Successful Repair of a Severely Damaged HP Scrubber Sphere

February 2018, a leak was visible in the spherical dome part of a HP Scrubber in a urea plant. The plant was stopped immediately to attend the leak. Upon opening of the HP Scrubber sphere, it became clear that severe corrosion occurred on the liners. The liner was covered with huge amount of corrosion products and many cracks were visible. Unfortunately, these cracks resulted in leaks which were not noticed. Therefore, corrosion of the carbon-steel pressure part commenced undetected. The paper describes the root cause of the corrosion damages as well as the successful repair. This case demonstrates the importance of a reliable and robust leak detection system to operate critical high-pressure equipment safely.

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Introduction

The urea plant is a 1750 tpd urea plant based on Stamicarbon CO_2 stripping technology. The plant was commissioned in 1998 and the high-pressure synthesis section comprises four pieces of process equipment; namely the Urea Reactor (1), HP Stripper (2), HP Carbamate Condenser (3) and HP Scrubber (4), see Figure 1.

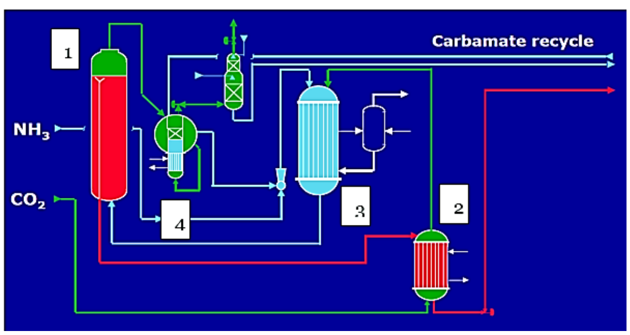

Figure 1. High pressure synthesis loop of a Stamicarbon CO_2 stripping process: [1] Urea Reactor, [2] HP Stripper, [3] HPCC, [4] HP Scrubber

The process conditions in the high-pressure synthesis loop are extremely corrosive due to the presence of ammonium-carbamate as an intermediate process step in the synthesis of urea from ammonia and carbon dioxide.

High pressure equipment utilizes a corrosion resistant barrier as a liner on the process side to protect the carbon steel pressure shell from corrosion. In the said urea plant, for the liner 316L UG (UG = Urea Grade) and X2CrNiMo25-22-2 austenitic stainless steels are used. It is important to passivate these stainless steels by adding passivation air to avoid onset of active corrosion (high corrosion rates).

Furthermore, these critical high pressure equipment must be monitored continuously for leakages of the stainless steel barrier (lining) by use of a leak detection system. The plant is equipped with a leak detection system based on the detection of ammonia vapor. The leak detection pipes are dipped in a bottle containing an ammonia sensitive reagent (Phenolphthalein solution), see Figure 2.

Figure 2. Leak detection system; bottle is filled with Phenolphthalein solution. Colorless at low pH, turns pink at pH>8

At the beginning of February 2018, a leak to the atmosphere was observed in the spherical dome part of the HP Scrubber, which resulted in the plant being stopped to attend to the leak, see Figure 3.

Upon opening the high-pressure HP Scrubber sphere, the corrosion damage was shown to be quite severe, which required a quite complex and comprehensive repair.

Figure 3. leak spot at the outside of spherical dome

It was also concluded that the leak in the corrosion resistant barrier was not detected, which resulted in late detection and consequently severe corrosion of the carbon-steel part. The incident can be classified as a near miss. Fortunately, in this case the corrosion of the pressure retaining part resulted in a so-called "leak-before-break" scenario (LBB), allowing the plant owner to timely shut down the plant to avoid catastrophic failure.

This paper describes the root cause of the corrosion damages as well as the successful repair. The plant was started up successfully April 6th, 2018.

Case history

The HP Scrubber (see Figure 4) consists of a heat exchanger and a spherical scrubbing part. The sphere is constructed of 20MnMoNi45 DIN 17201 carbon-steel plate; mono-wall, actual thickness is 53 mm (2.087") protected at the inside with a 9 mm (0.354") 316L UG liner.

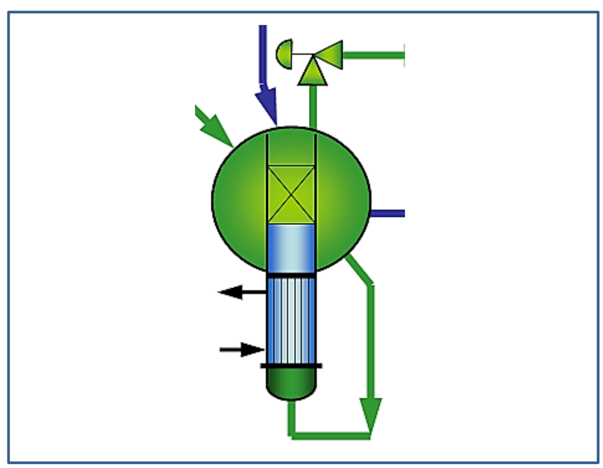

Figure 4. HP Scrubber with dome

Upon opening the spherical dome (February 7th), severe corrosion and large amounts of corrosion products was observed on the 316L UG liner, as can be seen in Figure 5.

Figure 5. 316L UG Liner plates covered with large amount of corrosion products

All corrosion products were removed by grinding. Dye Penetrant Testing (DPT) revealed large number of cracks in the liner, see Figure 6.

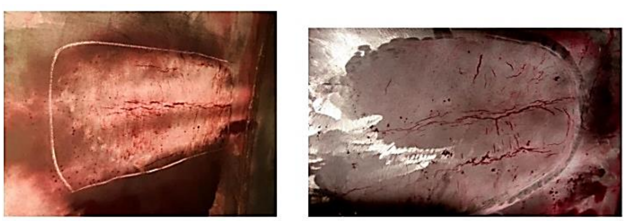

Figure 6. DPT of the liner revealed many cracks in the 316L UG liner

Based on these observations it was decided to remove and replace all liner segments. After removal of all liner segments the Wet Fluorescent Magnetic Particle Test (WF-MPT) revealed many cracks in the carbon-steel pressure shell, as can be seen in Figure 7. Also, it became clear that the leak detection system (grooves and holes) was partly blocked by corrosion products, making the system unreliable.

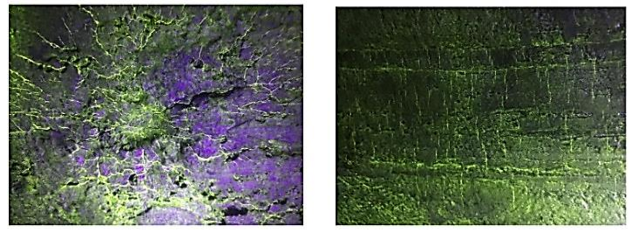

Figure 7. WF-MPT revealed many cracks in the carbon-steel pressure shell

The repair strategy was developed based on a fit-for-service (FFS) assessment. An important aspect of the repair was also to restore an effective leak detection system.

Root Cause Analyses

Metallurgical examinations of following samples were carried out, see Table 1:

SAMPLE ID NUMBER	DESCRIPTION
S09176	Liner plate sample: 316L UG including liner weld
S09177	Boat samples c-steel shell part (20MnMoNi45)
S09178	Corrosion products
S09179	Boat samples c-steel shell part (20MnMoNi45)

Table 1. Samples

Investigation results

Liner plate sample (S09176)

On the process medium side, the liner plate was partly covered with a blue oxide layer. Local absence of an oxide later indicates condensation of gasses on the liner surface (see Figure 8).

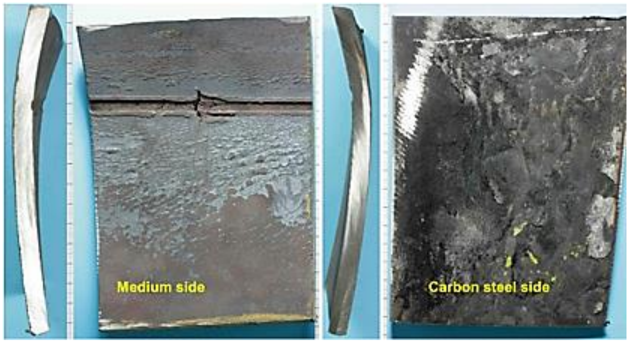

Figure 8. Liner sample (S09176); medium side covered partly with blue oxides. Backside covered with black oxides

The back side of the liner plate was covered with black corrosion products. The cracks started from the process medium side and progressed almost perpendicular to the back side, see Figure 9.

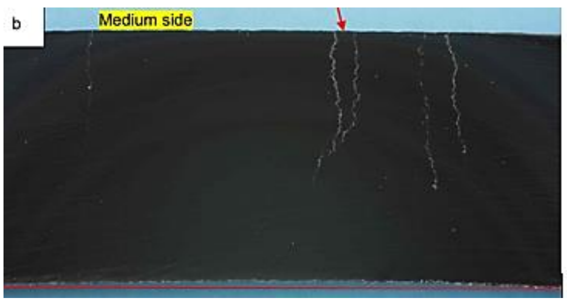

Figure 9. Cracks starts at medium side

Microscopic examination of the cracks shows that the cracks are intergranular stress corrosion cracks, which are filled with corrosion product (oxides), see Figure 10. This indicates that the cracks propagated slowly.

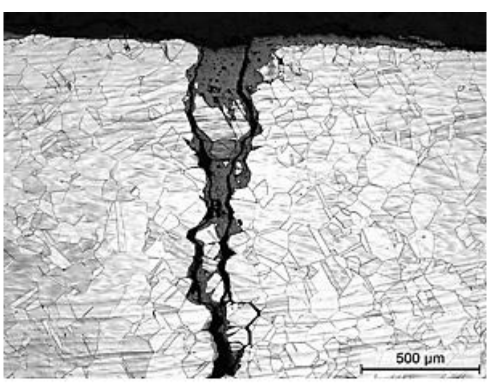

Figure 10. Intergranular stress corrosion cracks with oxides inside the cracks

At the liner plate surface (process medium side) typical deformation patterns in the austenitic grains are visible, see Figure 11. This indicates strain in the material.

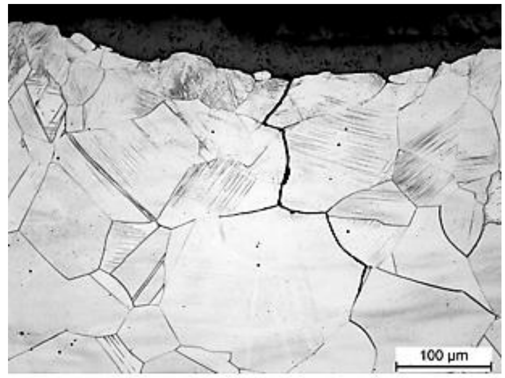

Figure 11. Typical deformation pattern in the austenitic grains indicating cracks starts at surface plastically deformed

This plastic deformation of the liner is mainly due to the bending of the liner plates during manufacturing. However, also temperature and pressure cycles (start-stops) could play a role as well.

Examination of the corrosion products found at both the process medium and the backside of the liner shows they consist mainly of iron oxides (corrosion product). However, at the backside of the liner also Sulphur, Copper and Nitrogen are found, see Figure 12.

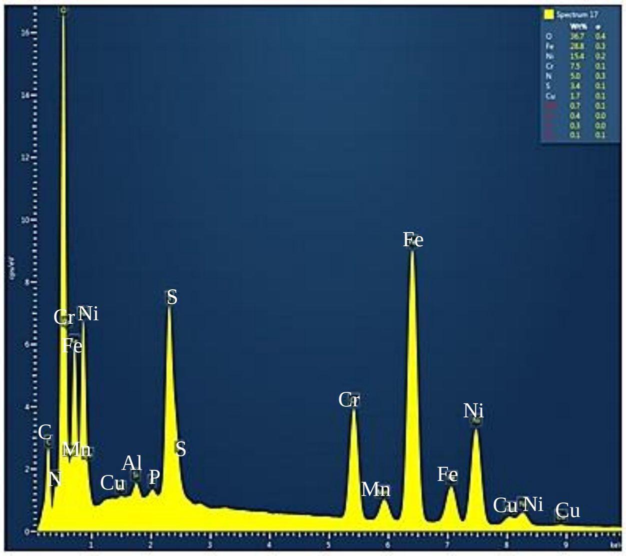

Figure 12. EDX spectrum of the elements found in the corrosion deposits at the liner backside. Apart from the normal elements found in 316L UG material, foreign elements such as Sulphur, Copper and Nitrogen are found

The origin of the Sulphur and Copper is unclear. The presence of ammonium-carbamate trapped behind the liner also attacked the liner at the backside; i.e. intergranular corrosion attack is observed.

Boat samples carbon steel shell (S09177 and S09179)

Two boat samples were removed from the carbon-steel sphere for metallurgical investigations, see Figure 13.

Figure 13. Two boat samples from carbon-steel sphere; left hand side S09177, right hand side: S09179

Metallographic examination of both boat samples indicated branched trans granular stress corrosion cracks, see Figure 14. The corrosion products were mainly containing iron oxides, but also traces of Sulphur were found. In the crack itself oxides are found, which also indicates that the crack propagated slowly.

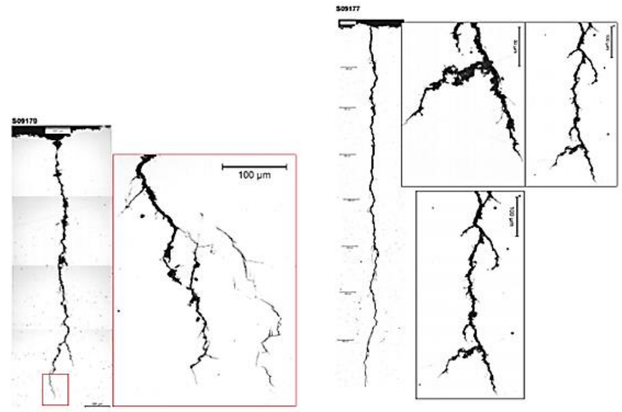

Figure 14. In both boat samples trans granular stress corrosion cracks are visible.

Root Cause of the Damages

The leakage in the 316L UG liner was due to intergranular corrosion cracking, initiated at the process medium side of the liner. Since the inner surface was plastically deformed (strain) and the presence of oxides in the cracks indicated that the failure mode was so-called Strain Induced Intergranular Cracking (SIIC). This failure mode has been observed in other urea equipment lined with 316L UG liners in the gas phase area.

SIIC is an electrochemical corrosion mechanism supported by mechanical deformation. Condensation of ammonium carbamate gas will create an electrolyte on the liner surface. Plastic deformation of the liner material was evident and also the presence of Sulphur was proven. Sulphur is believed to enhance this failure mode.

Ammonium-carbamate entering the space behind the liner started to corrode the carbon-steel. This resulted in localized wall thinning of the carbon-steel pressure shell as was observed in the sphere. The observed cracks in the carbon-steel are believed to be related to hydrogen. The hydrogen is originating from the corrosion of the carbon-steel due to the presence of ammonium-carbamate. Following reactions play a role:

$NH_2COONH_4 \leftrightarrow NH^{4+} + NH_2COO^-$ (Acidic behaviour ammonia carbamate)

$2Fe + 2\ NH^{4+} \rightarrow 2Fe^+ + 2H_{atm}\ (H_2) + 2NH_3$ (dissolving Iron and producing hydrogen)

Atomic hydrogen (H) is capable of diffusing through steel and the cracking failure mode is called hydrogen induced stress corrosion cracking (HISCC) or hydrogen induced cracking (HIC). The presence of Sulphur found on the back side of the liner sample promotes the entry of atomic hydrogen into the steel. The atomic hydrogen diffuses in the lattice to areas with increased tensile stresses brought about by the presence of notches, the microstructure (martensitic), geometric discontinuities and flaws in the lattice. The presence of hydrogen in the metal lattice reduces the toughness and resistance to fracture. Especially the high-tensile steel used for the Sphere is susceptible for hydrogen induced cracking. Hydrogen induced cracks are also known to propagate slowly.

REPAIR

The repair of the Scrubber sphere can be divided in two phases:
Phase 1: Removing the damaged liner and repair the carbon-steel pressure shell
Phase 2: Installation of the new liner segments

Phase 1: Repair of the C-steel pressure shell

First the existing liner segments were removed from the sphere. The inner surface was cleaned from rust and debris, see Figure 15.

Figure 15. Left side before cleaning, right side after cleaning

All cracks were removed by grinding under guidance of WF-MPT testing, see Figure 16. Since the carbon-steel was loaded with hydrogen, grinding was done carefully in order not to propagate the cracks or the formation of new cracks. The time needed to remove all cracks was approx. 11 days.

Figure 16. Grinded areas; at this location minimum remaining wall thickness is 10 mm

Stamicarbon performed strength calculations (FFS) to determine the minimum required wall thickness. This varied between 37 mm (1.457") up to 45 mm (1.772") depending on the location of the grooves. The buttering layers to attach the new liner plates were restored by grinding and /or welding. The leak detection grooves and holes were cleaned and repaired when necessary.

To avoid crack propagation during repair welding, the pressure shell was heated for approx. 2 hours to outgas any hydrogen still present in the carbon-steel.

Repair welding was done at a pre-heat temperature of approx. 120 °C (248 °F). A heating system was installed at the outside of the sphere, see Figure 17.

Figure 17. Insulation wrapped on all ceramic fiber heating elements

Covered electrodes (SMAW: AWS E7018 type) were used with low hydrogen content to minimize the uptake of hydrogen during welding. An impression of the repair activities is presented in Figure 18. The time needed to repair all grinded areas was approx. 6 days.

Figure 18. Repair welding in progress

After completing the repair welding, the temperature was increased again to soaking temperature (approx. 300 °C, 572 °F) for some time to outgas any uptake of hydrogen during welding. Finally, the temperature was lowered to ambient and after waiting for 48 hours the repaired zones were checked for cracks. No cracks were found, and the hardness was well within the maximum allowable values.

Subsequently a post weld heat treatment (PWHT) was performed in accordance to the design code for stress relieving and tempering. After the PWHT the repaired areas were checked again, and no cracks were found. Finally, the wall thickness in the welded grooves was restored to original wall thickness (53 mm; 2.087") by applying a two-component metal-epoxy compound, in order that the liner was supported in these regions to avoid plastic deformation.

Phase 2: Installation of new liners

The liner in the HP scrubber sphere is divided in 16 pre-shaped segments, as can be seen schematically in Figure 19.

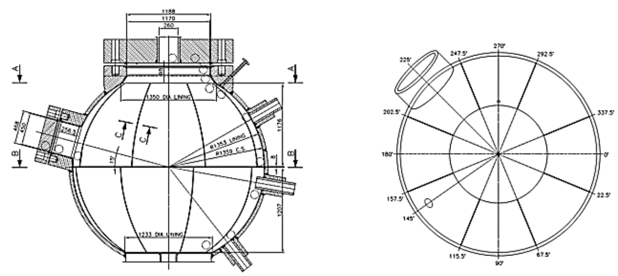

Figure 19. Schematic overview of the 16 liner segments to be installed. Right hand sketch shows 8 segments in top half

The new liner plates are 6 mm thick X2CrNiMoN 25.22.2. The liner plates were delivered with an over length. The plates were cut to fit the existing buttering layers. Welding was done by Gas Tungsten Arc Welding (GTAW) method using matching filler wire. The installation and welding of all liner segments took about 11 days. Some impressions of the liner installation are presented in Figure 20.

Figure 20. Installation and fit-up of liner segments in top part of the sphere.

After the pressure test, the HP Scrubber sphere was opened again to perform an ammonia leak test, no leaks were found. Before boxing up, the internal pall ring cylinder was welded in.

The plant was started up successfully on April 6th, exactly 2 months after the leak was detected and the plant was shut down (February 5th).

Discussion and Recommendations

The severe corrosion of the pressure bearing part of the sphere is due to the fact the liner leakage preceding this corrosion could not be noticed probably due to chocking of leak detection holes. This demonstrates the importance of a reliable and robust leak detection system.

Nowadays Stamicarbon recommends using state of the art leak detection system, which is based on continuous forced air flow fed to an ammonia analyzer (so-called pressurize system), which can be connected to the DCS system (see also Reference [1]). The principle of the pressurized system is presented in Figure 21 and 22.

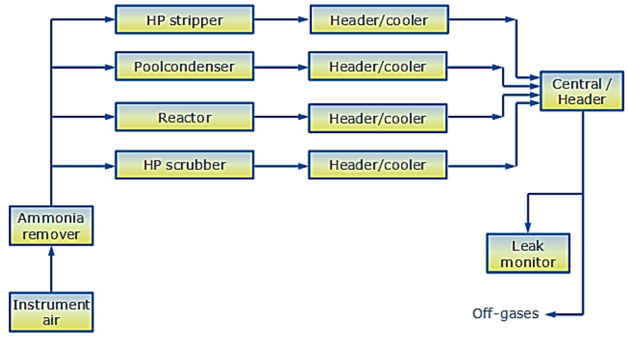

Figure 21. Principle of the pressurized leak detection system (schematic overview for a Stamicarbon pool condenser plant)

Figure 22. Ammonia analyzer

The leakage in the liner occurred due to so-called strain induced intergranular corrosion (SIIC). This is the result of condensation of reactor off gasses in combination with plastic deformation of the 316L UG liner. The plastic deformation is mainly the result of bending the liner plates during manufacturing. However frequent temperature and pressure cycles may play a role as well. Condensation of the hot reactor off gases cannot be avoided completely in the HP Scrubber sphere, despite the presence of a steam tracing. Plastic deformation of the 316L UG liner material cannot be completely avoided either. Due to the liner leak, ammonia-carbamate started to corrode the carbon-steel pressure shell. Besides wall thinning, also hydrogen induced cracks (HIC) were developed in the carbon-steel. Unfortunately, the selected steel (20MnMoNi45 DIN 17201) for the HP Scrubber sphere is prone to this failure mode (HIC) due to the high strength properties.

Corrosion of the carbon-steel pressure retaining part should be avoided always. This is managed by having a reliable leak detection system in place. Furthermore, the risk of hydrogen induced cracking can be reduced by applying so-called low strength steels (typically ASME P1 types; such as for instance SA-516 Gr70 or SA662 Gr. C) instead of high strength steels.

References

[1] Safeguarding Stamicarbon high pressure urea vessels. AIChE Ammonia and Related Facilities Safety Symposium, San Francisco, California Sept. 12-16, 2010. Alex Scheerder, Stamicarbon by, The Netherlands.