Hydrogen Induced Cracking Analysis of a Pressure Vessel Made of SA 516 Grade 70 Steel by the Use of Phased Array Technology

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1. Abstract

Information regarding type, size, shape and location of the defects in objects can be obtained easily by the new generation of ultrasonic instruments which use Phased Array technology. This investigation studies the results of ultrasonic test with Phased Array technology done on a storage vessel and matches them with environmental conditions like corrosion to detect the type of the defects with 100% certainty. Inspections show that the detected cracks in the shell metal are originally formed by hydrogen induced cracking and calculations show that these cracks will not grow up if the hydrogen diffusion through the metal is stopped. Therefore, it is predicted that the operation of the pressure vessel in normal condition and under regular supervision can be continued if a suitable coating is applied to the interior of the vessel to prevent hydrogen diffusion.

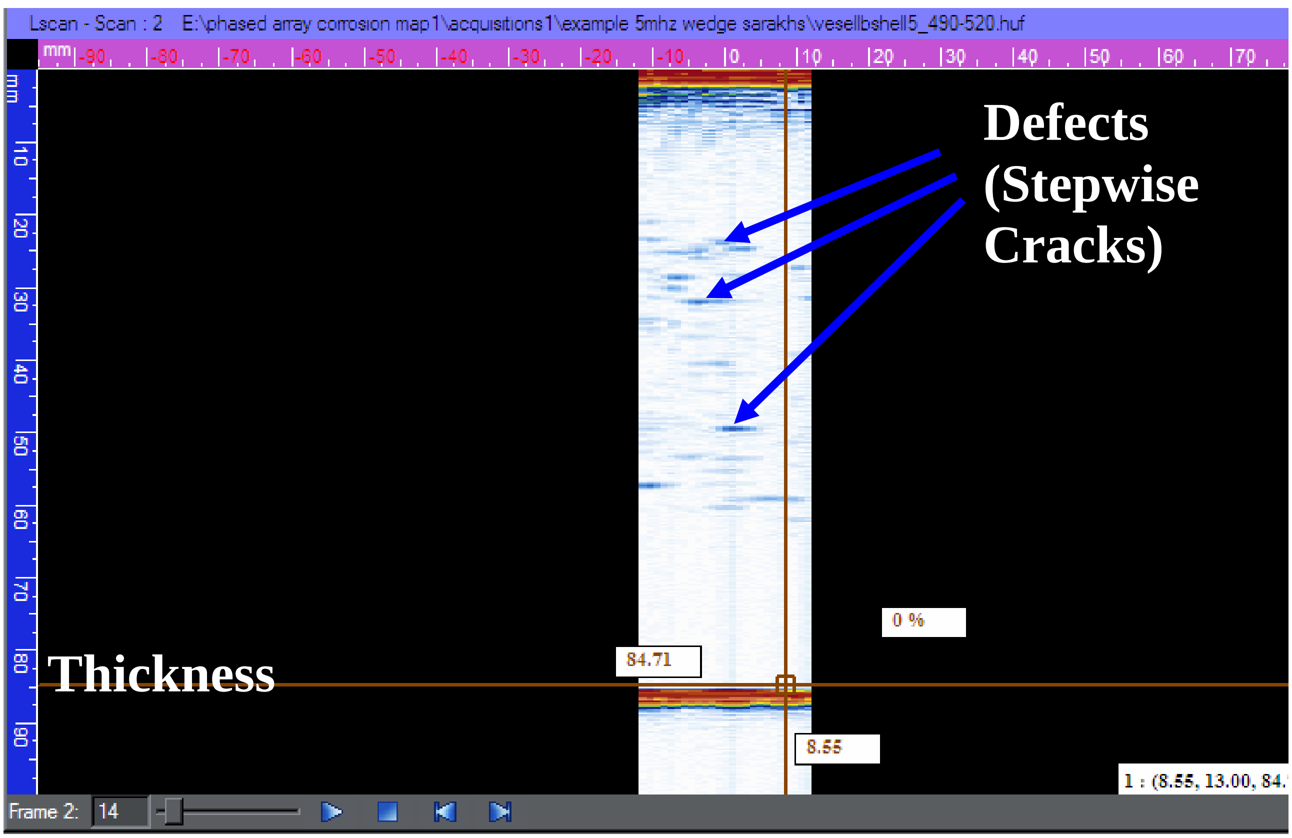
2. Conditions of Storage Vessel

The storage vessel is a horizontal pressure vessel which had been in service for more than 30 years. Sour water and condensate after separation from gas enter the vessel from top. These two substances will separate from each other in the vessel and water will drain from the bottom. Results of the ultrasonic test with Phased Array technology which is done on the external surface of the vessel shows many defects in the bottom of storage vessel which have been observed up to 24 mm from the external surface. Figure 1 shows these defects. The defects are at the bottom of the vessel and at the top which is not in continuous contact with sour water no defect is observed. This shows that these defects are related to the presence of sour water at the bottom portion of the vessel which is in continuous contact with sour water. These defects resemble hydrogen induced cracking since they are stepwise, narrow and elongated cracks. How ever the environmental conditions should be checked. Table (1) shows a brief description of the vessel.

Table 1: Description of The pressure vessel

Material	SA 516 Grade70
Outer Radius	994 mm
Inner Radius	915 mm
Minimum Wall Thickness	79 mm
Working Pressure	9.93 MPa
Working Temperature	60 °C
Yield Point	262 MPa

Figure1: Linear Scan from Ultrasonic Test on the Storage Vessel with Phased Array Technology Showing Stepwise Cracks.



3. Checking Environmental Conditions and Material Microstructure for Hydrogen Induced Cracking

There is a type of hydrogen damage called “Hydrogen Damage Due to Wet H_2S (Sour Service)”.

Three factors are necessary for this type of damage to occur [1]:

1. A corrosion reaction that generates hydrogen atoms.
2. A chemical environment to enhance atomic hydrogen absorption into the steel (commonly sulfides).
3. A susceptible microstructure.

Investigations show that all of the above 3 factors are satisfied as follows for this pressure vessel. For this type of corrosion to occur the H_2S concentration of the environment should be greater than 50 ppm. Chemical analysis of the sour water which is taken from the bottom of the pressure vessel shows that the concentration of the dissolved H_2S in liquid phase is 14.5% (wt%) which is much more greater then 50 ppm. Hydrogen damage in wet H_2S services is caused by the generation of atomic hydrogen as a byproduct of the corrosion reaction, and the subsequent diffusion of that atomic hydrogen into the steel. Atomic hydrogen is produced in many corrosive environments as in Equation (1):

$$Fe + 2H^{+} \rightarrow Fe^{++} + 2H^{\circ} \quad (1)$$

Then two atoms subsequently combine to form a molecule of hydrogen gas as Equation (2):

$$2H^{\circ} \rightarrow H_2 \quad (2)$$

However, certain compounds such as sulfide, cyanides (e.g. HCN), and arsenates, called recombination poisons or catalyst poisons, retard the conversion of atomic hydrogen to molecular hydrogen. In the presence of a catalyst poison, the surface concentration of atomic hydrogen rises, and a corresponding increase occurs in the amount of hydrogen diffusing into the metal.

In this vessel the concentration of H_2S as the recombination poison as previously said is much greater than 50 ppm and since the vessel had been in service for more than 30 years then there was enough time for the diffusion of hydrogen. This elevated concentration of atomic hydrogen can affect the steel in several ways:

1. At laminations or inclusions, the hydrogen atoms may recombine to form molecular hydrogen; which is then too large to diffuse further through the steel and is trapped. If laminations are large enough, the internal hydrogen pressure may become sufficient to cause distortion and formation of a bulge on the surface (blistering).
2. The high concentration of atomic hydrogen can result directly in embrittlement and cracking of the steel, particularly high strength or high hardness steels. This often includes the heat affected zones in low strength steels that have not been PWHT (SSC).

3. A combination of the two effects may occur, wherein laminations on parallel planes are linked by cracks in the through-thickness direction (HIC).

Some powder samples were taken from different parts of the pressure vessel, by grinding to evaluate the chemical analysis. Chemical composition of the vessel is analysed by atomic absorption method and the results are shown in Table (2).

Table 2: Chemical Analysis of the Vessel (wt%)

Element	%C	%Si	%Mn	%P	%S	%Cr,Ni,Mo,V
wt%	0.20	0.30	1.10	0.025	0.037	0

This table shows that there are two elements as manganese and sulphur in this alloy which form MnS during casting in steels. MnS in this alloy resides at grain boundaries. Atomic hydrogen after diffusion to the metal lattice resides at MnS. There, any two hydrogen atoms combine to form molecular hydrogen and will be trapped there [2]. Hydrogen Induced Cracking (HIC) which is produced due to internal hydrogen pressure in metallurgical defects has happened in this storage vessel. These cracks are elongated and narrow and this is the thing observed in Linear Scan of the vessel. In Figure (2) samples of HIC are shown to compare with Figures (1) and (3) which are Linear Scan view of the cracks observed in the vessel. Compare show that cracks in Figures (1) and (3) are similar to HIC cracks and are stepwise.

Figure 2: Samples of HIC in Steel

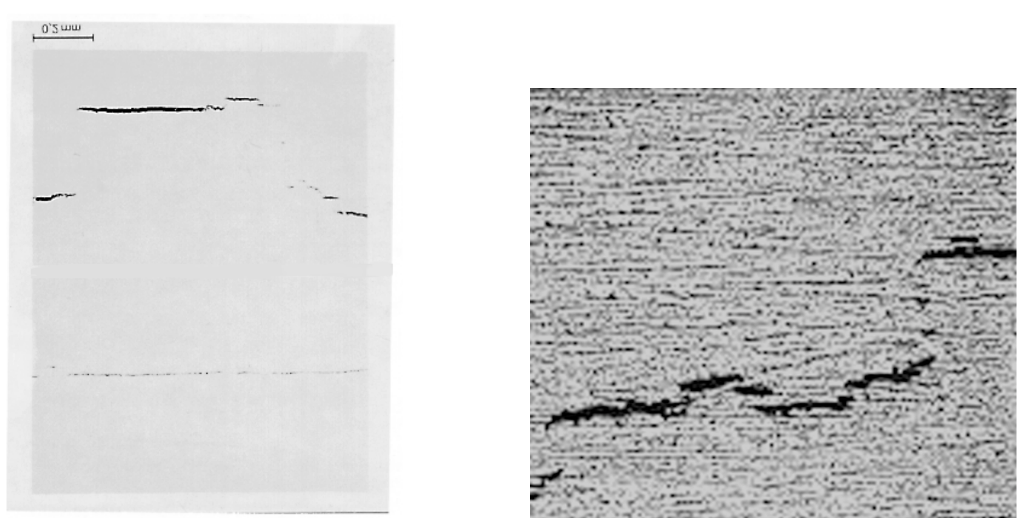
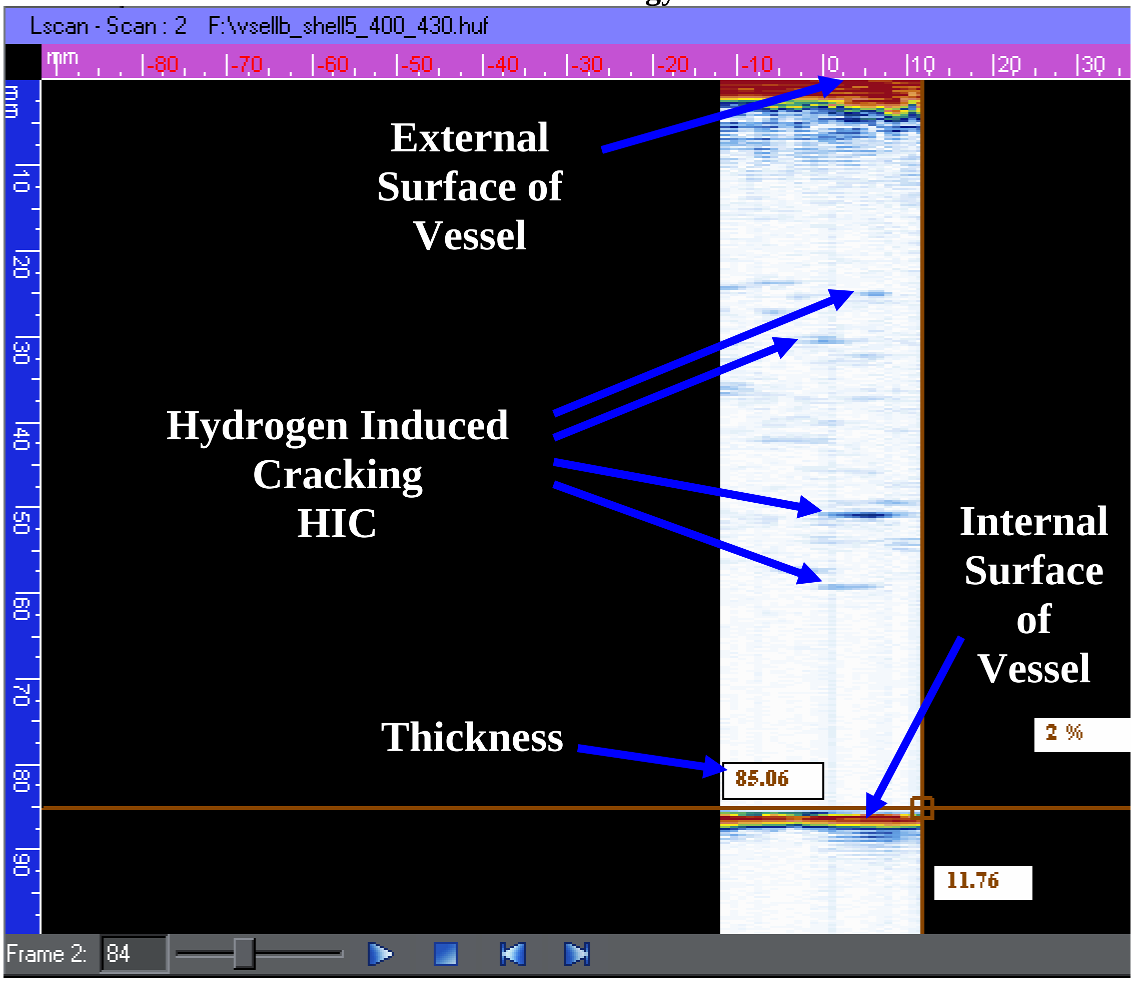
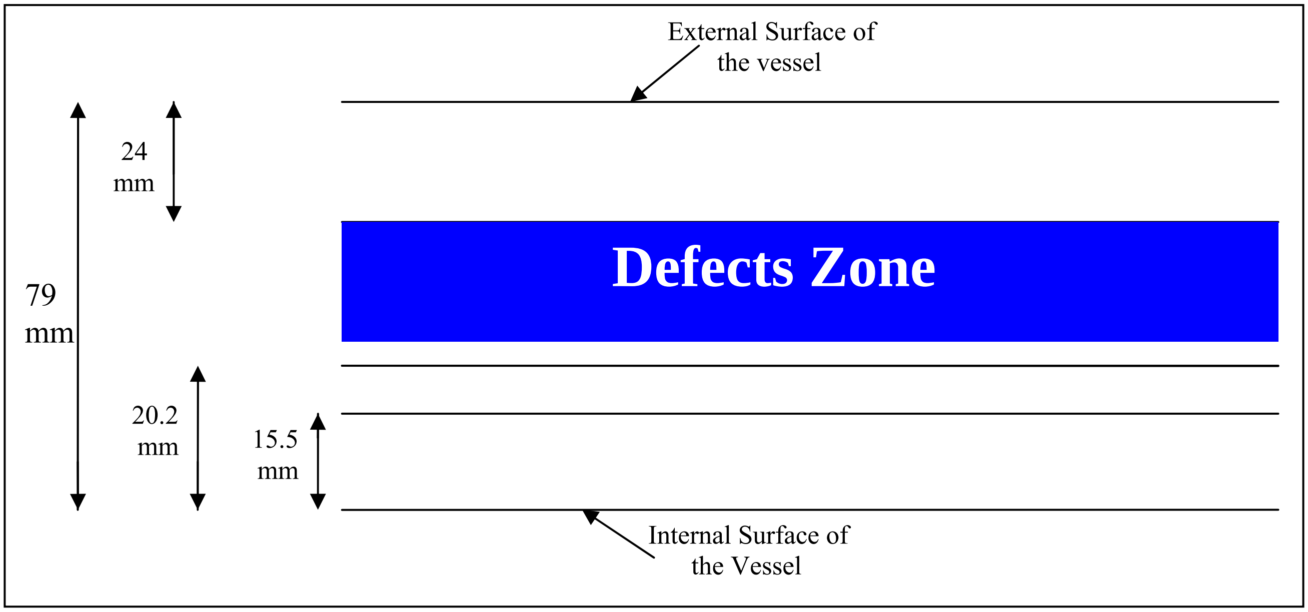


Figure 3: Actual Picture of HIC in the Pressure Vessel Using Phased Array Technology.



By analogy Figure (3) shows that cracks are stepwise like figure (2). By increasing size and frequency of the cracks the possibility of forming HIC or stepwise cracks increases. This goes on by continuing hydrogen diffusion and finally causes failure of the shell. There fore hydrogen diffusion must be stopped. These HICs do not lie in the zone of minimum thickness. Except some limited points which are not connected. So according to standard API 510 [3] these cracks are within the safe region. Also another 24 mm layer exists which increases pressure retaining ability of the material. Figure (4) shows limited zone of the observed defects in the shell of the vessel in blue. This figure is based on the results of ultrasonic test with phased array technology.

Figure 4: The Limited Zone of Detected Defects



Hydrogen damage is mentioned as one of the deterioration modes which commonly occurs in pressure vessels in standard API 510 [3].

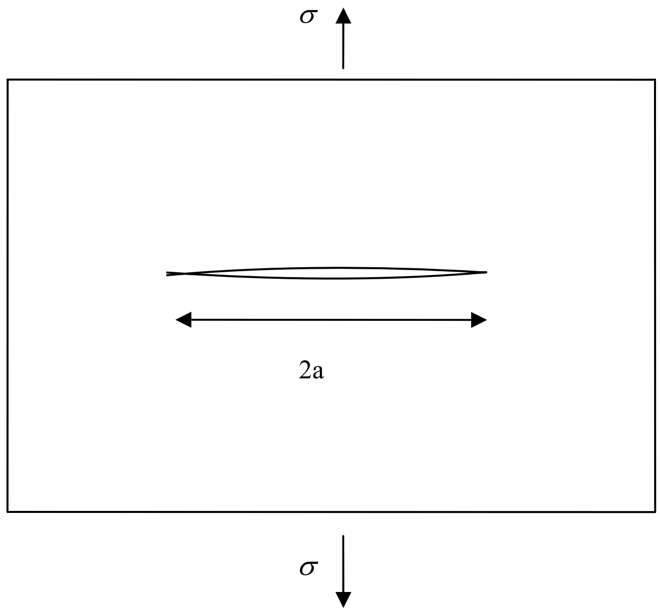
4. Is It Safe To Operate Under Normal Conditions If Hydrogen Diffusion Is Stopped?

To answer this question we use fracture mechanics. In fracture mechanics a crack will result in failure when stress intensity factor becomes greater than fracture toughness (K_{1C}) of the material [4]. Equation (3) gives stress intensity factor for the crack of Figure (5) [5]. Figure (5) shows the parameters of this equation.

$$K = \sigma\sqrt{\pi a} \qquad (3)$$

K = Stress Intensity Factor, MPa$\sqrt{m}$
σ = Applied Stress, MPa
a = Crack Size, m

Figure 5: Fracture Parameters



We obtained the length of the longest crack to be 20 mm (2a =20mm). Based on the shape and position of the detected crack, the hoop stress is the most important component of the applied stress which can develop the crack. This stress can be calculated by the following Equation (4).

$$\sigma = \frac{p}{K_1^{\,2}-1}\left(1+\frac{r_o^{\,2}}{r_i^{\,2}}\right),\ K_1 = \frac{r_o}{r_i} \qquad (4)$$

Where σ is the hoop stress, P is the internal pressure; r_o and r_i are outside and inside radii respectively. So

$K_1 = 1.09$, $\sigma = \frac{9.93}{1.09^2-1}\left(1+\frac{994^2}{915^2}\right) = 114$ MPa.

There fore from equation 5 we have:

$K = 114\sqrt{\pi \times 0.01} = 20\ \text{MPa}\sqrt{m}$

Fracture toughness (K_{1C}) is a property of the material and is specific to each material. The value of fracture toughness for the steel applied in the storage vessel is equal to 78.2 MPa$\sqrt{m}$ [7]. Comparing the value of K_{1C} with K shows that K is lower than K_{1C}. Therefore the crack would not grow under normal operating conditions supposed that hydrogen diffusion is stopped. The reason why these cracks happened is the existence of hydrogen and corrosive environment which reduces K_{1C}.

5. Conclusion and Remedial Actions

In possible methods for control of hydrogen damage, if corrosion of steel is stopped, no hydrogen atom will produce. There fore hydrogen will not diffuse in to the metal and the cracks will not extend and will not link together. The best way to prevent hydrogen damage in this case is the use of nonmetallic coatings which are highly applicable, cheap and easy to install. Other methods such as coating with cladding and thermal spray are not advised. Since the pressure vessel has been built and it is impossible for cladding to be done on the internal surface and thermal spray is not good because it is very difficult to bring the necessary equipments inside the pressure vessel. After applying a suitable coating under regular supervision the pressure vessel can operate in normal operating condition.

6. Acknowledgements

The authors thank Engineer M. R. Naghibi the president of East Oil and Gas Production Company for making this research effort possible and Engineer J. Mostowfi for his technical support.

7. References

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