blisters in the order of several millimeters in size.

Stage 3 Crack (C) damage has been observed to be very difficult to detect using all available ultrasonic techniques, including TOFD. The tips of coalesced fissuring can be extremely tight. The gape of such individual fissures is small compared to the grain size, so the energy diffracted at the crack tips can be expected to be very low in amplitude. Furthermore, Stage 3 (C) coalesced cracks can be expected to be accompanied by adjacent Stage 2 (V) & (B) damage that increases attenuation and superimposes a level of scatter onto the diffracted energy from crack tips. The combined effects of energy loss through scattering from Stage 2 (V) & (B) damage and coalesced, or even macro-cracking within the same volume of material insonified by the probes can lead to complete obscuration, or loss of the reflected or through transmitted energy.

Identification of coalesced Stage 3 (C) damage using TOFD is enhanced through careful use of advanced contrast tools. Pattern recognition is important, as a linear response can potentially be identified by its shape amongst random scatter patterns, even when the amplitudes of responses are similar. For this reason the signal-to-noise ratio is a key factor for the TOFD technique.

Stage 3 (C) damage can give rise to post-back wall responses caused by energy from the crack tip being delayed after being redirected towards the back wall, possibly undergoing mode conversion for part of the path before arriving at the receiver. Stage 3 (C) cracks with distinct material separation (i.e. macro-cracks) may be filled with contaminants such as oxides that lead to increased transparency.

B.4 Reporting levels

The reporting level is dependent on the objectives of the inspection, and the demonstrated capabilities of the inspection vendor. Two levels of reporting are:

1. **Stage 2 (V) & (B): Acoustic scatter patterns caused by grain structure and/or micro-damage.** As stage 1 (V) micro-damage is not detectable using NDE methods, the precise stage it which it has an influence on the ultrasonic beam cannot be reliably defined. Equally, higher alloyed steels and prolonged exposure to heat causes the steel to exhibit higher levels of

scatter, together with concentrations of flaws of manufacturing origin and metallurgical variances. A finely-tuned TOFD technique can be used to capture the material ‘signature’, or fingerprint. This can be used to form the basis of comparison with future data collected from the same location using identical equipment and techniques. Stage 2 (V) & (B) micro-damage has the following effect on the TOFD beam:

   a. Diffraction: Vertically-oriented fissures will generate diffracted responses from upper and lower extremities that may find its way to the receiver probe,
   b. Reflection: Horizontally oriented discontinuities may cause energy to be forward-scattered through reflection that may also be detected.

2. **Stage 3: Macro-damage (C).** This is defined as a continuous flaw, or a collection of lesser flaws of sufficient concentration to be considered to be a continuous flaw. Stage 3 damage would normally be expected to exhibit at least two of the following responses:
   a. TOFD:
      i. Delay and/or obscuration of TOFD responses.
      ii. Linear responses that may potentially be very weak.
      iii. Post-back wall responses indicative of planar flaws.
      iv. Dense clusters of indications.
   b. PAUT & TFM:
      i. Continuous indications of flaws with horizontal extent exceeding five millimeters individually, or through-wall extent exceeding two millimeters in height for blisters and vertically aligned planar flaws respectively.
      ii. Dense concentrations of indications that are localized, and of sufficient concentration to be considered to be a continuous flaw.

As it is generally considered to be not possible to reliably discriminate between grain structure, Stage 2 (V) & (B) damage, metallurgical anomalies and discontinuities of manufacturing origin, HTHA inspections may be carried out with the objective of ignoring Stage 2 (B) damage, quantifying the level of damage through metallography, and/or of capturing it as a fingerprint for comparison against future inspections. This process has been used to provide confirmation that HTHA has not been active in the intervening period between inspections.

B.5 TOFD Set-ups

TOFD probe frequencies for HTHA are recommended to be between 5 MHz and 15 MHz. Pulse Duration (ringing) should be less than two times the wavelength at 10% (-20dB) below peak amplitude. Actual probe sizes and frequencies should be selected according to material type and thickness and should be demonstrated to be optimum for the application in conjunction with the instrumentation to be used. Recommended encoder A-scan collection intervals are 0.5 mm for materials equal to or less than 15 mm in thickness, otherwise 1 mm.

It is recommended that calibrations are performed at the start and end of each day/task and at 4 hourly intervals. Recalibration should be performed where any items of equipment are replaced and any variables other than PRF or gain for surface adjustment are made. The system should be recalibrated if the operator considers any parameter might have changed. A thickness verification scan of at least twenty A-scans shall be stored for all pre, post and intermediate calibrations. Once set up and calibrated, a centreline validation plus 1 off offset scan should be performed showing the detection of all representative flaws in the zone of interest. Failure to detect any of the flaws since a previous calibration would require the defective equipment or setting to be replaced or rectified, and all scans since the previous calibration are to be repeated.

The selection of scan variables should be in accordance with the referenced code or standard but should also take into consideration the inherent acoustic properties and noise levels of the material under examination. Selection of scan variables should be verified on the test item and accordingly adjusted.

Adjustment of pulse widths, digitizing and filtering is recommended to obtain the optimal signal to noise ratio in the area of interest.

B.6 Sensitivity levels

The amplitude of the lateral wave signal from the weld shall be adjusted to be between 30% and 40% of full screen height (FSH)plus 6 to 12dB. If use of the lateral wave is not appropriate, then the amplitude of the backwall signal shall be 24 dB – 30 dB above FSH. If neither the lateral wave nor backwall signals are appropriate, the material grain noise should be around 5 % FSH.

- Signal averaging is recommended in cases where random noise interferes with interpretation.
- All sources of electronic noise and interference should be minimized, as this background 'clutter' is superimposed over the scatter patterns caused by HTHA damage, and forms a veil, or fog that obscures the responses of interest.
- A good indicator of electronic noise is the A-scan trace prior to the arrival of the lateral wave. This should ideally be a perfectly flat line (maximum noise level ahead of the lateral should be 50% of that after the lateral).
- Standing signals and reverberations in the area of interest are to be avoided as these will interfere with interpretation of weak responses from HTHA damage.
- Regardless the method for setting Sensitivity, the acoustic grain scatter amplitude should be visible at 3% to 5% FSH throughout the area of interest.
- The use of reference blocks as comparators is recommended. The signal-to-noise ratio for a given set-up is to be documented to enable the inspection to be faithfully replicated at a future date, and to observe changes in acoustic scatter levels.

B.7 Surface preparation

As TOFD inspections for HTHA require the highest frequencies the material will support, the actual frequency range of interest tends to be higher than for conventional inspections. The shorter wavelengths used have a tendency to be scattered by rough surfaces. Surface preparation is therefore very important. Pressure equipment that has operated in HTHA service for prolonged periods will sometimes have a hard scale baked onto the surface that is difficult to remove. This may be further exacerbated by pitting and/or general corrosion taking place under insulation. The surfaces of some inspection items may also have been previously affected by heavy-handed grinding. The extent and choice of surface preparation is based on the presented condition of the inspection surfaces once the thermal insulation has been removed as well as the ultrasonic frequencies being deployed.

For reasons of expediency, grit blasting and grinding tend to be the first choices. Grinding however, leaves behind surfaces that are not conducive to effective HTHA inspections that are dependent on higher ultrasonic frequencies, and are to be avoided if possible.

Figure B2. Surface before grinding (left) and after grinding before grit finish (right).

Grit blasting leaves a coarse texture to the surface and grinding tends to leave ‘flats’ that are traps to couplant beneath the probe wedge causing ‘ringing’ effects as the ultrasound reverberates within these small spaces.

— The preferred method for pre-cleaning is using a sand-blast finish.
— Surface preparation by grinding should be used as a last resort. If surfaces are pre-cleaned by grinding, care must be taken to retain a smooth and even surface.
— Surfaces to be inspected with 5MHz probe frequencies may be finished to a wire brush or sandblast finish.
— Surfaces to be inspected with 10MHz probe frequencies require finishing to an 80-grit finish.
— Surfaces to be inspected with 15MHz probe frequencies require finishing to a 120 grit finish.

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Figure B3. Grit finishes can be achieved using flapper disc or wheel.

B.8 Data collection temperature

Inspections may be possible at elevated temperatures. Techniques used at scan surface temperatures exceeding 150˚F (65˚C) should be validated using representative samples as sensitivity can be expected to decrease with increasing temperature above this level.

B.9 Analysis

The following functions are recommended to aid in the analysis:

— Scan axis and depth cursors
— Contrast adjustment with sufficient adjustment of palette depth to aid in imaging of coalesced damage which may be “buried” in general acoustic noise levels.
— Soft Gain (or multi- channel capability)
— Frequency measurement

Analysis of HTHA data should be conducted by personnel with demonstrated training and experience. It is recommended that all data is evaluated by at least two suitably qualified personnel.

The following responses have been shown to be potentially indicative of HTHA and should therefore be investigated together with any other suspect areas:

— Any areas where potential cracking is noted.
— Any areas where disruption of lateral and / or backwall signals is noted, regardless of whether there are associated responses from potential HTHA damage.
— Any areas where there is a noticeable damping/ reduction of the inherent levels of acoustic noise
— Any areas where weak linear responses are evident along a weld axis or parallel to a stress-riser, such as an internal geometry change.
— Any areas there is a noticeable difference in the acoustic grain noise patterns.

It must be noted that responses from HTHA damage can and will can differ from one extreme to the other, ranging from “obvious” responses to subtle losses or reduction in returning energy levels.

B.10 Clad material

Vessels with internal cladding are often used in HTHA service. It should be noted that for weld clad materials, a meaningful evaluation of the clad material is unlikely, however any HTHA damage is more likely to be present within the base material.

The approach to examine clad materials using TOFD should be similar to those of the carbon steel or low alloy materials, however the focal area should be 5mm above the cladding interface. Care should be taken when evaluating data in identifying disturbances of acoustic noise levels and/or patterns emerging out of, or in close proximity to the interface.

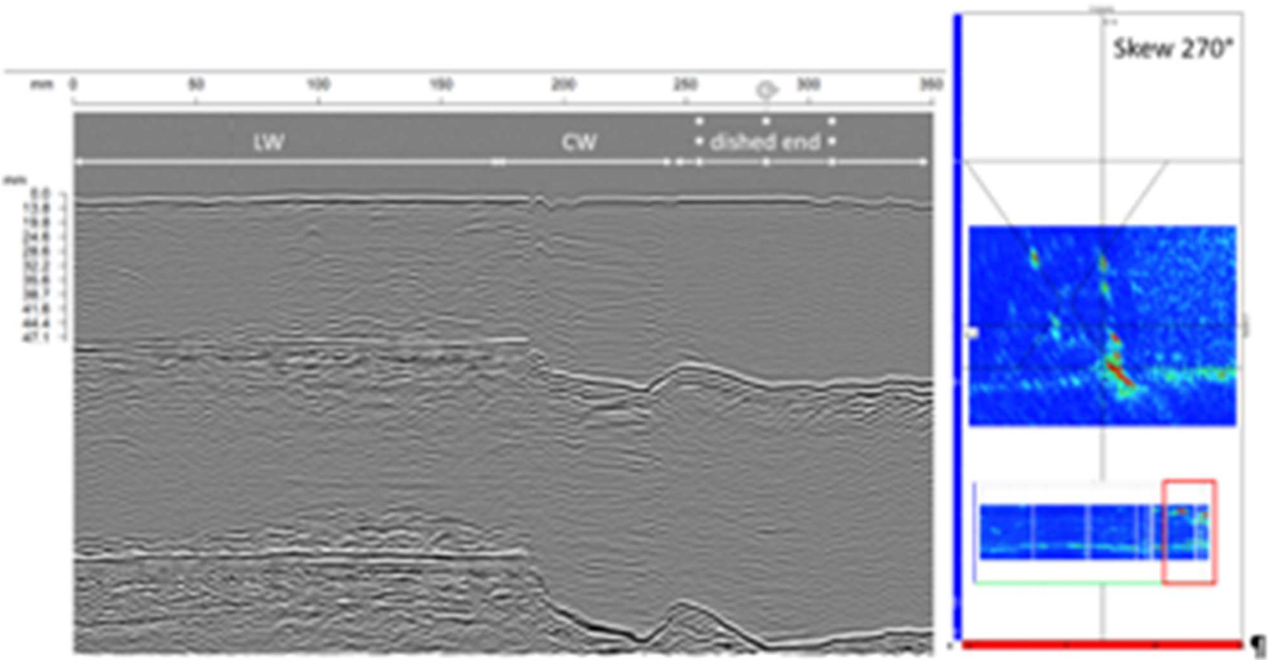
An awareness of fabrication practices is advised as cladding thicknesses can vary, especially at weld locations.

B.11 Weld repairs

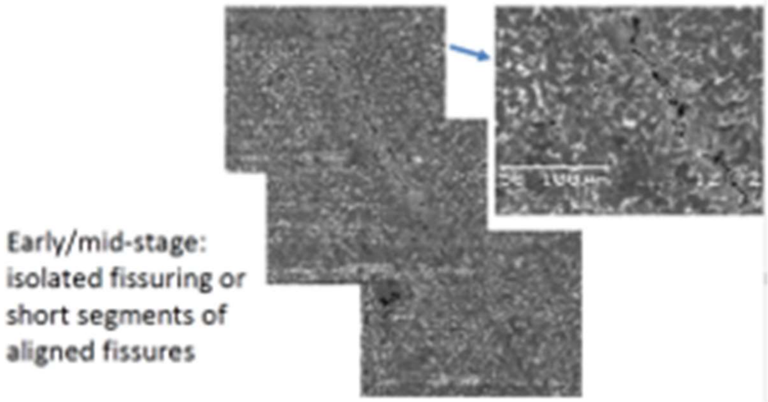
TOFD data can/ will often image the natural grain boundary incurred where a weld is reheated during manufacturing or in-service rework or repair. During evaluation of HTHA data, any such variation in acoustic patterns can be misinterpreted as potential HTHA damage. It is therefore recommended for the analyst to have an awareness of repair locations.

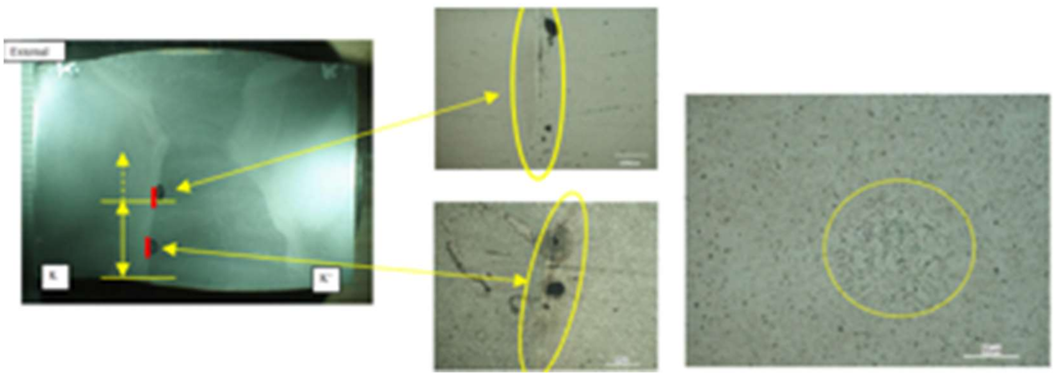
B.11 Examples of HTHA Damage Images

Example B1 - Suspect Area at Junction of Circumferential and Longitudinal Welds.



a)





b)

Figure B4. HTHA Imaging using: (a)TOFD - left and FMC/TFM - right; (b) optical metallography. Reprinted with permission from Sonomatic.

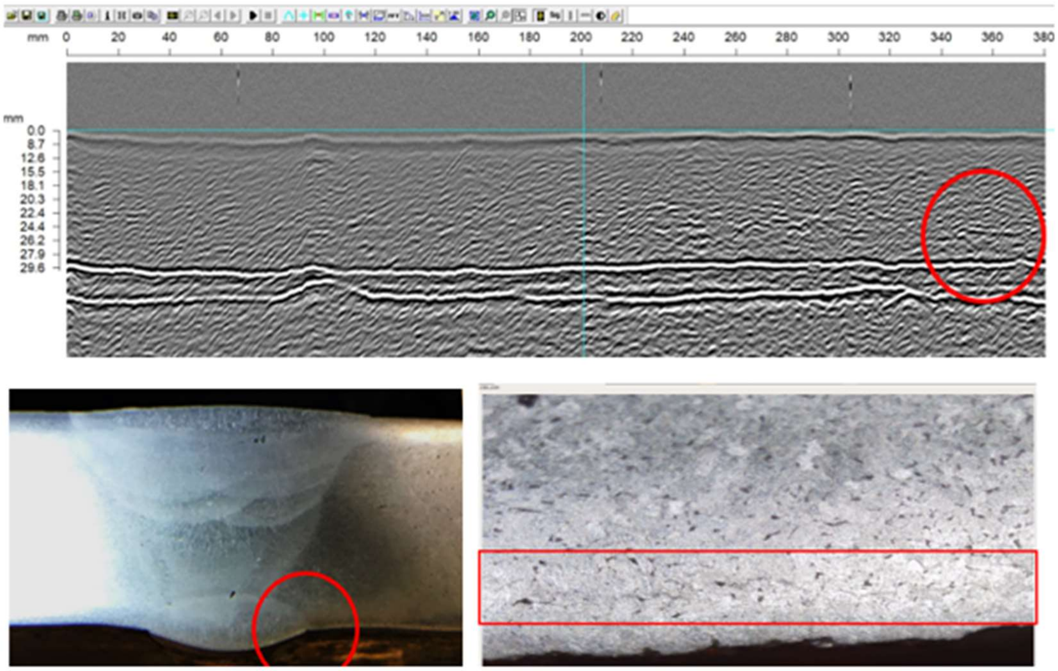
Example B2 - Through Wall HTHA damage on ½” thick piping weld.

…….. **Pending approval**

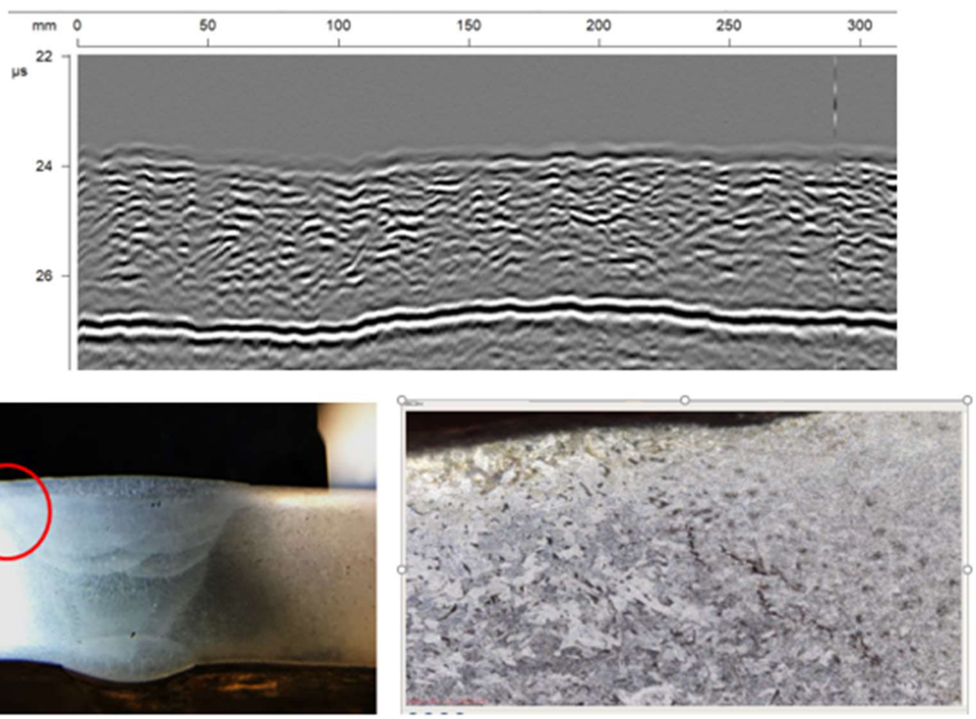
a) b)

Figure B5. HTHA Imaging using: (a) TOFD - top and FMC/TFM - bottom); (b) optical metallography. Reprinted with permission from Sonomatic.

Example B3 - 28mm thick reactor.



a)



b)

Figure B6. Confirmed Decarburization and Fissuring: (a) at ID; (b) at OD (TOFD - top and optical metallography - bottom). Reprinted with permission from Sonomatic.

Example B4 - Synthetic created material damage.

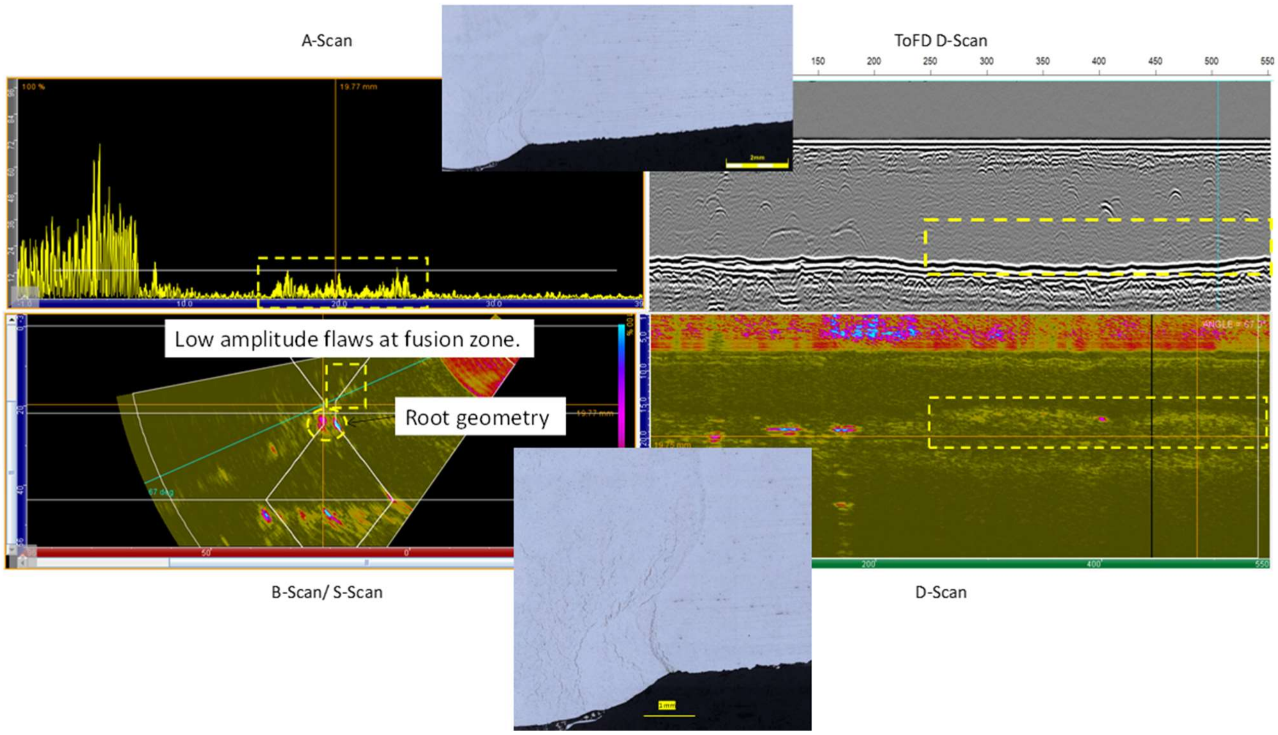


Figure B7. Microstructure cracking in material synthetically exposed to simulate extended HTHA operating conditions. Reprinted with permission from Sonomatic.

Annex C (informative)

Acoustic Emission Testing

C.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of AE techniques for HTHA inspection.

C.2 Application Examples

The application of Acoustic Emission Testing (AET) to identify active damage from HTHA has been documented in several applications. The technique was widely applied in the period of the 1990’s into the early 2000’s but has declined in application lately due to a lack of activity and reduction in the application skills across the industry. These are now starting to return and are critical as the technique requires a key understanding of the right test conditions to apply the technique.

As with most applications of AET the damage mechanism must be creating some form of activity during monitoring that drives the elastic wave from the damage source as an acoustic signal that can be recorded. Typical methods to stimulate potential damage include pressure cycling of the component or monitoring during heat up or more usually cooldown where differential thermal stress can lead to flaw excitation. In one well documented test referenced in the bibliography activity was most readily detected during transition in the ranges 400^0F (204^0 C) and 600^0F (315^0 C). These ranges have also been quoted in other test regimes. The use of AET in this manner has been verified with the application of ultrasonic techniques discussed elsewhere in this document and subsequently by metallographic examination of damaged components removed from service.

It is critical that the stage of damage created by HTHA is understood and at what point in the damage cycle flaws or degradation states may occur that result in flaws that will produce an acoustic response. Early-stage decarburization is unlikely to produce an effect. As damage progresses acoustic signals may become more prominent. AET is not definitive for damage discrimination but indicative of activity and in located areas if you have significant amount of sensors to identify where to look with complimentary NDT techniques.

The application of AET online or through cooldown monitoring requires the installation of waveguides to protect sensors on hot surfaces and careful monitoring of extraneous emission sources These are key areas where expertise and experience are critical in the design and execution of AET tests for this application. The ability to manage these items has been the main source of ‘false positive’ results that may lead to reduced confidence in the technique.

Annex D (informative)

HS WFMT

D.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of HS WFMT techniques for HTHA inspection.

D.2 Surface Preparation and Application

The following is a description of the work process associated with HS WFMT. The following steps are recommended to provide and enhance the inspection sensitivity, which have been developed and optimized for HTHA damage detection, especially of non-PWHT carbon steels where cracking is most likely related to welds.

— Surface Preparation:

  — Abrasive blasting (gar net is the preferred media) followed by smooth blending of weld cap, heat affected zone, and base material.

  — Metal removal performed using fiber discs with a final grind of 80 to 100 grit. Surface roughness should not impair particle mobility.

  — Remove 0.030 in to 0.090 in. of the wall thickness within the area to be inspected. Be mindful of the corrosion allowance.

  — Macro-etch the ground surface to be inspected. Success has been reported using three rounds of 5 % Nital in 3 minute intervals. The advantage of etching is to remove smeared metal from grinding that bridges grain boundaries. Care should be taken to avoid overetching as this may result in false positive indications.

— Application

  — Use multiple directions for both magnetic flux lines and HSWFMT solution flow. Primary direction is with the yoke positioned across the weld with the arms spaced close to concentrate magnetic flux to only 4 to 6 in. of weld length.

  — Apply magnetic fluxes using an AC yoke and HSWFMT solution for extended durations (at least 15 seconds per orientation and location) in areas to be inspected.

  — Use nonaerosol-based deployments of HSWFMT solution to allow for better particle flow control. Aerosol deployments can have similar performance, but experience has shown that indications take longer to appear.

  — Follow ASTM guidelines for fluorescent particle-to-carrier solution ratio.

  — Assure ultraviolet (UV) light source intensity and wavelength is correct.

— Check AC yoke magnetic field strength frequently. Long durations of use can cause overheating and lack of magnetic flux line strength. Having two yokes will allow one to cool down while the other is in use and will ensure magnetic field strength.

— Background light limits should be checked and managed in area of inspection.

— Acute vision is essential for this inspection.