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# Evaluation and Prevention of Hydrogen Embrittlement by NDT Methods: A Review †

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**Abstract:** This paper comprises of hydrogen embrittlement phenomena in material, factors responsible for the hydrogen embrittlement and non-destructive methods to evaluate the internal defect in machines or components when working in hydrogen atmosphere. Hydrogen embrittlement is responsible for sub-critical crack growth in materials, fracture and mechanical properties such as ductility, toughness, and consequently loss of strength. This hydrogen is induced into the material during electrochemical reactions and in a high-pressure hydrogen gas environment. The paper covers the review on the capabilities of non-destructive testing methods regarding advantages and disadvantages. Sometimes one non-destructive technique does not provide sufficient information about physical integrity and therefore a different combination of methods is required. Ultrasonic testing is very useful to detect internal defects.

**Keywords:** hydrogen embrittlement; NDT; HEDE; HELP



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## 1. Introduction

Some of the typical damage that hydrogen induces to metals and alloys is the formation of hydrogen bubbles. HE, breakup due to hydride forming, hydrogen attack, or breakup of inner hydrogen distribution are all forms of hydrogen embrittlement. Hydrogen embrittlement has been the most common effect of hydrogen on high-strength materials. It is defined as a process in which the introduction of hydrogen atoms while working in a hydrogen environment can significantly reduce the strength of a material, Because of their low sensitivity to hydrogen embrittlement, austenitic stainless steels have become commonly accepted for the manufacture of hydrogen-based equipment [1–3].

NDT is a method for evaluating the integrity of a material against surface or internal defects or metal conditions without interfering with the conformity destruction of the material or service in any way. There are various methods for evaluating materials and components according to the conditions of their application. In other words, NDT refers to the process of evaluating or inspecting materials or components for characterization or defects against certain standards without changing the original characteristics or testing the object. This may require a combination of methods and can also lead to exploratory and invasive exposure. A better understanding of the context, advantages and limitations of each NDT methodology is needed to ensure a successful assessment. Composite NDT applications can include many locations such as factories, pipe and tube plants, storage tanks, aerospace, military and defense, nuclear industry, and general defect characterization.

## 2. Hydrogen Embrittlement

Hydrogen Embrittlement refers to a loss of ductility of material or it becoming brittle. If embrittlement occurs due to effects of hydrogen absorption then it is known as hydrogen embrittlement. High-strength steels, high-Mn steels, aluminums alloys, titanium, magnesium and magnesium alloys, and other materials are susceptible to Hydrogen embrittlement. This high-strength steel has been used in a variety of applications, like aerospace, nuclear, high-pressure hydrogen storage facilities, automotive, and transportation. This high Mn grade steel has a number of benefits, including high flexibility and strength. High Mn steels, on the other hand, have chemical properties that cause HE emission and sensitivity problems [1–4].

### 2.1. Factors Responsible for the Sensitivity of the Material to HE-

- Material strength and residual stress in the material.
- Pressure, temperature, and time of exposure.
- The degree of strain applied and the surface conditions of the material.
- Amount of hydrogen or number of hydrogen traps.
- Certain metal layers and deposits.
- The microstructure of a material.
- Solutions that react with metals (acid solutions).
- Heat treatment of a material.

### 2.2. Mechanism

#### 2.2.1. Hydrogen Enhanced Decohesion Mechanism (HEDE)

Troiano actually proposed this structure in 1959, and it is the simplest. It depends on lessening the strength of the material in the crack tip locale by the acceptance of hydrogen particles. The strength of the differential connection between molecules diminishes as the 1 s electron from the hydrogen enters the 3D cell from the iron particle. Decohesion happens when the tip of the break arrives at tip removal (CTOP) [1,3].

#### 2.2.2. Hydrogen Enhanced Local Plasticity Model (HELP)

This system was first introduced in 1972 and is a generally acknowledged component. In this model, the gathering of hydrogen close to the break tip diminishes the protection from separation movement so the versatility of the disengagement increments and the separation carries on as a transporter for plastic disfigurement in the metal cross section. In any case, it was likewise discovered that there was no immediate connection between the arranged or proposed HELP model. Distinctive break modes can be noticed, for example, intergranular, transgranular, and semi gap, contingent upon the hydrogen focus, microstructure, and stress power at the break end [1–3].

#### 2.2.3. Adsorption-Induced Dislocation Emission (AIDE)

This part is essentially a hybrid of HEDE and HELP. In this component, the hydrogen particles of the solute adsorbed on a superficial level in the territory of stress fixation for the break end. The adsorbent of hydrogen only at the break tip debilitates the durable power of the holding or interatomic material by the HEDE. Staining and separation at the tip of the break happens because of outflow. Because of the synchronous development of breaks and breaks decohesion there is separation of outflow at the tip of the break. The enormous measure of hydrogen adsorbed on a superficial level was recognized in Ti, Fe, and Ni as proof to help the AIDE system [1,2].

#### 2.2.4. Hydrogen Enhanced Macroscopic Ductility (HEMP)

Hydrogen-enhanced macroscopic plasticity model is another name for this. Hydrogen also affects the mechanical properties of steel when it is accessible in huge amounts. The dissemination of hydrogen and mellowing of strong arrangements by hydrogen particles, can also be affected by the mass of the material and the whole example volume. It is additionally certain that, because of yield, there is an increment in pliancy because of plasticization over the whole length (volume) of the whole example. This yield is decreased by the impact of hydrogen, known as Hydrogen Enhanced Macroscopic Ductility (HEMP) [1,3].

#### 2.2.5. Hydrogen Changed Micro-Fracture Mode (HAM)

Hydrogen changes the miniature break method of the material, so the crack formed is changed from malleable to fragile. Hydrogen charge decreases the flexibility of the material and the crack mode at the last rigidity changes from cup and cone to fragile shear break mode. This change in miniature break mode because of the impact of hydrogen is called Hydrogen Changed Micro-Fracture (HAM) [1,2].

#### 2.2.6. Decohesive Hydrogen Fracture (DHF)

Basically, this is a brittle fracture initiated by the hydrogen effect and decohesion from the hydrogen, which causes the material or sample to fracture [1].

#### 2.2.7. Hydrogen Assisted Micro Void Coalescence (HDMC)

Micro-void coalescence (MVC) is essentially a flexible break system. MVC break spread happens in different stages, for example, zero nucleation, zero development, zero covalence, and extension of the break and burst of the current tendon by methods for shearing. Because of the hydrogen impact, nearby disengagement and plastic disfigurement developments happen in the material [1,2].

### *2.3. Hydrogen Charging Characteristic*

The charge of hydrogen assumes a significant part during test investigations of the hydrogen accessible in materials. By and large, the hydrogen charge of an example (material) is conveyed by an electrochemical charge (cathodic charge) or a high weight hydrogen charge. This filling procedure makes hydrogen diffuse in the material to debase the properties of the material and makes hydrogen embrittlement of the material. Now and then this hydrogen charge causes or results in a hydrogen trap in the material and the trap accumulates hydrogen molecules [1,3].

### *2.4. Techniques and Tools to Measure HE*

#### 2.4.1. Linearly Increasing Stress Test (LIST)

This is a mechanical test technique for determining the HE in a material. In that, two methods that are generally used to decide the impact of HE on materials are the consistent burden test and the second is the persistent extension test. Another strategy called CERT (Constant Expansion Rate Test) has been presented. This test is additionally called a moderate strain rate (SSRT) test. This is an unrealistic procedure [1,3].

#### 2.4.2. TDS

The most well-known technique in the investigation of HE and hydrogen induced dissatisfaction is temperature desorption spectroscopy (TDS), also known as temperature customized desorption (TCD). Diffusible hydrogen can be eligible and characterized using TDS. Traps are present in steel and are responsible for collecting hydrogen. Hydrogen consumes the thermal energy that is delivered when a significant volume of assimilated energy is delivered when steel is heated. The temperature at which hydrogen atoms are distributed in this manner is known as desorption temperature [1].

#### 2.4.3. Hydrogen Permeation Test

This transit test is likewise used to quantify diffusive hydrogen in steel and is the most straightforward estimation procedure. For the right execution of this transit test on steel, it is utilized related to other testing methods. This transit test consists of two cells, one from an input space (also referred to as a charge cell) and another with an oxidation space (also referred to as an oxidation cell) (output cell) [1,2].

#### 2.4.4. Microstructural Analysis

Microstructure examination assumes a significant job in evaluating the affectability of materials and alloys. Scan Analytical methods are broadly used to contemplate electron microscopy (SEM) and transmission electron microscopy (TEM). SEM is the least difficult to utilize, most adaptable, and most loved technique for this. TEM is the most remarkable and favored strategy. TEM works at higher amplifications and goals to defeat SEM challenges. TEM is fit for working at a large number of times of nanometric amplification. Crystallographic data is additionally gotten from this magnifying lens. The example should be under 100 nm [1,3].

#### 2.4.5. Hydrogen Microprint Technique (HMT)

This method is utilized to discover the way of diffusible Hydrogen in metals. In the event that this way is known, it is explicit that the microstructure of these pathways can be recognized and impacted hydrogen should be distinguished. This HMT procedure is basic and it is accessible with interesting and prevalent exactness and high goal. HMT strategies can be applied to various materials, for example, low carbon, high strength steel, austenitic preparations, and hardened steels [1].

## 3. Nondestructive Testing (NDT)

NDT is the most widely used method for internal defect identification and nondestructive inspection is a technique for evaluating structural stability for surface or internal defects, as well as metallurgical condition, without destroying the material or endangering its suitability for use. In many other terms, NDT refers to a method of measuring, testing, and examining products or parts in order to characterize or locate faults and flaws in contrast to other criteria while maintaining the original qualities and causing no damage to the product being examined. NDT procedures make a cost-effective way of testing a specimen for specific investigation and possible analysis, or they may be used to verify the whole sample in a manufacturing quality management system. In certain cases, detecting a defect generally requires use of more than one NDT test method. It may be appropriate to use a variety of strategies as well as experimental, destructive openings [5].

### *3.1. Non-Destructive Testing Methods*

There are several NDT methods available. These techniques may be used to detect holes, inner defects, surface cavities, hydrogen embrittlement, imperfect faulty welds, and whatever other fault that may lead to premature breakdown of plastics, metals, ceramic materials, composite materials, porous materials, and coatings [5].

#### 3.1.1. Visual Inspection

The demonstration of collecting visual information about the state of a substance is known as visual inspection. Visual inspection is the best tool for investigating objects or articles without making any modifications. Visual inspection may be performed with the use of a magnifying glass, with overseers examining any object or property from the outside. A Remote Visual Inspection (RVI) tool, such as a camera, may also be used to perform visual examination [5,6].

#### 3.1.2. Ultrasonic Testing

The method of transmitting high-frequency sound waves through a material to detect changes in its properties is known as ultrasound testing. The principle of operation of an ultrasound test is similar to echo sound in some cases. In general, ultrasound tests utilize sound waves to identify deformities or flaws in the outside of the subsequent material. Perhaps the most widely recognized ultrasonic test techniques are beat reverberation. With this strategy, the administrator embeds sound into the material and measures the echoes (or sound reflections) created by defects on the outside of the material as they re-visit the collector [5,6].

#### 3.1.3. Radiography

Radiography is the demonstration of utilizing X radiation or gamma on a material to recognize abandons in non-damaging testing. The radiographic test coordinates radiation from a radioactive isotope or X-beam generator through the test material and onto a film or other kind of indicator. The identifier readings structure a picture chart, which uncovers the basic parts of the investigation material [5,6].

#### 3.1.4. Eddy Current Testing

Eddy current test is a type of electromagnetic test that measures the strength of an electric current (also called eddy current) in a magnetic field around a substance to determine the extent to which the material is damaged. The supervisor tests the movement of eddy currents in the magnetic field around the conductive material to detect blockages caused by defects or imperfections in the material during the eddy current test [5,6].

#### 3.1.5. Magnetic Particle Inspection

Magnetic particle testing is the process of detecting defects in a material by looking for disruptions in the movement of magnetic fields within it. This method uses a magnetic field and small magnetic particles, such as iron dust to detect damage to components. The only requirement from the point of view of inspection capability is the components checks should be made on ferromagnetic materials such as iron, nickel, cobalt or some of their alloys, because these are materials that can be magnetized to a level that allows inspection [5,6].

#### 3.1.6. Acoustic Emission Testing

Acoustic emissions non-destructive testing is the act of using acoustic emissions to detect possible flaws and shortcomings in a substance is known as non-destructive testing. Investigators looking at acoustic emission samples look for blasts of acoustic radiation, also known as acoustic emissions, which are induced by material failures [5,6].

#### 3.1.7. Liquid Penetrate Testing

This technique is based on the ability to draw liquid to a "clean" surface. Defects are solved with capillary action. Usually materials that use DPT or LPI include metal (aluminum, steel, titanium, copper, etc.), glass, many materials ceramics, rubber, plastics [5,6].

## 4. Literature Survey

**Bae et al., (2014)** Using acoustic emission (AE) a non-destructive methods, investigate the results of different hydrogen charging concentrations in austenitic stainless steel for designed to allow improvements in periods of 2, 4, 10, and 24 h. The effect of hydrogen charging concentrations was investigated using 18cr-8ni stainless steel (AISI 304) in this analysis. The discovery exposes a dimple type ductile fracture mode with a large number of quasi-cleavage type brittle fracture mode, as well as several micro and macro fractures. This research discovered a number of AE occurrences in the elastic zone, such as hydrogen free specimens, but not so many in the plastic zone [7].

**Capriotti et al., (2000)** XRD residual stress identification procedure, mechanical experiments, and microscopy were used to validate the hydrogen embrittlement detection capability. In this research, AISI 4130 steel was used, and hydrogen embrittlement of high strength was observed after the electroplating and pickling processes. The discoveries show that XRD strategy can successfully be utilized as fundamental NDT test to check pressure varieties of airplane high strength steel segments which are associated with hydrogen embrittlement [8].

**Yashar Javadi et al., (2020)** The effect of welding residual stress (WRS) on the shape and size of hydrogen-induced cracks (HIC) in S275 structural steel plates was investigated using a water quenching method used for hydrogen crack manufacturing in a predetermined location, phased array ultrasonic testing (PAUT) used during the welding process, and a high temperature in-process method used to detect hydrogen induced cracks (HIC) in real time (WRS). This research examines the impact of residual stress on hydrogen cracking in multi pass-robotic welding using four samples with thicknesses of 15 mm and lengths of 300 mm. The finding shows the no. of large cracks deposition of filling process from (PAUT, inspection and welding camera) process. Residual stress measurement using the hole drilling methods gives the difference of 78 MPa measured in transverse direction [9].

**Motomichi Koyama et al., (2011)** observed hydrogen embrittlement in Fe-18Mn-1.2C (wt.%) austenitic steel, then tensile drastically reduced by hydrogen charged using tensile testing method. In this way, rigidity and malleability were both diminished by hydrogen charging (about 20% decreased strength and about 40% diminished pliability). In discovering two kinds of breaks intergranual and transgranular cracks are noticed in particular along twin limits. The present outcomes propose significant elements in hydrogen embrittlement of Fe-Mn-C austenitic steel, which are decrease of union energy grain limits and twin limits and the pressure fixation brought about by disfigurement twins. The breaks were started from twin limits in light of the fact that twinning is basically needed to accomplish the prevalent mechanical properties of TWIP steel [10].

**Haiting Zhou et al., (2020)** studied non destructive testing (NDT) to evaluate mechanical performance based on eddy current signals analysis. The low alloy (S500MC) steel was tested under tensile condition with the aim of qualifying hydrogen embrittlement (HE). An electrochemical hydrogen charging experiment and tensile test was conducted to study the hydrogen embrittlement assessment. The findings are that hydrogen content low alloy steel increases with increasing hydrogen charging time and then reaches the saturation level after 40 h. This suggests that increasing the hydrogen charging time will reduce the tensile elongation of sample [11].

**Dmitry. L. Merson et al., (2008)** studied the obvious difficulties of hydrogen embrittlement in steel that is used in gas and oil producing industries. They used an NDT method named acoustic emission spectral analysis method. In this study corrosion resistant pipe steel (13HFA) was chosen. AE appears to be sensitive to hydrogen damage during first 10 h of immersion in $H_2S$ solution. This is commonly obtained during standard testing, noticeably only after about 300 h holding the same solution [12].

**D. X. Yang et al., (2001)** magnetic-based nondestructive evaluation (NDE) and ultra low carbon (ULC) steel was studied, to correlate the magnetic and mechanical properties and to examine the development of barkhausen effect and measurement of hysteresis loop in the sample. The NDE test equipment can detect minor variations in the stress strain curve that appear below the 0.2 offset strain. Jumpsum and jumpsum rate, as well as deferential absorption, are carefully variable with minor defects well below the 0.2 offset strain in extremely low carbon steel, according to the results of this report [13].

**Shejun Xie et al., (2014)** observed the type of micro damage in structure developed during manufacturing process in plastic deformation in austenitic stainless steel using the NDT method namely eddy current testing. In this study 9 test pieces of AISI304 austenitic stainless steel are used. The thickness adjustment of specimens may not give massive impact on the pulsed ECT signals, and subsequently, the analysis of the ductile fracture. Furthermore, the influence of electromagnetic physical properties on plastic deformation has been investigated using numerical analysis, with the findings revealing a reduction in electrical conductivity and an improvement in magnetic flux density as the plastic strain increases [14].

**Jinyi Lee et al., (2008)** showed an efficient non-destructive testing tool (NDT) for detecting surface cracks in magnetized ferromagnetic materials using magnetic flux leakage test (MFLT), which tests the spread of a magnetic field over a magnetized specimen using a magnetic sensor such as a Hall sensor. In this article, we have proposed 64 Inba LIHaS with Ni-Zern ferrite wafers with spacers 0.52 mm resolution for reduced height differences and protectors of each sensor on the PCB. Cracks were detected by using two processed image, the smallest cracks detected was a hole type with radius 0.25 mm and depth 0.4 mm [15].

**Takayuki Shiraiwa et al., (2020)** measured the hydrogen-induced cracking activity of high strength steel using the acoustic emission (AE) technique as well as the finite element process (FEM) in the slow strain rate tensile (SSRT) test as well as the welding test. In this study HT980 high tensile strength steel was used. The onset of crack was detected by the time evaluation of AE signals, and stress concentration and hydrogen diffusion was calculated by FEM. In SSRT test, AE signals were detected due to crack introduced. The initial crack stress estimated from AE signals decreases as the hydrogen content increases from the initial deviation. Hydrogen diffusion coefficient and solubility of hydrogen are determined by Vickers hardness and equivalent plastic distribution of plastic deformation in FEM [16].

**AV Bochkaryova et al., (2015)** studied the effect of hydrogen embrittlement on mechanical properties of aluminum alloy. In this aluminum alloy duralumin (D1) alloy is used as sample. It is found that the mechanical properties of aluminum alloy are negatively affected by hydrogen embrittlement. Hydrogenated alloy has lower degree of ductility with respect to the original alloy; however, the behavior of plastic flow in material has practically not changed. Micro hardness test is carried out for treatment of D1 alloy [17].

**Xingle Chen et al., (2015)** evaluated the electrical conductivity measurement of ferromagnetic metallic materials by using pulsed eddy current testing (PECT) method. In this a ferromagnetic metallic plate is used as sample. It resolved the least squares problems between the estimated and tested induced voltage values. The findings of electrical conductivity tests for three carbon steel plates were compared using the DCPO method and the four-point PECT method for calculating electrical conductivity verification of ferromagnetic metal plates [18].

**Meisam Sheikh et al., (2009)**. In this article the discontinuities of materials were studied. A standard carburizing low-carbon low-alloy steel (AISI4118) and eddy current technique/method were used to detect discontinuities, physical and metallurgical properties of steel. In this article, the relationship between surface carbon content and various parameters like impedance, phase angle and voltage were established. In this study the findings showed that any measured or calculated parameter has a good relationship with surface content [19].

**K. Beyer et al., (2011)** this study showed the feasibility of measuring hydrogen effusion in austenitic stainless steel (1.4301) using neutron radiography NDT method. This method is suitable to measure hydrogen effusion of concentration as small as 20 $PPM_H$. In this study temperature is between room temperature to 533 k. Neutron radiography is the suitable method to study the hydrogen effusion behavior in austenitic stainless steel. The findings of the study was that increase in temperature increases hydrogen flow [20].

## 5. Summary of Literature Survey

Table 1 represents the summary of literature survey.

**Table 1.** Summary of literature survey.

| S.No. | Author Name (Year) | Remarks/Findings |
|---|---|---|
| 1 | Bae et al., (2014) | It depicts the dimple type ductile fracture mode in conjunction with the sum of quasi-cleavage type brittle fracture mode. |
| 2 | Capriotti ed al. (2000) | It reveals that the XRD technique is being used as a basic NDT test to determine residual stress differences in aircraft high strength steel components. |
| 3 | Yashar javadi et al.(2020) | The micrograph and microscopic investigation shows very large no. of cracks have been measured from water quenched process and large number of cracks was subsequently detected. |
| 4 | Motomichi koyama et al., (2011) | Two types of cracks are observed namely intergranual fracture and transgranular fracture along twin boundaries. |
| 5 | Haiting Zhou et al., (2020) | The finding is that hydrogen content low alloy steel increases with increasing hydrogen charging time and then reaches the saturation level after 40 h. |
| 6 | Dmitry. L. Merson et al., (2008) | AE appears too sensitive in hydrogen damage during first 10 h of immersion in $H_2S$ solution. Noticeably only after about 300 h holding the same solution. |
| 7 | D. X. Yang et al., (2001) | The results extracted three properties from the study, which are jumpsum and jumpsum rate and deferential permeability. They vary in sensitivity with small deformations well below the 0.2 offset strains in ultra low carbon steel. |
| 8 | Shejun xie et al., (2014) | With increasing plastic pressure, the findings indicate a decrease in electrical conductivity and an improvement in magnetic permeability. |
| 9 | Takayuki shiraiwa et al., (2020) | Two processed images were used to locate cracks; the smallest crack found was a hole form with a radius of 0.25 mm and a depth of 0.4 mm. |
| 10 | Takayuki shiraiwa et al., (2020) | The initial crack estimated from AE signals decreases as the hydrogen content increases from the initial deviation. |
| 11 | AV Bochkaryova et al., (2015) | Hydrogenated alloy has lower degree of ductility with respect to the original alloy; however, the behavior of plastic flow in material has practically not changed. |
| 12 | Xingle Chen et al., (2015) | The Pulsed eddy current testing conductivity measuring approach is highly useful for sorting ferromagnetic materials. |
| 13 | Meisam Sheikh et al., (2009) | They established the relationship between surface carbon content and impedance, phase angle. The carbon content of surface increases with decreased the calculated and measurement parameters. |
| 14 | K.Beyer et al., (2011) | The finding of this study is that increase in temperature increases hydrogen flow. |

## 6. Evaluation of Hydrogen Embrittlement through NDT

A nondestructive method named ultrasonic testing was used to study and analyze the mechanical properties of hydrogen-charged stainless steel. The velocity and magnitude of ultrasound waves for hydrogen charged specimens was measured. Those measured values were compared with the tensile strength according to hydrogen charging concentrations. To remove the impact of couplant, an ultrasonic test was conducted in water with a 10 MHz sensor. Using an electronic oscilloscope, the velocity was determined by measuring the thickness (t) of the sample and the propagating time (T) of the ultrasound waves through the sample. It represents the variations in ultrasonic wave velocity as a function of hydrogen charging time. Given material brittleness induced by hydrogen charging, the waves propagating velocities remained stable at around 5800 m/s. The shear wave, which was about 3200 m/s in both specimens, was very similar to the longitudinal wave. It was obvious that the velocity of the ultrasound waves was not a good criterion for determining the degree of embrittlement caused by hydrogen charged in stainless steel. Due to the ultrasonic testing methods evaluating that the attenuation coefficient and tensile strength have a similar relationship, we will be able to measure the difference in tensile strength by calculating the attenuation coefficient of ultrasound waves. The attenuation coefficient of hydrogen charge sample was increased compared to uncharged sample, due to brittleness induced by hydrogen charging [1]. The acoustic emission event generated at hydrogen charged samples for 12 and 24 h was completely different from the acoustic emission event generated at hydrogen free samples. That is, several acoustic emission events occurred in the elastic region, such as in the hydrogen free sample, but few occurred in the plastic zone [7,16].

## 7. Conclusions

Hydrogen embrittlement is a very serious problem in automotive and hydrogen transportation industries as they are using a high strength material. This paper is a critical review of various NDT methods and HE mechanism, investigating how these NDT methods can be used for defect analysis in hydrogen related research. With the help of NDT, internal defects or irregularities are known and prevention activities are taken care before the final failure of a material. Ultrasonic testing is very useful for determining internal defects in material. Sometimes one NDT method is not sufficient to give accurate results, in this case two or more NDT methods are used for accurate defect analysis of a material and then prevention activities will be implemented to increase the availability and reliability of machine or critical components.

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