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# Challenges in ultrasonic NDT/NDE of small-scale structural defects in metal pipelines of the energy sector

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## 1. Abstract

This research investigates the ultrasonic detection of small-scale structural defects in pipelines, pressure vessels and heat exchangers used in thermal and nuclear power plants, petrochemical facilities, refineries and hydrogen infrastructure. These components operate under harsh conditions (high temperatures, pressures and hydrogen-rich environments), that promote the formation of defects such as creep damage and hydrogen-induced cracking (HIC). Creep typically initiates in welds and heat-affected zones (HAZ) due to residual stresses and microstructural changes, while HIC results from hydrogen diffusion into the material. Although early-stage inhomogeneities are initially harmless, they can evolve into critical cracks, leading to failures, costly downtime and environmental risk. Detecting such early-stage defects remains a major challenge for non-destructive testing (NDT). Conventional X-ray and ultrasonic techniques often fail to detect features smaller than the ultrasonic wavelength or obscured by structural noise or low density variation.

This study evaluates higher frequency ultrasonic transducers and arrays for early-stage creep and HIC detection. Structural noise analysis, amplitude ratio and artificial intelligence (AI) techniques proved effective in identifying microstructural degradation in the HAZ. Cracks smaller than 0.2 mm became detectable as they progressed. The findings demonstrate an enhanced approach for characterizing small-scale defects and overcoming current NDT limitations in critical energy infrastructure.

**Keywords:** ultrasonic NDT / NDE; detection and characterization; structural defects; creep damage; hydrogen-induced cracking (HIC)

## 2. Introduction

Components in thermal and nuclear power plants, refineries, petrochemical facilities and emerging hydrogen infrastructure, including pipelines, pressure vessels and heat exchangers, are exposed to combined high-temperature, high-pressure and hydrogen-rich environments that accelerate creep [1,3,4] and hydrogen-induced cracking (HIC) [2,5]. In particular, type IV creep cracking in the heat-affected zone (HAZ) of creep-strength-enhanced ferritic steels (Grades 91/92), and HIC/step-wise cracking in carbon and low-alloy steels remain among the most safety-critical degradation mechanisms in the energy sector [1–5]. While isolated early inhomogeneities are harmless, they can aggregate into clusters, nonlinearly progressing into cracks that jeopardize structural integrity and lead to catastrophic failures, loss of human life, costly outages/downtime and environmental harm. Early-stage detection of cavity clusters and micro-cracks with dimensions less than 0.5 mm is beyond the capability of conventional ultrasonic and radiographic NDT methods because the defects are smaller than the wavelength and are masked by coherent structural noise [1,3].

## 3. Results

This study evaluates the performance of high-frequency focused transducers


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(>20MHz), backscatter signal processing, advanced high-resolution phased-array imaging (TFM etc.), AI / machine learning (ML) - assisted classifications for reliable early-stage detection and characterization of creep and HIC in real components, highlighting the essential role of advanced NDT and evaluation (NDE) techniques in pre-critical microstructural evaluation.

The findings demonstrate an enhanced approach for detecting and characterizing small-scale defects (approx. 0.2 mm) and overcoming current NDT limitations in critical energy sector infrastructure. The post processed B-scan image (25 MHz frequency) of a detected group of creep damages in the heat-affected zone of a welded P91 steel sample being used in pipelines of a thermal power plant is presented in Fig.1.

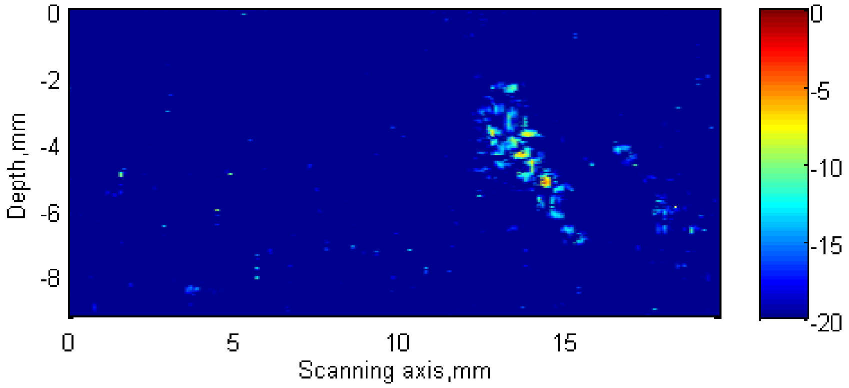


**Fig. 1.** The B-scan image after post-processing, showing the selected weld region of a P91 steel sample affected by a spatially distributed group of creep damages. Absolute amplitude values are displayed on a logarithmic colour scale (dB).

## Conclusions

The obtained results confirm that specialized high-sensitivity ultrasonic methods, employing higher-frequency transducers (above 20 MHz), advanced phased-array imaging and AI / ML assisted techniques, enable reliable detection and characterization of small-scale defects such as creep damage and HIC in critical energy sector components. These approaches, enhanced by signal, image processing and AI, overcome NDT limitations for characterizing small-scale defects with approx. spatial dimensions of 0.2 mm, thereby mitigating the risks of harmful accidents of pipelines and other critical infrastructure in the energy sector.

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