Identification Corrosion Hydrogen Attack on Carbon Steel Using Magnetic Particle Inspection (MPI)

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Abstract. Damage mechanism on carbon steel pipeline due to hydrogen attack (HA) in refinery was identified using magnetic particle inspection (MPI). Visual inspection at external do not reveals any failure which may cause catastrophic accidents. Non-destructive evaluation (NDE) using MPI reveals some fissuring contribute to cracks penetrate from internal to the surface of pipeline caused the leak to propagate. MPI technique also may detect closely up to 20mm of crack length and proven can be one of the best NDE to identify corrosion attack in high temperature process. The findings also revealed HA not only affected at welded area, but also on base metal. Visual observation was continued with microscopic analysis reveals fissuring crack initiate from intergranular corrosion. Mechanical properties analysed using hardness test revealed that, the steel toughness cannot be rely as a guideline to assume pipeline integrity even though decreasing the amount of carbon at elevated process temperature due to HA reactions. The conclusion is, MPI technique can be relied as one of the NDE tools to identify corrosion failure due to HA.

Keywords : Corrosion, hydrogen attack, magnetic particle inspection, non destructive evaluation

1. Introduction
At elevated temperatures with high hydrogen partial pressure in refinery equipment, carbon steel potentially exposed to degradation of metal over time due to decarburization process known as hydrogen attack (HA) [1-3]. When this steel used at elevated high temperature, hydrogen may diffusing into the steel and react with carbon from metal carbides to form methane gas (CH₄). The methane gaseous cannot escape from the steel and cause fissures further to crack. The formation of methane bubbles at grain boundaries and the decarburization of the steel reduce the toughness of the material without any measurable reduction in thickness [2]. Decarburization is one of corrosion attack as the diffused hydrogen react with the carbide to produce methane gasses. As the role of carbon is provide a toughness to the steel, reduction of carbon due to reaction in carbide form, may contribute to loss of steel toughness in elevated temperature. The attack more severe in high temperature especially at 243°C and higher with high hydrogen partial pressure [4-8].

MPI using simple concept of magnetic field around with magnet by applying a fine ferromagnetic powder over flaws and formed a visible indication. Once the cracks identified, further inspection was
performed to the expose microstructure details contribute to cracks. Quick, simple, shows surface and near surface defects, low cost and mobile are among the advantages of MPI technique. However, this technique only restricted to magnetised and ferromagnetic materials.

2. Experimental Method
Magnetic particle inspection (MPI) starts with cleaning all the contaminants, debris and corrosion product. Then the sample was spray with magnetic particle to induce a magnetic field in the sample (Fig. 2) according to ASTM E709-15: Standard guide for magnetic particle testing. The powder containing fine particles were attracted by the presence of discontinuity in a magnetic field. Then visual inspection done to detect and classified size of indication.

3. Result and Discussion
3.1 Visual Inspection
Surface analysis starts with visual inspection for visible cracks and defects at external flaws. Prior to visual inspection, as received tee-spool was cleaned with brush to remove debris and corrosion products to reveal any cracks or flaws on base metal.

Figure 1. Visual inspection on external surface reveals no crack and flaws. Top: front and back view, bottom: top and bottom of pipe tee-spool.

Figure 2. Cut-off tee-spool was sprayed with magnetic particle for further visual inspection
Fig. 1 shown different views of the tee-spool. To secure any corrosion defects at elbow angle, the tee-spool was cut cross section as shown in Fig. 1 with red dotted line. Cut-off sample was proceed for magnetic particle inspection as shown in Fig. 2.

3.2 Magnetic Particle Inspection
MPI is applied to detect defects at or near surface of objects made from ferromagnetic or magnetic materials. The principle of MPI is considered as combination of two non-destructive testing methods which are magnetic flux leakage testing and visual testing. Any place that a magnetic line of force exits or enters the magnetic line of force exits or enters the magnet is called a pole [6-9]. A pole where a magnetic line of force exits the magnet is called a north pole and a pole where a line of force enters the magnet is called a south pole. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack [10]. The magnetic field exits the North Pole and enters at the South Pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field [11].

Visual inspection on cleaned surface reveals several cracks that has already propagated as shown in Fig. 3. The crack morphologies found in both metallographic sections revealed similar features, initiated at the internal surface and propagated in a relatively jagged (Fig 4). Fig.3 reveals that with MPI technique, crack length can be detected close to 20mm and proven can be one of the best NDE to identify corrosion attack in high temperature process such as refinery assets.

![Figure 3. MPI reveal a clear cracks propagation](image)

3.3 Microscopy Analysis
The selected sections were mounted, ground, polished and etched in accordance with ASTM E3-11 and ASTM E407-07e1 to reveal the microscopic features and microstructures. The area near the external surface appeared not decarburized but had numerous intergranular fissures. Since the methane molecule is much larger than the hydrogen atom, and too large to diffuse out of the matrix, this leads to very high internal pressure. Bubbles form that over time, coalesce and lead to macroscopic fissuring, loss of strength, ductility, and toughness.
Figure 4. Visual inspection using MPI reveals crack propagate at internal elbow off tee-spool.

Metal dusting is another form of decarburization resulting in accelerated localized pitting which form on the surface and may contain soot or graphite dust. Yellow circle in Fig. 5 showing pearlite carbide (dark layered phases) and ferrite phase (light grains). Decarburization cause pearlite phases decomposed due to removal of carbon atoms by diffusion to the surface [3]. The crack morphologies found in both metallographic sections revealed similar features. Figure 5 (c) shown the crack severely attacked at internal and almost stopped at area close to external. We can concluded that, the crack was initiated at the internal surface and propagated in a relatively jagged and intergranular manner along the grain boundaries (Fig. 6), towards the external surface.

Figure 5. Optical microscopy reveals about 0.20% carbon content in magnification 500X. (a) Internal, (b) External
The internal surface was decarburized with numerous intergranular fissures, found at areas adjacent to and away from the main crack (Fig. 5). The extent of decarburization diminished with increasing distance away from the internal surface. However, numerous intergranular fissures were generally observed throughout the section examined. The internal surface was decarburized with numerous intergranular fissures, found at areas adjacent to and away from the main crack.

3.4 Microscopy using scanning electron microscopy (SEM)
Visual inspection with naked eyes, proceed with optical microscopy microstructure As shown in Fig. 5, the cracking image was identified at 500X magnification the condition of the smooth area between the structure confirmed that the cracking types is intergranular corrosion attack analysis using scanning electron microscope (SEM) Hitachi SU-1510 Compact Scanning Electron Microscope (SEM) and reveals that crack propagated at grain boundaries caused the intergranular corrosion and decarburization as shown in Fig. 6. The crack area cleft split and observed using SEM for further identify of intergranular corrosion. Fig. 7 reveals groovy surface in solid metal reveals intergranular corrosion with some decarburization. The findings also revealed HA not only affected at welded area, but also on base metal.

![Figure 6. Groovy surface.](image6)

![Figure 7. Smooth microstructure reveals intergranular corrosion attack (red arrows).](image7)

3.5 Micro hardness measurement at failed area
As mentioned earlier, decarburization happen due to reaction of hydrogen with carbide producing methane gasses. Reducing carbon content contribute to mechanical decreases. Hardness measurement (Table 1) was performed at internal and external affected tee-spool and revealed that hardness reading has no significant effect to hardness. However, HA may potentially reduce in tensile and creep strength which do not measure in this research.
Table 1. Micro-hardness results

| Section         | Hv  | Std. dev. |
|-----------------|-----|-----------|
| External        |     |           |
| Along crack     | 120 | 4.04      |
| Base metal      | 135 | 3.96      |
| Internal        |     |           |
| Along crack     | 115 | 1.29      |
| Base metal      | 124 | 2.61      |

4. Conclusion
Damage mechanism on carbon steel pipeline due to hydrogen attack (HA) can be identified using magnetic particle inspection (MPI). Visual inspection at external do not reveals any failure which may cause catastrophic accidents however, internal reveals several cracks. Non-destructive evaluation (NDE) using MPI reveals some fissuring contribute to cracks penetrate from internal to the surface of pipeline caused the leak to propagate. MPI technique also may detect closely up to 20mm of crack length and proven can be one of the best NDE to identify corrosion attack in high temperature process. The findings also revealed HA not only affected at welded area, but also on base metal. Microscopic analysis reveals fissuring crack initiate from intergranular corrosion and hardness test revealed that, the steel toughness cannot be rely as a guideline to assume pipeline integrity even though decreasing the amount of carbon at elevated process temperature due to HA reactions. The conclusion is, MPI technique can be relied as one of the NDE tools to identify corrosion failure due to HA

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References
[1] American Petroleum Institute (API RP 571). 2011. Damage Mechanisms Affecting Fixed Equipment in the Refining Industry, 2nd Edition pp 32-168
[2] Abdullah, M.O., Zen, J. and Yusof, M. 2011. Stress Corrosion Cracking, Crack Growth Prediction, and Risk-Based Inspection of Industrial Refrigerated Ammonia Tanks. Corrosion 67(4) pp 1-12.
[3] Bouaeshi, W., Ironside, S. and Eadie, R. 2007. Research and Cracking Implications from an Assessment of Two Variants of Near-Neutral pH Crack Colonies in Liquid Pipelines. Corrosion 63(7) pp 648-660
[4] Thomas, V. Itw, T. 2008. Application of Magnetic Particle Inspection in the Field of the Automotive Industry. pp 1-10
[5] Wei-Chang, Z. 2008. The Magnetic Dipole Theory for Non-Destructive Testing. 17th World Conference on Nondestructive Testing. pp 1-9.
[6] Mukherjee, R. 2004. Practical Thermal Design of Shell- and- Tube Heat Exchangers. Series in Thermal & Fluid Physics & Engineering, Begell House, ISBN : 1567002056
[7] Postlethwaite, J., Dobbin, M. H. and Bergevin, K. 1986. The performance of aluminium alloys and particulate reinforced aluminium metal matrix composites in erosive-corrosive slurry environments. Corrosion 42 pp 514-524.
[8] Burstein, G. T. and Sasaki, K.. 2001. Detecting electrochemical transients generated by erosion e corrosion. Electrochimica Acta 46 pp 3675-3683.
[9] Poulson, B. 1983. Electrochemical measurements in flowing solutions. Corrosion Science 23(4) pp 391-430.
[10] Lu, B. T. and Luo, J. L. Synergism of electrochemical and mechanical factors in erosion-corrosion.2006. Journal of Physical Chemistry B 110 pp 4217-4231.
[11] ASTM G15-05, Standard Terminology Relating to Corrosion and Corrosion Testing