Copper Contamination Cracking in Austenitic Stainless Steel Welds

Welding of austenitic stainless steel with cupro-nickel wire resulted in cracking, which was not detected by radiography, but subsequently leaked during pressure testing

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Newly installed austenitic stainless steel piping joints leaked at girth welds during a precommissioning hydrotest and low-pressure air leak test. The piping was ASTM A312 Grade TP316L seamless pipes and was part of a natural gas liquids (NGL) recovery project. The failed joints were intended for hydrocarbon gas, diglycolamine (DGA) or instrument air service. Some of the failed joints were subjected to radiographic testing in the field and accepted prior to pressure testing as part of the code and company standard requirement. Failure analysis of the welds and the subsequent inspection plan to inspect thousands of suspected welds in the project are discussed.

Failure Analysis

Background

The NGL recovery project consisted of extensive austenitic stainless steel piping of ASTM A312 Grade TP316L. The piping was intended for hydrocarbon gas, DGA, and instrument air. The piping meant for hydrocarbon gas and DGA service was required to be hydrotested, and the piping intended for instrument air was required to be air leak tested at low pressure. During pressure testing, seven welds from three different lines leaked during different times. All the failed girth welds between seamless pipes were of 2-in. diameter and 0.154-in. wall thickness. Three of the leaked welds were radiographed prior to pressure testing and accepted as per ASME B31.3. Details pertaining to the leaked welds are given in Table 1.

The first two welds (SB-103 and SB-106) that leaked were repaired and rehydrotested and no investigation was conducted on the cause of failure. Subsequently, three more welds (FB-100, SB-101, and SB-22) leaked during hydrotest. These three welds were sent to the Saudi Aramco lab for failure analysis. During the same time period, two more welds (FB-30 and FB-31) leaked during an air leak test. These two welds were sent to a third-party lab by the EPC contractor for failure analysis. The NGL recovery project also had 90/10 cupro-nickel (UNS C70600) piping.

Nondestructive Testing

Radiographs of all three welds (FB-100, FB-30, and FB-31) that had passed radiographic testing before the leak testing were reviewed again after the leaks and no relevant indications were seen. Figure 1 shows the samples as received for failure analysis. The leaked welds were tested by dye penetrant. A round to linear indication was seen at the location of the leak as shown in Fig. 2. Cracks were

Fig. 1 — The as-received samples.

Fig. 2 — Indication at the leak location.

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Delta ferrite was measured at the cap and root by ferrite scope and it was found to vary from 4.65 to 8.51%.

Metallography and Energy Dispersive Spectroscopy

One of the failed welds was sectioned carefully at the leak and subjected to metallographic examination. Figure 3 shows the sectioned sample in the unetched condition. Fine cracks can be seen on either side of the weld. Figures 4 and 5 show the same sample after etching at a higher magnification. Figure 4 shows the cracks on the left side of the weld, and Fig. 5 shows the cracks on the right side of the weld. Cracks on both the sides extended to the weld, heat-affected zone (HAZ), and the base metal. The top-left corner of the weld in Fig. 4 shows a small part of the weld that etched darker than the rest of the weld. This is shown in Fig. 6 at a higher magnification. This area was analyzed by energy-dispersive spectroscopy (EDS) and was found to contain about 42% Cu and 27% Ni. Copper content in the rest of the weld, as determined by EDS varied from 0.41 to 2.10 at.-%. Figure 7 shows that the cracks are intergranular in nature.

Elemental Mapping and Line Analysis

Elemental mapping and line analysis were done for further identification of elements inside the cracks. Figure 8 shows elemental mapping at the crack presented in Fig. 6. Line analysis at the same location is shown in Fig. 9. It can be seen from both the elemental mapping and line analysis that the crack is rich in copper and also relatively rich in nickel as compared to the adjacent weld metal.

Discussion

The EDS analysis, elemental mapping, and line analysis showed that the small darkly etched part of the weld in Fig. 4 is primarily an alloy of copper and nickel. This part of the weld is probably from a tack weld that was made with ERCuNi welding wire. It is possible that a mix-up in filler metal was realized and the tacks were ground off. The removal of cupro-nickel tack weld by grinding was incomplete as revealed by Fig. 4. The chemistry of the residual cupro-nickel tack weld and the rest of the weld are consistent with the assumption that the rest of the weld was made with the gas tungsten arc welding (GTAW) process, using the required ER316L welding wire, taking dilution into consideration. It was concluded that accidental use of ERCuNi filler metal resulted in copper contamination cracking (CCC) due to penetration of molten copper into the grain boundaries of the weld, HAZ, and base metal. The source of copper is the residual cupro-nickel weld. Copper is known to penetrate the grain boundaries of an austenitic stainless weld, HAZ, and base metal up to a zone that experiences a temperature higher than the melting point of copper (Refs. 2-7). Solidification cracking in the weld due to unfavorable chemistry is also possible (Ref. 8). It is noted that the third-party lab also independently reported that the welds failed due to CCC.

Accidental use of ERCuNi filler metal in lieu of ER316L was possible because the project also had 90110 cupro-nickel piping that was welded with the GTA process, using ERCuNi filler metal. The contractor had set up a fabrication shop on the site. Cupro-nickel and stainless steel piping spools were being fabricated by the same contractor in the same shop although in different bays. It was found that cupro-nickel spools were being fabricated during the same time period as the failed stainless steels spools. Some of the welders were qualified on both materials and they were welding in both the bays when required. It should be noted that three of the leaked welds were welded in the field (FB-100, FB-30, and FB-31) and the rest were welded in the shop.

Once the damage mechanism was established as CCC, it was required to establish the integrity of thousands of welds that were already completed. Hydrotesting for most of these welds were completed. Since the leak was minor and some of the girth welds were in inaccessible locations, the reliability of the hydrotest/leak test was questionable.

Mock Ups

To develop an inspection plan for the completed weld and to ascertain the damage mechanism, mock ups were welded to simulate the failure. Two mock ups were
welded using pipes of the same size (2 in. diameter, 0.154 in. thick) and grade (ASTM A312 Grade TP316L). The first mock up (Mix-1) was welded with the GTA process, using ERCuNi welding wire, for the complete root and ER316L for the rest of the passes. The second mock up (Mix-2) was welded with the GTA process, using ER316L for the root and the rest of the passes, except that one full circumferential pass at one edge of the capping pass was made with ERCuNi.

Both welds were subjected to dye penetrant test, radiographic test and hydrotest. These tests were carried out in the presence of the project inspectors as these tests (except radiography) would be used to inspect the suspect welds. The results of the dye penetrant tests are shown in Figs. 10 and 11. It can be seen from Fig. 11 that the indication can be minute and could be missed. This possibility was highlighted to the inspectors concerned.

Subsequently both welds were subjected to radiographic testing. Radiographs of both welds were interpreted to ASME B31.3 requirements by ASNT Level II qualified personnel. Linear indications were seen in the radiograph of Mix-1 and the weld was rejected. No indications were seen on the radiograph of Mix-2 and the same was accepted by the film interpreter. This is consistent with the DP test results.

The two welds were subsequently hydrotested and found to leak at a pressure of 900 lb/in² for Mix-1 and at 500 lb/in² for Mix-2. The leak during hydrotest was very minor and the same is shown in Fig. 12. It is possible that leaks of this magnitude could have been missed, especially at joints in locations inaccessible to the inspector.

Positive metal identification (PMI) was done on the pipe and capping pass of the weld metal on both the mock ups. The results are shown in Table 2.

To ascertain the correctness of the damage mechanism, both mock ups were subsequently sectioned and subjected to metallographic analysis, elemental mapping, and line analysis. The results of these tests were in agreement with what was observed on the failed welds. The cracks seen in the failed weld were essentially reproduced on the mock ups.
The time these leaks were seen. Since the stainless welds in this project. Hydrotest-Inspection Plan for most of the lines was completed by inspection during the initial field hydrotest. There were several thousand austenitic spools were being fabricated were identified. There were about 9500 such welds that some of the leaks were not detected and inaccessible positions, it was possible to the possibility of accidental use of ER-CuNi filler metal. It was decided to inspect 5% of the suspect welds, and the level of inspection was to be raised based on the results. The inspection plan was based on the following salient points:

- All piping in nonhazardous service such as instrument air was excluded from the inspection plan.
- Dye penetrant test (DPT) was included in the inspection plan. The DPT on mock ups was used to demonstrate the manifestation of CCC to the inspectors.
- Based on the literature (Ref. 9) and the present work, CCC cannot be reliably detected by radiographic testing. Hence, radiographic testing was excluded.
- The PMI was to be done on four locations (12, 3, 6, and 9 o’clock positions). Since use of ER-CuNi was possibly restricted to tack welding, multiple locations were specified to increase the possibility of detecting the mix up. It was specified that Cu content greater than 1% should be considered as a possible case of mix-up requiring further inspection for confirmation. A lower level of Cu could not be set because some heats of A312 Grade TP316L pipes had 0.6% Cu, which could show up in the weld due to dilution. Moreover ER316L can contain up to 0.75% Cu as per ASME Section II part C.
- Careful inspection was recommended during hydrotest for the welds that were yet to be hydrotested. Leaks on the mock ups during hydrotest were demonstrated to the inspectors.
- Some of the critical lines were recommended to be rehydrotested.
- Some of the 90/10 cupro-nickel welds were also included in the inspection plan due to the possibility of accidental use of ER316L welding wire.

Inspection results on about 425 suspect welds did not show any indication of possible CCC. The scope of inspection was not increased any further. The plant has been commissioned without reporting any leakage.

Conclusions

Austenitic stainless steel welds leaked during hydrotest due to CCC caused by accidental use of cupro-nickel filler metal. These cracks could not be detected by radiographic testing that preceded leak testing. Mock ups simulating the mix up of filler metal were welded and tested to assist in inspection of suspect welds and to ascertain the correctness of the damage mechanism. A detailed inspection plan comprising of DPT test, PMI, and hydrotest was developed for inspection of the completed welds that were suspected to have CCC.

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References