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On-site determination of an uncommon cracking mechanism due to composition gradients in a nickel steel weld

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ABSTRACT

This article analyzes a 3.5% Ni steel cryogenic cylindrical vessel, after the detection by nondestructive inspection of cracks in a circumferential weld. Possible in-service damage mechanisms are discussed, in particular, vibration, low cycle thermal fatigue and hydrogen embrittlement. On-site experimental analysis allowed defining that cracks were due to a manufacturing problem. A final weld bead with much greater concentration of Ni generated an uncommon mechanism of thermal fatigue. In Ni alloyed steels, small variations of Ni around 36% involve variations of almost an order of magnitude in the coefficient of thermal expansion. Proposed actions for integrity assurance of the vessel and lessons learned for fabrication of future vessels are briefly discussed.

1. Introduction

This article originates in a failure analysis of cracks found in the shell-to-cap circumferential weld of a 2440 mm diameter, 82 mm thick cryogenic vessel at a petrochemical complex, Fig. 1. All studies were performed on site, during a programmed plant stop. Two vessels with the same characteristics and operational history were operated at the facility, but only one presented discontinuities.

This horizontal, cylindrical vessel with semispherical heads was manufactured in 1978; specified base metal for shell and cups is SA 203 Gr. E, a ferritic pearlitic steel alloyed with 3.5% nickel [1]. Stress relieving post weld heat treatment was done according to ASME VIII, parts UW-40, UCS-56 and UCS 65 [2]. Welds were also completely radiographed. Pre-operational hydrostatic testing was performed at 115 bar. Maximum design working temperature and internal pressure are 101 °C and 77 bar, respectively. Specified minimum mechanical properties are 275 MPa yield strength and 20% elongation, with a UTS between 485 and 620 MPa, minimum specified chemical composition is detailed in Table 1.

The vessel has a 140 mm thick polyurethane insulation, and is used as a liquefied gas separator, prior to shipping to expander valves. Normal operational conditions are − 60 °C, 58 bar internal pressure. The process gas is C1+ and is composed of methane, ethane, propane, butane and gasoline. It is a "dry" gas, water content is 0.16 ppm, with a pH between 3.3 and 4.1. The content of hydrogen sulfide in gas is 0.000165% and the content of carbon dioxide (CO_2) is 0.54%.

Fig. 2 shows the record of pressures during 2011 and 2012. This vessel was taken out of service, on average, 6 times per year. At scheduled stops the temperature rise up to room temperature was very slow, at a rate of 0.4 °C/min, but could be up to 2 °C/min during unscheduled stops. Cooling rates during commissioning again were always controlled below a maximum of 0.3 °C/min.

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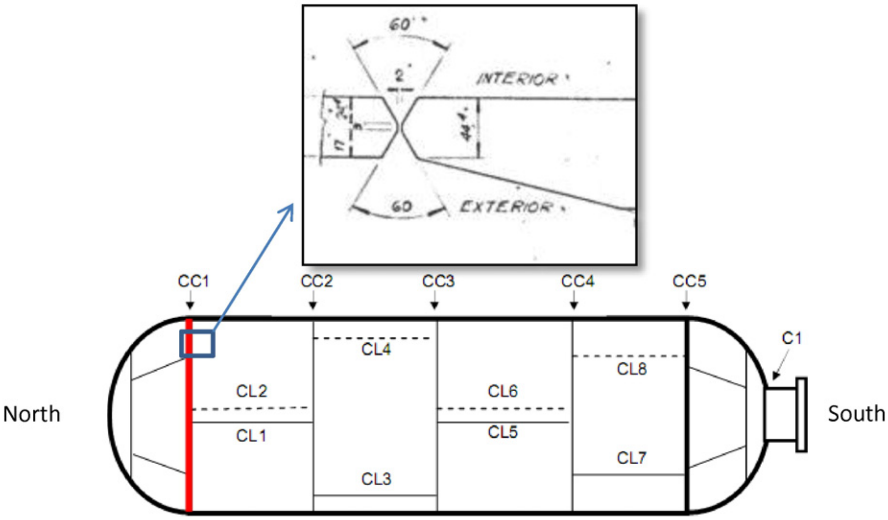

Fig. 1. Cracked vessel. Inset: detail of the Cap — surround welded joint.

There are no records of inspections since reception up until 2010, since the vessel had been classified as of low risk. In 2010 nondestructive testing (NDT) was performed, and cracks were detected in one of the cap to shell circumferential welds. These cracks were small and mainly in the direction of the weld, i.e. circumferential to the vessel, and were repaired by grinding. During inspection carried out two years later, cracks were found again, this time spread in different directions [3].

Documents containing specific information about the MMA (manual metal arc) welds are not available. Electrodes recommended for welding this SA 203 Gr E steel are C2-S8016 [4], C2-S8018 or ENiCrFe-2 [5]. Pure weld metal chemical compositions for each are presented in Table 2. Note that the first two have a composition similar to the base material, while the third contains a high content of nickel and chromium. Table 3 shows pure weld metal mechanical properties corresponding to each electrode.

2. In-situ metallographic analysis

As mentioned, circumferential cracks in the weld of the North cap detected during the NDT inspection carried out in 2010 were eliminated by grinding. Evidence of the indications was not kept. During the NDT inspection in 2012 in. penetrant testing, chemical analysis, hardness and field metallography were used to identify the new cracks detected. All these techniques were used "in situ", directly on the component during the plant stop. This time, cracks were in different directions. Fig. 3(a) shows the detected mid-weld cracks, as detected by penetrant ink.

Hardness of most of weld material is 150 to 170 HB, similar to the hardness of shell base metal. But very high hardness was detected at specific sites, with values between 330 and 415 HB. These sites were subsequently identified by chemical etching with Nital 10% and the presence of two dissimilar materials was identified: one, susceptible to etching, and the other, non-susceptible. Immune areas to Nital etching are delimited In Fig. 3(b) [3].

In situ chemical analysis of these areas detected three materials with different compositions:

1. Base material, with a nickel content between 1.5 and 5.5%.
2. Metal of "normal" weld metal, with a content of Ni between 3 and 3.75%.
3. Non-susceptible filler material to etching, with high hardness.

Composition of region 3 corresponds to electrodes E8018-C2 or E8016-C2, as recommended for this steel type [6]. Detected cracks were all located in weld metal, on the edge of zones 2 and 3, on the side of the harder material. In these hard areas contents of Ni of up to 7.5% and of Cr up to 12.5% were found. Zn was also detected in both weld metals.

This high Ni and Cr material can correspond to an electrode of the type ENiCrFe-2, which provides a pure weld metal with 70% Ni and 15% Cr [5]. This type of weld metal is commonly recommended for welding 3,5% nickel alloy steel, but it is noticed that when using austenitic stainless steel electrodes, the coefficient of expansion must be kept in mind [7]. It is estimated that in this case it was used to perform a repair during the construction stage.

Table 1
Chemical composition of 203 SA Gr. E steel.

C	Mn	P	S	Si	Ni
≤0.23	≤0.8	≤0.035	≤0.04	0.15–0.4	3.25–3.75