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The development of techniques to detect high temperature hydrogen attack – A mini review

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A B S T R A C T

High temperature hydrogen attack (HTHA) is classified as one of the problematic failure mechanisms which normally occurs in petrochemical refineries. It causes degradation in a material due to high temperatures and pressures that are involved. Carbon steel and low alloy steels are the materials that are most prone to this damage mechanism. The main challenge facing refineries is the early warning systems that can be used to detect this failure before it is at an advanced stage. Due to the challenges of HTHA inspection, several advanced non-destructive examination techniques have been developed over the years. This includes acoustic emission testing (AET), automated ultrasonic detection and classification (AUDC), and more, where many of these techniques are microstructural based. Although there have been several new developments for detecting this failure mechanism, some developments are more focused on continuous monitoring of material behaviour under operational conditions. However, most techniques being used are normally deployed to detect all possible material failures including corrosion. These techniques can't be used as a stand-alone for HTHA detection due to complexity and the nature of data. This paper briefly reviews the techniques that have been developed to detect HTHA. The detection accuracy of the systems being developed, and the level of implementation are also discussed. The techniques used to track the sites of hydrogen in metals are also reviewed with the purpose of establishing whether those techniques can be used in monitoring the HTHA. This will assist in understanding the gaps around HTHA detection.

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1. Introduction

The continuous exposure of a material to harsh conditions always comes with a penalty. This is manifested through one of the material that is produced to withstand such conditions called steel. Steel is considered as one of the best materials suitable for deployment in harsh environmental conditions like high pressure and temperature, extremely low pressure and temperature. In as much as this material performs under these harsh conditions from various industries, there is, however, one common failure that has been experienced by mostly oil & and Gas refinery industry called high temperature hydrogen attack (HTHA). This failure mechanism has been in existence for decades and its existence is influenced by the high temperature and pressure through which the material is constantly exposed to [1-5]. High temperature hydrogen attack is a failure mechanism that is normally associated with carbon steel that is exposed to a high temperature environment. This failure mechanism is caused by decarburization which emerges from methane molecules that are formed when hydrogen atoms react with carbon atoms. The reaction of these atoms is influenced by the high temperature through which these atoms are exposed to. The accumulation of methane molecules within the grain boundaries of steel results in a formation of bubbles which in turn leads to internal pressure build-up and the loss of fracture toughness. The loss in fracture toughness leads to fissures and cracks [6-10]. The fact that this failure mechanism originates from a chemical reaction, it is, therefore, crucial that it is detected at an early stage. There are several mechanisms and techniques that have been developed in trying to detect this failure at an infantile stage. The majority of works have been focusing on testing the non-destructive detection systems and this includes acoustic emission testing (AET), ultrasonic techniques, etc. [11]. Non-destructive techniques are normally preferred as the best option because they operate automatically which means human interference is very minimal. The downside of these techniques is that they require a highly skilled technician to operate and analyze its output [12]. This paper presents various techniques that have been developed

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for the identification and the quantification of HTHA for in-service structures. The main aim is to track the effectiveness, the challenges associated with the existing techniques and to identify the gap.

2. Available hydrogen related damage detection techniques

It is seen from the literature that HTHA has been in existence and has been a subject of interest to various researchers. The interest is gauged through the progress that has been made in developing techniques that can be used in detecting HTHA. However, there is still no technique that is currently ready to be implemented in the real environment due to various reasons. This section reviews the existing HTHA detection techniques that have been developed to date. Allevato [11] have employed acoustic emission testing (AET) in detecting the HTHA in Cr-Mo reformer reactors and piping during temperature gradients. AET is classified as one of the non-destructive testing technique that can be useful in detecting and locating the damage of the material. The small-scale Catalytic Reformer Unit (CRU) was designed to test the capability of AET towards detecting the growth of HTHA. The system was installed on various parts of the small-scale CRU. The system was operated with conditions similar to the actual system and the operating conditions were also in reference to API standard. The AET showed a promising capability towards the detection of HTHA from various parts of the system. The pipe elbows were showing a high concentration of stress. The areas which were shown to have a high possibility of failure were then extracted out from the system for microstructural analysis and the microscopes revealed cracks that were growing along with the elbows.

Yamani [12] developed the system that could be used in the identification of the HTHA defects from numerous other non-HTHA defects. The out-of-service pressure vessel with many HTHA defects was used in creating the database that was tested. The system with three major components was used to create three different datasets i.e. HTHA defects, laminated defects, and the flat bottom hole defects. These datasets were captured using the compression wave probes, SONATEST Masterscan 340 flow detector, couplant, and calibration blocks. The flaw detector used for this experiment was a normal commercially available flaw detector that had the capability to detect and record a maximum of 100 RF A-scan signals. The datasets that were created were subjected to analysis for the identification of HTHA using automated ultrasonic detection and classification (AUDC) system. AUDC system is known to have the capability of interpreting the large data volume with minimal errors. The three databases were analyzed using the AUDC system. It should be noted that the identification of the intended signal depends on the training that is conducted on the system prior to the operation. A similar procedure was also followed in this study and the system was able to detect and classify an average of 98.4% HTHA defects. It was noted that this system does not necessarily require a highly skilled operator in interpreting the results.

It is a known fact that the failure of various structures due to HTHA is always linked to the microstructural phenomena which emerge from unintended chemical reactions. Various techniques have been developed with the purposes of detecting the hydrogen reactions within the material which leads to structural failures [13]. This involves the hydrogen microprint technique (HMT), electrochemical impedance spectroscopy (EIS), thermal desorption spectroscopy (TDS), Devanathan-Stachurski method (DS), and electrochemical noise (EN) [14-18]. The HMT technique works like any other hydrogen visualization technique, however, its outstanding feature is its capability of perfectly showing the local distribution of hydrogen atoms through the molecule reduction method [19-21]. The HMT technique is better suited to the studies that deal with the correlative analysis between hydrogen degassing and the character of the grain boundary [21]. The EIS is an electrochemical technique that is mostly used in studying the barrier properties of the polymer coating, the understanding of the dissolution metal patterns, and corrosion rates [22-25]. The EIS technique has its own feature which makes it suitable for HTHA detection in metals i.e. sensitivity of impedance circuit parameters towards hydrogen content [17].EN is also an electrochemical technique that works with the variation of resistance with noise which is linked to current and voltage fluctuation patterns of identical electrodes connected to a cell [18]. This technique has its limitations when it is exposed to different working conditions [26,27]. However, this technique has its outstanding feature that can be useful towards the detection of HTHA i.e. capability of establishing hydrogen evolutions in metals [28]. The TDS technique is a technique that involves the heating up of the specimen with the purpose of ejecting the hydrogen trapped inside the metal. The identification and the quantification is performed through a gas chromatograph [29]. However, the data collected from this technique requires some post-analysis using well-developed models [30-32]. This one of the thermal techniques which showed an outstanding capability towards the detection of the HTHA from steel pipes [33,34]. The DS technique can be classified as one of the electrochemical techniques which operate through the adsorption–desorption principle in providing the diffusion pattern and trap density of hydrogen in metals [16,35-37]. This technique has the ability to quantify and locate the area with high hydrogen entrapment which might lead towards a metal failure [38,39]. The summary of different techniques available for the detection of various damages occurring in steel pipes is presented in Table 1. A short explanation of how the technique is installed is also presented in Table 1.

3. Challenges towards the implementation of existing techniques

This section gives some details on the configuration of some selected hydrogen and HTHA detecting techniques and the relevant major components. The possibility and the challenges of each technique to be implemented in the real environment for monitoring of HTHA are also discussed

3.1. Hydrogen microprint technique (HMT)

The performance of HMT requires that the sample to be tested be charged with hydrogen and be polished prior to the application of the silver bromide emulsion [14].

These are the three stages of HMT:

- Emulsion Coating – this is where AgBr emulsion is coated on polished steel.
- Reduction of Ag ions – The reduction of Ag^+ to Ag occurs, this is due to the evolvement of H atoms from steel.
- Fixing - This is a stage where unreacted AgBr crystals and reveals of Ag grains are removed.

The surface polishing was reported to have an impact on the efficiency detection [40,41]. Looking at how the way the HMT works, it may be difficult to employ this technique for monitoring duties in a real environment. This hindrance to such duties is caused by the requirement that this technique gives useful information [42,43]. HMT would be better suited for the examination of out-of-service metal structures.

Table 1
Summary of recent hydrogen and hydrogen-based damage detection technique

No.	Technique	Metal type	Installation	Data post-processing	Ref.
1	Acoustic emission testing (AET)	Cr-Mo steel	The sensors are being distributed and laminated to the outside surface of the structure being examined. This technique produces stress concentration in various sections of the structure being examined. The technique has the ability to display the colour coding associated with stress concentration. This technique can be employed while the structure is in service.	No	11
2	Flaw detection system	Cr-Mo steel	This is the scanning technique that scans the outside surface of the structure being examined. The variety of unique signals are captured and classified into different groups for further analysis/processing. This technique is better suited for the structures that are not in-service.	Yes	12
3	Hydrogen microprint technique (HMT)	Duplex stainless steel, low-carbon steel, and austenitic stainless steel	This technique uses the chemical approach where the silver solution known as silver bromide is used as the paste. The solution is applied on the surface of the metal piece extracted from a structure being inspected. The chemical reaction is allowed to take place. This chemical process is followed by the examination of the surface through microscopes. This technique is not suitable for in-service structures.	No	14,19–21
4	Electrochemical impedance spectroscopy (EIS)	Pipe steel	This technique uses the electrochemical approach to evaluate the coating barrier characteristics applied on the outside surface of a material. The impedance sensitivity response data can be easily linked to the content of hydrogen present in the material. This technique can be employed in the in-service structures.	No	22–24
5	Electrochemical noise (EN)	X70, X80, X100 pipeline steels	This technique is also identified as one of the electrochemical techniques which use noise to evaluate the damage on the material. This technique is not installed to an in-service metal structure but is applied on a small portion of an outside surface area of metal being examined. This technique requires extensive surface preparation which makes it better-suited samples extracted from the parts of the materials being examined.	No	25–29
6	Thermal desorption spectroscopy (TDS)	X80 stainless steel, low-carbon steel	TDS is a thermal-based technique that involves the heating up of the sample being tested. This technique is not installed to the structure being tested instead a portion is sampled out from the metal structure and undergoes heating and measurement processes. The data captured from this technique requires extra processing.	Yes	33–34
7	Devanathan-Stachurski technique (DS)	X60, X60SS pipeline steel	DS technique is also considered as the electrochemical technique which involves the double-cell apparatus in providing the information about the diffusion pattern and trap density of hydrogen in a metal. The technique works better with small portions of samples from the metal structure being examined.	No	36

3.2. Acoustic emission testing (AET)

The AET works with the detection of waves produced by the structure being monitored [44-46]. This technique does not require extensive preparation for it to work perfectly, hence it works with metal and non-metal structures [47-53]. The enhancement of the AET involves the coupling of the thermal cameras and other image recording devices [54-57].

The simplicity associated with the installation of the AET makes it versatile and compatible with various applications. The minor challenge is the wiring that may be required for the monitoring of the huge pipe network. This type of real-time monitoring system can be suited for the detection of damages emerging from hydrogen in metals like HTHA.

3.3. Electrochemical impedance spectroscopy (EIS)

EIS is the technique that is perfectly used to monitor metal degradation mostly corrosion [58-65]. This technique has been used in various fields. This includes biological applications and non-biological applications [66-73]. The developments around this technique have improved the data acquired from this system such that it does not require extensive post data processing. However, this technique could be limited to the lab-scale application which means it cannot be used to monitor the degradation like HTHA at a large scale due to the configuration of this technique.

3.4. Thermal desorption spectroscopy (TDS)

The proper operation of TDS requires a certain furnace temperature range for the hydrogen desorption to take place and be detected by a gas detector like chromatograph or quadrupole mass spectrometer [74,75]. The data logged from the experiment itself requires certain models for further processing. This then suggests that the system cannot be used as a standalone unit for monitoring metals degradation but will require extra support for the meaningful data. The operating principle of this technique makes it difficult for it to be deployed for HTHA detection that occurs on the pipe network that carries the fluid at elevated temperatures like in the oil & gas industry.

4. Concluding remarks

HTHA remains the main existing problem that various industries. The various failure events that occurred from different industries due to HTHA has led to the reproductive of standards. It is clearly seen from the literature that various methods have been developed for various purposes. The development of those methods normally spans from the detection of hydrogen based failures. The developed methods include methods that can be used or installed to monitor the service life of the metal that is exposed to various working conditions. However, some techniques are not suited for the installation in the real environment but work better at a laboratory scale. The techniques reviewed in this paper were found to have some limitations due to various specifications and the nature of the technique. This includes the type of tests associated with various techniques and the procedure to be followed in conducting those particular tests. In some techniques, it appears to be impossible to employ the technique in the field for in-service metal structure. Some techniques can be used for in-service metal structures and can give real data. However, the installation would be a challenge since some techniques use sensing technology for real data capturing. This then brings the conclusion that there is a need for improving the existing hydrogen based techniques in order for them to be practical viable and can be used to provide real-time data.

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CRediT authorship contribution statement

Noxolo NTP Hlongwa: Data curation, Formal analysis, Writing - original draft. **Sipokazi Mabuwa:** Writing - review & editing. **Velaphi Msomi:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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