e-Journal of Nondestructive Testing - ISSN 1435-4934 - www.ndt.net
14th European Conference on Non-Destructive Testing, Verona, Italy (ECNDT 2026)

Detection and staging of hydrogen induced damage in heat exchanger shells using machine learning techniques

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1 Abstract

This study presents a hybrid artificial intelligence framework for the automated detection and classification of hydrogen-induced cracking (HIC) defetcs in heat exchanger shells. The proposed methodology integrates supervised and unsupervised machine learning techniques to classify HIC evolution into four stages: isolated voids, clusters of voids, mixed void–crack regions, and fully developed cracks. Multi-plane wave ultrasonic imaging enhanced by Circular Coherence Factor (CCF) reconstruction served as the input modality. A dedicated training dataset containing 29,000 HIC cases from heat exchanger shell with naturally occurring damage, labeled by non-destructive testing (NDT) experts, was used for model development. Eighteen statistical and morphological descriptors capturing geometrical, textural, and relational characteristics of defects were extracted and analyzed. Feature selection algorithms were applied to identify the most discriminative features, improving model interpretability and robustness. Multiple classifiers, including ensemble and deep learning architectures, were evaluated for sensitivity, specificity, and generalization capability against unsupervised clustering approaches. Validation on unseen samples demonstrated strong generalization across different HIC stages. The proposed technique aims to assist in the detection of HIC damage, automate defect classification, and serve as a supporting approach for estimating the stage of HIC progression, emphasizing the defect classes that are more related to the advanced damage progression.

Keywords: Hydrogen induced cracking, non-destructive testing, phase coherence imaging, machine learning, HIC defect staging.

2 Introduction

Hydrogen-induced cracking (HIC) is a major degradation mechanism in low to medium strength carbon steel pipelines exposed to high-pressure gaseous hydrogen environments. Atomic hydrogen permeates the steel matrix and accumulates at microstructural trap sites such as non-metallic inclusions, voids, grain boundaries, and laminations [1,2]. This accumulation leads to internal crack initiation, which at advanced stages can interconnect, resulting in a significant reduction of the safe internal pressure that can be maintained by the pressure vessel.

Several ultrasonic non-destructive testing (NDT) techniques such as conventional ultrasonic testing (UT), time-of-flight diffraction (TOFD), and phased array ultrasonic testing (PAUT) have been employed for the detection of hydrogen-induced damage [3-5]. However, a major challenge remains in reliably classifying and staging HIC defects according to their severity, which is critical for assessing structural integrity and guiding maintenance decisions.

https://doi.org/10.58286/33110

To address this issue, this study employs high-resolution plane wave imaging (PWI) enhanced with phase-based reconstruction, combined with machine learning models, to detect and classify the stages of HIC in heat exchanger shells. Training is performed on samples exhibiting various extents of natural HIC damage, labeled by NDT experts on the data that was acquired in the phased array PWI inspection and defect signatures were extracted using the phase coherence imaging. The HIC stages are defined as follows:

- Isolated HIC void – a single isolated response or area in PA imaging;
- Cluster of HIC voids – multiple responses in close proximity;
- Mixed HIC void/crack – elongated or interconnected responses;
- HIC blister – continuous elongated or backwall interconnected defect.

Both supervised machine learning algorithms (e.g., support vector machines, decision trees) as well as deep learning models such as convolutional neural networks (CNNs), are evaluated. Model performance is assessed in terms of generalization, sensitivity, specificity, accuracy, recall, ROC and confusion matrices. One example of the resulting classification outcomes is illustrated in Figure 1.

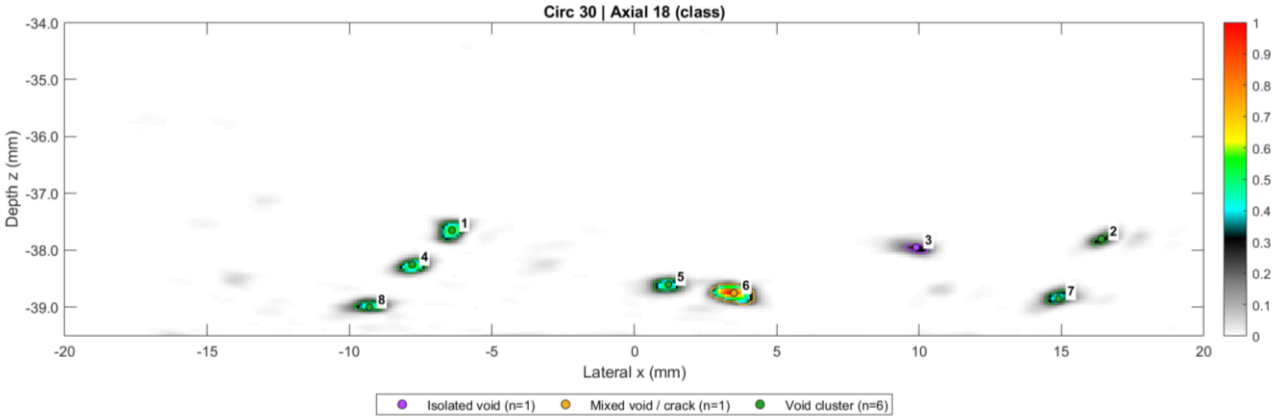

Fig. 1. An example of classified HIC inspection image showing different HIC defect stages obtained using the supervised machine learning

The study investigates the advantages and limitations of each AI approach in terms of accuracy and simplicity. Overall, decision tree models and neural networks demonstrated the best performance in distinguishing between different defect classes and in handling data imbalance.

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