e-Journal of Nondestructive Testing - ISSN 1435-4934 - www.ndt.net

JOURNEES COFREND 2023 – Marseille du 6 au 8 juin / June 6th to 8th

# Evaluation and Simulation of HTHA Damaged Specimen using UT Advanced Techniques

**Bastien CLAUSSE [1*], Nicolas NOURRIT [2], Serge DEMONTE [2], Mark LOZEV [3], Hugo CENCE [4], and Patrice HOULLE [5]**

[1] EXTENDE, France

[2] Institut de Soudure Industrie, France
[3] BECHT, United States of America
[4] EKOSCAN, France
[5] Materials Technology Institute
*Corresponding author, E-mail: bastien.clausse@extende.com



## Abstract

High Temperature Hydrogen Attack (HTHA) is a well-known phenomenon that impacts the design, operation, and maintenance for syngas production facilities (e.g., hydrogen and carbon monoxide plants). Recommendations regarding material selection and inspection are given by API 941 and API RP 586 [1], that is currently under revision after Tesoro accident. The new rules have highlighted the need to adapt inspection with more advanced NDT methodology, improving the detection of early stage HTHA damage, then supporting a Fitness for Service approach. This paper makes an overview of various projects funded by Materials Technology Institute (MTI) regarding the assessment and improvement of the performance of such UT advanced NDT for HTHA detection, by means of CIVA UT simulations after a detailed metallographic review and statistical modeling of material inclusions and HTHA damage distributions of field samples. HTHA damage inputs and comparisons between experimental and simulated UT images are consistent for different damaged samples (different levels and types of damage, especially for welded samples), different UT acquisition settings and different inspection frequencies. The unprecedented use of HTHA damage distribution laws and NDT simulations of nonmetallic defects and HTHA damage are promising tools which may then used to assess the limits of existing NDT and to define optimized probes and procedures relying on advanced ultrasonic examinations.

## 1 Introduction

High Temperature Hydrogen Attack (HTHA) is a well-known phenomenon that impacts the design, operation, and maintenance for syngas production facilities (e.g., hydrogen and carbon monoxide plants). The potential for HTHA attack on carbon steel and its alloys has been studied for some time. API has provided guidance on HTHA damage inspection [1], but several serious safety events have recently occurred bringing into question the validity of the "Nelson" curves. API is in the process of revising guidance on HTHA. MTI members in the US and Europe have continuing concerns about HTHA service operations and decided to create MTI projects to provide guidance to its members on fitness for service, damage detection and methodologies to predict remaining service life. HTHA programs require the availability of samples with actual HTHA damage, they are highly dependent on the technique used to detect it (which NDT and configuration, setup, probes…) and on the skill of the NDT operator (experience / know-how). Such programs may cover the following fields: training, qualification, R&D, improvement, expertise and investigation. Reducing or overcoming this dependence will contribute to decrease the cost of these programs, to widen the scope of investigation, to improve the reproducibility of program results and, hence, to make them easier to implement on field.

Simulation brings leverage to reduce this dependence as it will compensate for low availability of samples. Through modelling, one may simulate a wide range of damage distributions and component geometries. In addition, simulation may provide extensive results, enabling to observe phenomena within the inspected material such as the interaction between ultrasounds and HTHA damage. Advanced Ultrasonic Testing (UT) parameters can be optimized to perform the examination, bringing forth time savings and an increase of number of NDT test cases. It will, to a certain extent, allow to test NDT configurations with new probes before manufacturing them, proving modelling to be a useful tool for prototyping and optimization. Eventually, simulation is a powerful educational material for training.

This paper synthetizes the work done by the project team (INSTITUT DE SOUDURE INDUSTRIE, EXTENDE, EKOSCAN) in the frame of three MTI projects related to

 https://doi.org/10.58286/28687

evaluation and simulation of HTHA damaged specimen using UT advanced techniques ([3], [4] and [5]). These projects have several objectives: the identification of the sensitivity of available NDT-methods for HTHA, and the development of NDT-strategies in case of an HTHA-risk in a carbon steel component (issuance of recommended practices for HTHA inspection in terms of probes and procedure). During the projects' development, MTI has provided field exposed samples.

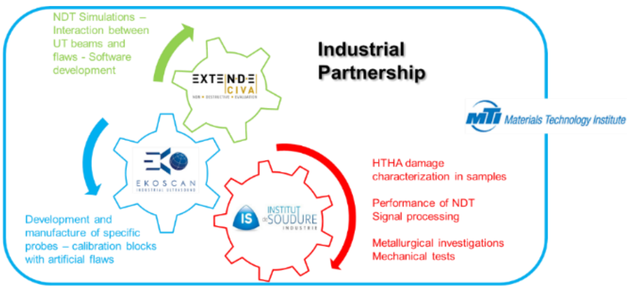


Figure 1: Illustration of industrial partnership to execute presented HTHA-related MTI projects.

## 2 Metallographic examinations of field-exposed samples

These simulation projects started with the description of actual HTHA damage from field-exposed samples. First, the studied samples were entirely screened to localize zones of interest which seemed to contain HTHA damage. Once this region of interest is determined depending on the studied sample, INSTITUT DE SOUDURE INSDUSTRIE proceeded to specific cuttings, surface treatments and metallographic examinations in order to assess the material inclusion content and to attest the presence of HTHA.

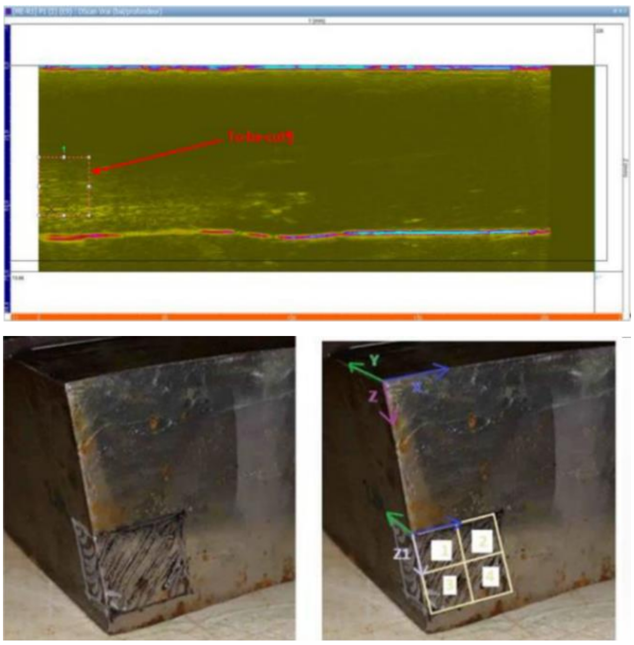

Figure 2: Illustration of sample screening (left) to localize an HTHA-damaged zone of interest (right).

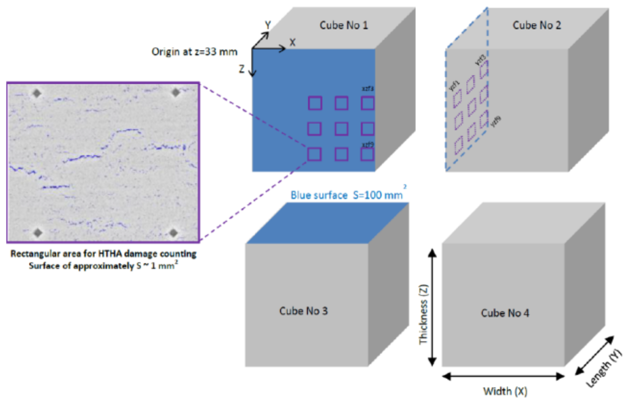


Figure 3: Faces observed on micrographic sections and areas of HTHA damage counting.

Then, image processing and analysis tools were implemented to provide quantitative data, characterizing HTHA damage distribution in terms of localization, density, geometry (length and aperture) and orientation in given planes. As a result of this HTHA damage counting step, an Excel file has been delivered to EXTENDE for each region containing the list of HTHA damage entities with their associated features for further statistical analyses.

Table 1: HTHA features extracted from analyzed fields.

| |
|---|
| Surface [µm²] |
| Max (Féret) [µm] |
| Orientation (Max (Féret)) [°] |
| Min (Féret) [µm] |
| Gravity center X [µm] |
| Gravity center Y [µm] |

## 3 Statistical analysis and synthetic HTHA damage generation

Based on measured HTHA damage features (Table 1) provided by INSTITUT DE SOUDURE INDUSTRIE, EXTENDE developed script tools to analyze and fit a sample damage statistic in terms of density, depth, size and orientation features. Two specific HTHA classes were identified during this study: defects of length smaller (HTHA class #1) and larger (HTHA class #2) than 40 µm. Depending on this class distinction, different density, depth-dependency, size, and orientation statistical laws were fitted based on field data from different field-exposed samples (with various HTHA distributions).

This study allowed then to artificially generate a random distribution of HTHA damage depending on the affected sample thickness and a severity degree. Such synthetic HTHA damage mimics the metallographic fields and interpolate the HTHA size and orientation statistical distributions outside the measured field locations/depths.

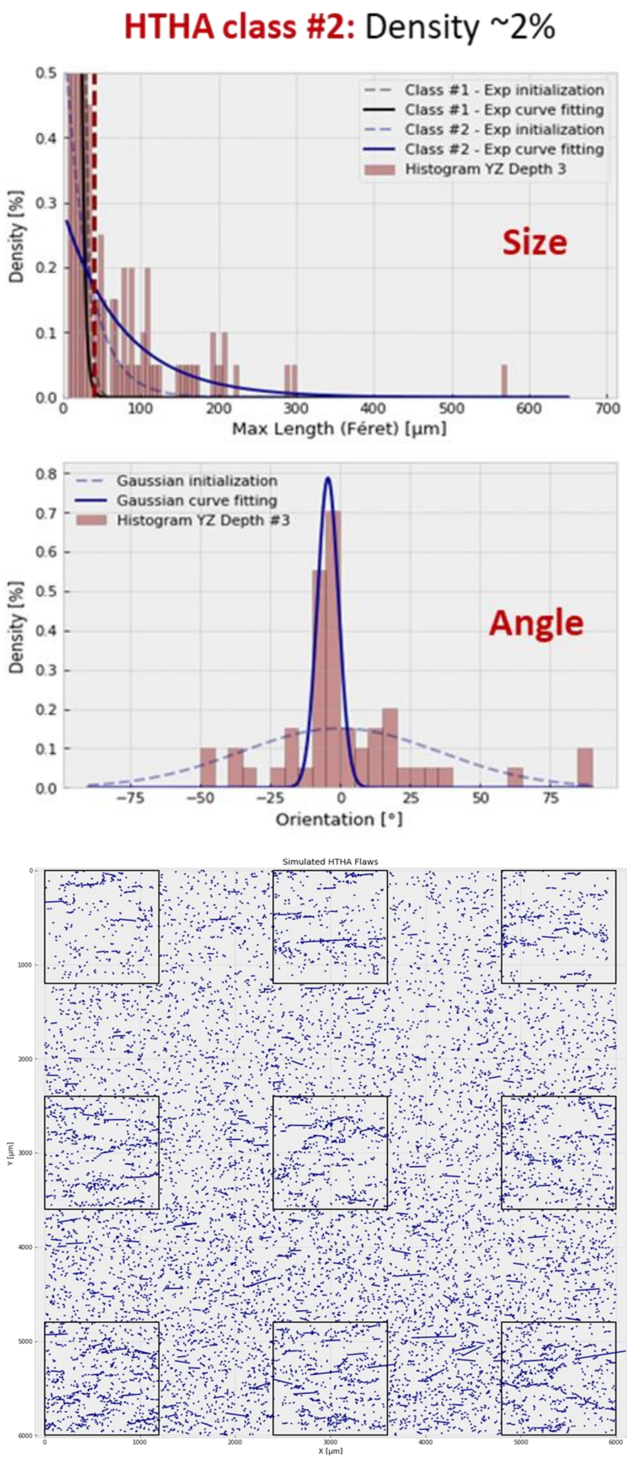


Figure 4: Statistical analyses of HTHA class #2 (size larger than 40 µm) and generation of synthetic HTHA damage (measured HTHA damage is displayed in the black boxes which correspond to the extracted fields).

As observed during the metallographic examinations of all the studied field-exposed samples, generated distributions of HTHA reproduce well the linear increase of defects with respect to the depth and the two different populations of HTHA with an important number of small entities oriented randomly and some larger objects oriented mainly around 0° (parallel to the inner surface).

The comparison between experimental and artificial HTHA from different field-exposed samples is satisfying and thus validates the developed generation process based on the separation in two different classes of HTHA damage with specific length and orientation statistical distributions.

## 4 Quantitative image criteria for CIVA UT simulation optimization

The previous statistical analysis allowed to generate HTHA damage in a volume of interest of a CIVA UT inspection simulation (with some assumptions to convert 2D fields statistics to a 3D volume).

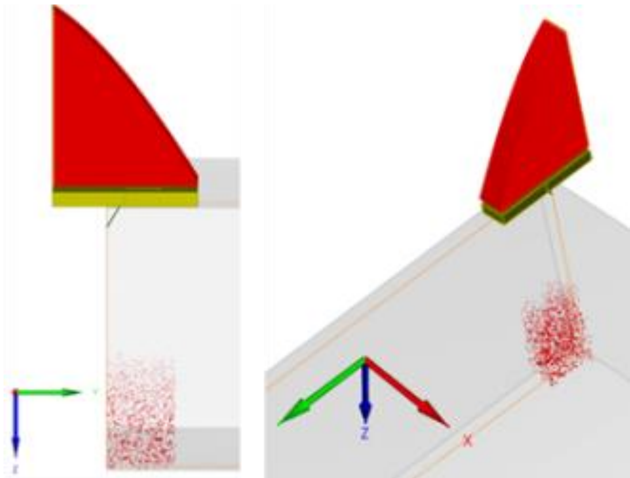

Figure 5: Synthetic HTHA damage in CIVA inspection simulation model.

Then, optimization of the generated HTHA distribution was performed with in-depth study of field-exposed samples. It consisted in analyzing the influences of the HTHA input parameters (volume density, surface filter, size/orientation features of classes #1 and #2) on the simulated UT images to find the best simulation input parameters to optimize the comparison result between experimental and simulated UT images.

To get both qualitative and qualitative observations, image criteria were defined during the optimization phase to quantify accurately the similarities between UT images. These criteria correspond to amplitude distribution along the depth (time or depth echodynamic) and acoustic indications statistics (in terms of depth, maximal amplitude, and size) after CIVA segmentation process. The target values for these criteria were determined from the analysis of experimental UT images depending on the inspection setup and the studied samples. These criteria also account for the observed experimental variability of the measured UT responses of the damaged area.

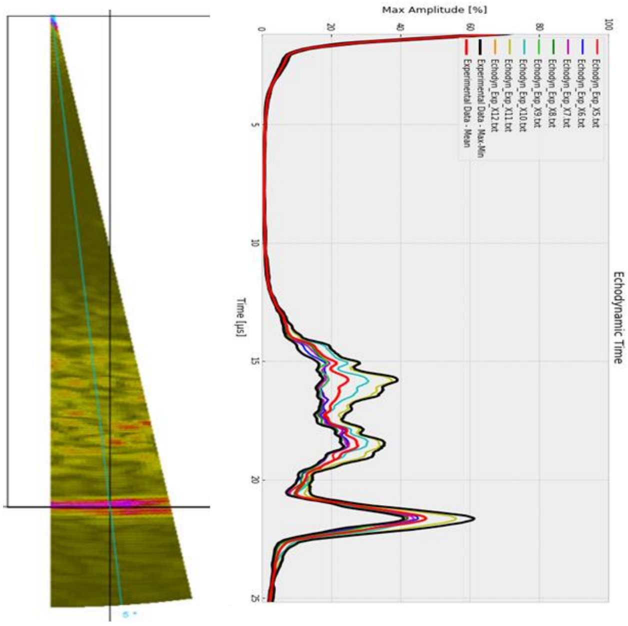


Figure 6: Criterion #1 – Amplitude distribution of UT images along the depth (time echodynamic).

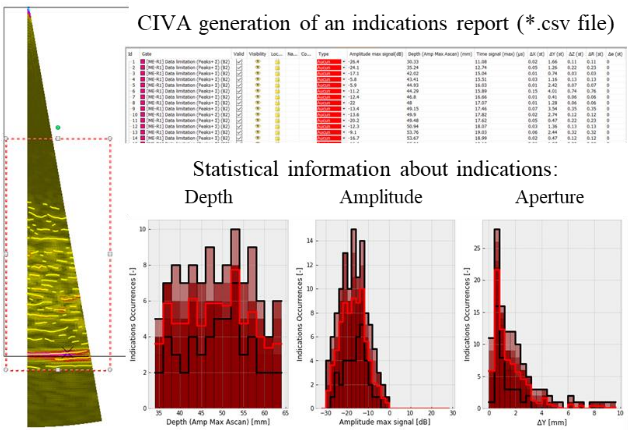


Figure 7: Criterion #2 – Statistics of acoustic indications features after CIVA segmentation of UT images.

Using these criteria and depending on the probes/samples, extensive simulation campaigns were performed to optimize the input parameters of generated HTHA damage distributions. These parametric studies were conducted for in order to define the best simulation options/parameters to predict UT images as close as possible to experimental ones. Once the simulation strategy was defined, blind tests (only the metallographic data are provided, not the experimental UT images) have been performed to validate the relevance and accuracy of the simulation methodology for HTHA damage model in CIVA UT.

## 5 Validation of CIVA simulations of HTHA damage UT responses

After the optimization phase, simulated ultrasonic images are fully consistent with experimental ones in terms of ultrasonic indications' amplitude and distribution, shadowing effect and backwall attenuation. These applies for different phased-array settings and probe frequencies. The damage generation tool is based on a statistical model with monitored input parameters which are optimized to predict accurate UT images. Different HTHA defect size/angle distributions can then be randomly generated using the same input parameters, but the quantitative comparison between these simulated images and the experimental ones (with also a variability along the mechanical scanning) will remain satisfying for both probes and acquisition settings. This simulation strategy has been successfully propagated to various field-exposed samples accounting for different microstructures, thicknesses and history (meaning different types and levels of HTHA damage).

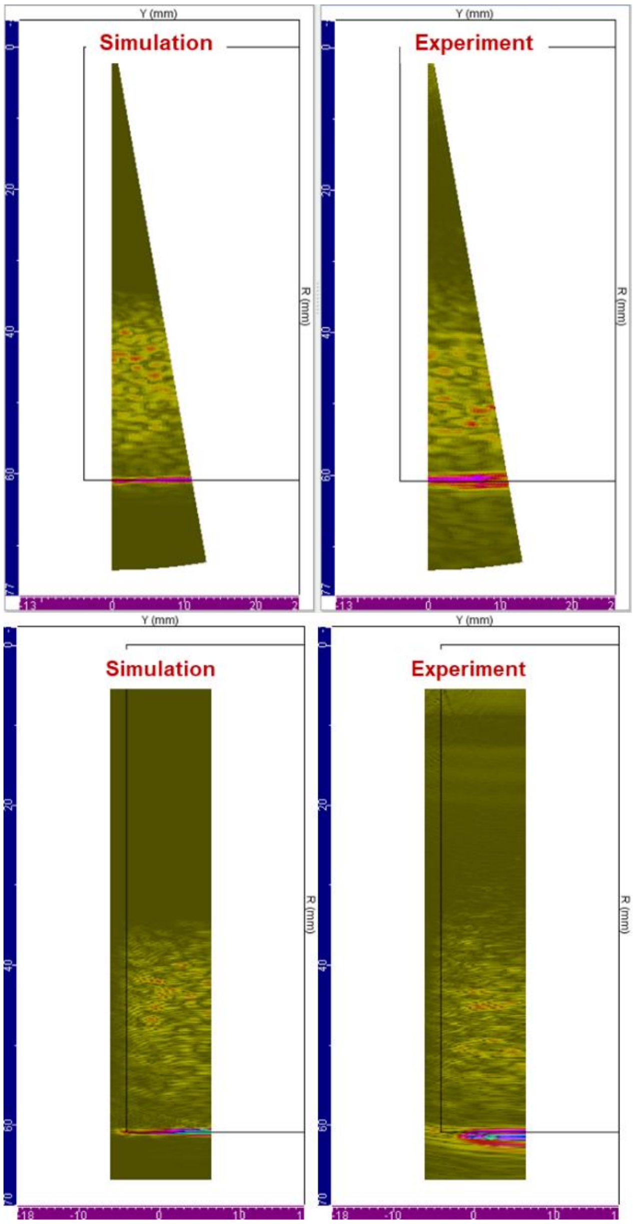


Figure 8: Simulated vs experimental sector scans (top) and FMC-TFM (bottom) images of HTHA-damaged sample [linear 64 elements, pitch 0.5 mm, frequency 7.5 MHz].

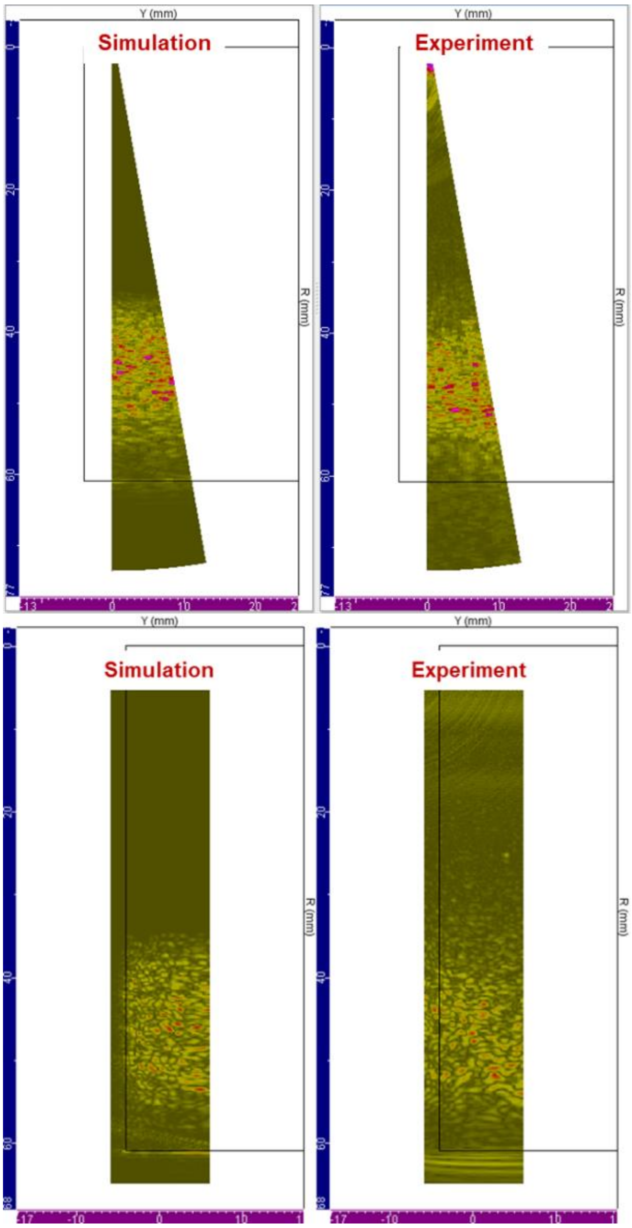


Figure 9: Simulated vs experimental sector scans (top) and FMC-TFM (bottom) images of HTHA-damaged sample [linear 64 elements, pitch 0.5 mm, frequency 12 MHz].

## 6 Model extensions to material inclusions and specific damage patterns of welded samples

Once the volumetric HTHA damage model has been developed, several extensions have been studied. They consist in challenging and improving the modeling and simulation methodology in order to deal with specific HTHA damage patterns and typical defects encountered during damaged welded samples inspection. The main model extensions deal with the flaw modeling and UT responses simulation of: globular non-metallic inclusions (Figure 10), elongated MnS inclusions, macro crack with volumetric HTHA damage at the tip (Figure 11), blister-like damage (MnS inclusions with HTHA damage at the edges), lacks of side wall fusion.

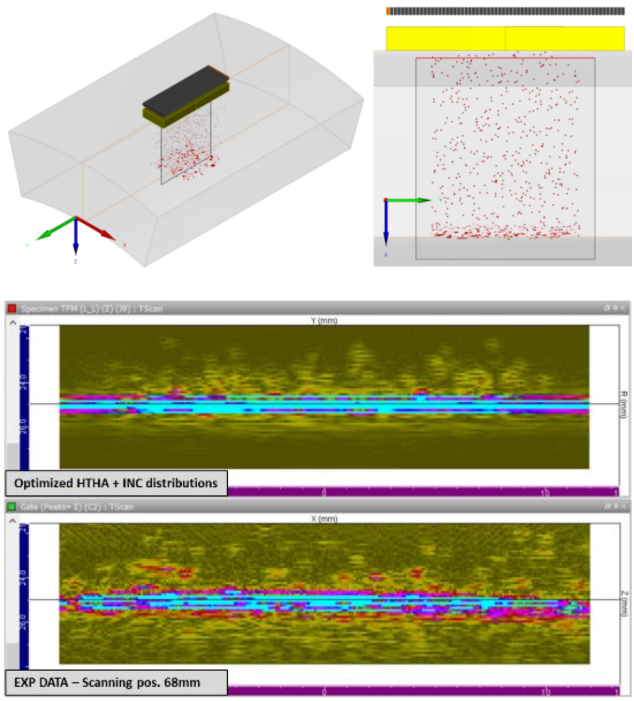


Figure 10: CIVA distributions of HTHA damage and globular non-metallic inclusions, and comparison between experimental and simulated FMC-TFM UT images.

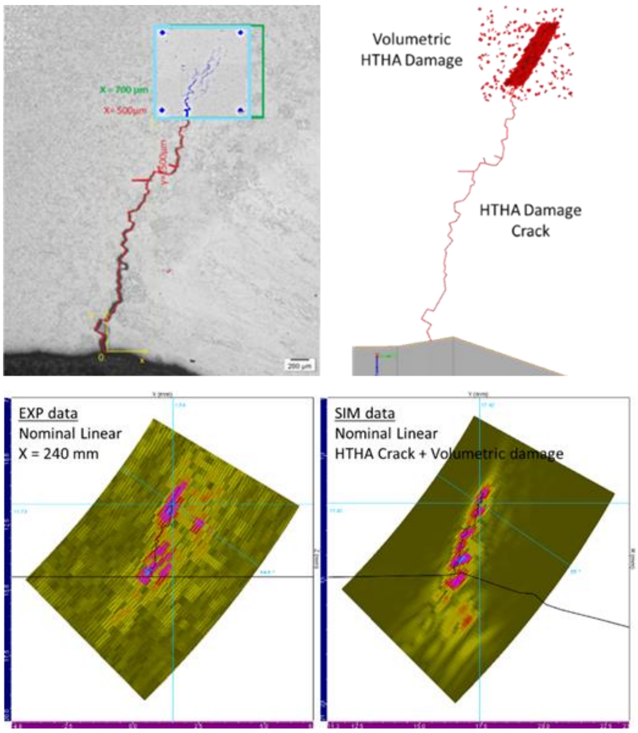


Figure 11: Metallographic examinations, CIVA synthetic HTHA damage and comparison between experimental and simulated sectorial scan UT images.

The same approach developed for volumetric HTHA damage was derived to predict the UT responses of such specific damage and inclusions. This approach covers metallographic examinations, statistical model of the defects' distribution, generation of synthetic distribution, optimization of its predicted UT response with CIVA UT, and simulation validation by comparison with experimental UT images. These model extensions are of paramount importance for HTHA inspection programs as they allow to investigate by simulation the possibilities for characterization and discrimination techniques to identify and separate the detection of volumetric HTHA damage from other types of ultrasonic indications encountered in damaged welds samples.

## 7 Probe parameters optimization for HTHA damage detection

Once the HTHA damage model is derived, simulation allows to test several NDT configurations with new probes before manufacturing them, proving to be a useful tool for prototyping and optimization for damage detection and characterization. Probe and inspection parameters can be easily tested and optimized in simulation, bringing valuable time savings, an increase of number of NDT test cases, and experimental costs reduction. During MTI projects, numerous probe types and inspection setups have been studied: linear and matrix phased-array (PA) probes, DLA/DMA probes, angled-shear wave probes, forward and backward TOFD setups. Guidelines or recommendation practices for HTHA damage detection depending on the sample configuration will be issued based on this work. Moreover, an optimal linear PA probe has been identified by simulation, then manufactured by EKOSCAN and tested on actual damaged sample to validate its enhanced detection performances.

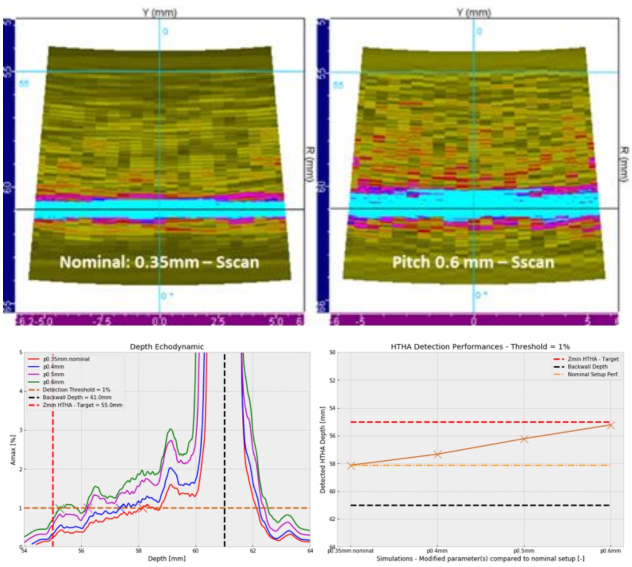


Figure 12: Optimization results example of linear phased-array probe pitch for HTHA damage inspection.

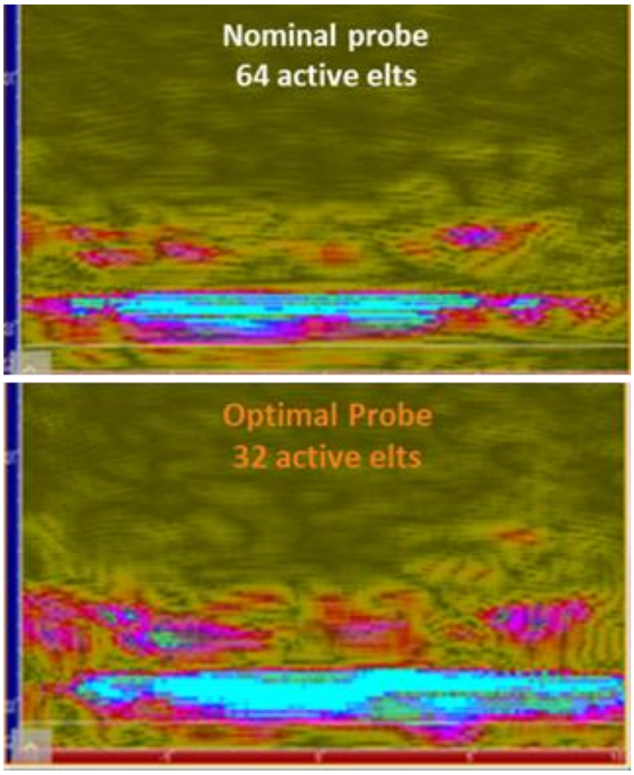


Figure 13: Experimental validation of optimal linear probe performances for HTHA detection [FMC-TFM].

## 8 Conclusions and perspectives

This paper synthetizes the modeling and simulation methodology developed to predict relevant UT images of HTHA-affected sample with CIVA UT software. It deals with the development of a statistic tool which generates artificial HTHA damage based on metallurgical input data of field-exposed samples and with the validation of CIVA simulations of different HTHA-affected samples in comparison with experimental UT images based on specific quantitative image criteria. This simulation strategy has been successfully validated with experimental acquisitions through the investigation of various field-exposed samples accounting for different microstructures, thicknesses and history (meaning different types and levels of HTHA damage), and various inspection techniques, phased-array settings and probe frequencies. The model has initially been derived for volumetric HTHA damage and extensions have been further added to account for specific HTHA damage patterns and typical defects (inclusions for example) encountered during welded samples inspections.

Probe parameters optimization can be studied by means of intensive use of the simulation. From this work, an optimal linear PA probe for HTHA detection has been deduced and manufactured by EKOSCAN for industrial applications. These projects highlight and justify guidelines and recommendation practices for HTHA damage detection and characterization improvement depending on the targeted inspection configuration (sample thickness, probe access constraints, wedge refracted angle to use, the frequency to define, etc.). Optimized inspection procedure resulting from the use of the simulation model will be issued and new API document update will mention the results in the frame of these MTI projects.

Some interesting perspectives can be investigated from the use of this modeling and simulation study such as: improvement of operator training on virtual HTHA damage (TraiNDE UT), development of automatic diagnosis tools (artificial intelligence for damage and inclusion patterns recognition), study and justification of performances reliability for HTHA damage detection and characterization of given probes and inspection setups.

## Acknowledgements

These HTHA-related projects have been supported by MTI and project partners would like to express acknowledgement to MTI and its members for providing field-exposed HTHA damaged samples needed for in-depth metallographic and UT inspection studies.

## References

[1] API 941 8th Edition, Section 6 and Annex E, Addendum 1, August 2020

[2] API RP 586, Section 2, Inspection for HTHA, 1st Edition-Draft, 2022 (to be published 2023).

[3] 5503-4ON7HC-V2 MTI Project 305 – Final Report Phase 1: Evaluation Capabilities of Advanced Ultrasonic Techniques for Detection and Characterization HTHA Damage; Development and Validation of Ultrasonic Simulation Model for an “Ideal” Volumetric Damage.

[4] 5503-62PDKT-V1 MTI Project 355 – Design of Optimized Phased-Array Probes for HTHA Inspection Intermediate Report.

[5] 5503-DFUR–V2 MTI P362 Enhancement of CIVA Simulation HTHA Volumetric Damage “Ideal” Model to Consider Inclusions and other Damage Manifestations in Affected Welded Areas Final Report.