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Analysis of intergranular stress corrosion crack paths in gas pipeline steels; straight or inclined?

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ABSTRACT

The failure analysis conducted on an X42 pipe steel showed that the combination of the operating and residual (mainly bending) stresses may have been sufficient to exceed the threshold stress for high pH stress corrosion cracking (SCC) to initiate, in the course of normal operating stresses and temperature. Comparison of the results obtained in this study for the X42 pipe sample (showing straight SCC cracks) together with those published previously for X65 pipe samples (showing inclined SCC cracks) suggested that the interdependency of crack tip plasticity, anisotropy in microstructural texture and residual stresses affect the resulting crack paths. The SCC crack paths are therefore believed to be dictated by the interdependency of the pipe manufacturing (residual stress, texture) and operating pressure parameters.

1. Introduction

Stress Corrosion Cracking (SCC) is an important damage mechanism of buried gas pipeline steels. In Australia, pipe line ruptures attributed to high pH SCC have been documented since the 80s [1]. High pH SCC results of the combination of three parameters: an electrolyte with a pH > 9, a tensile stress and a susceptible material [2]. Cracks are intergranular and usually travel perpendicular to the hoop stresses (in the through-wall direction). However, numerous instance of cracks propagating with an angle from the perpendicular and defined as 'deflected' or 'inclined' SCC have been observed both in Canada [3,4] and Australia [1,5–7] in X65 gas pipeline steels. Inclined SCC is a phenomenon which introduces variables into the possible severity of the SCC cracks, and also the possibility of more complex and potentially pipeline damaging interactions between cracks in close proximity. A large amount of work has been therefore conducted to understand this phenomenon and the effects of the texture, residual stresses and preferential dissolution of the highest strained areas at the crack tip have been advanced to explain it [3,5,7–10]. These hypotheses were however not tested against straight SCC cracks (due to the unavailability of suitable ex-service samples at the time). Nevertheless, an opportunity arose more recently to obtain pipe steel samples from the field (X42 grade) showing straight SCC cracks. This study therefore presents firstly a failure analysis of this lower grade pipe steel and secondly a comparison between the straight and inclined observed crack path characteristics.

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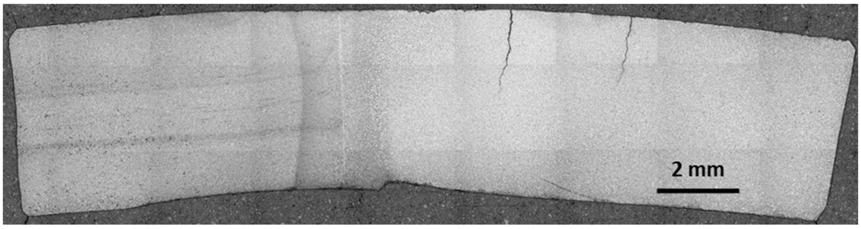

Fig. 1. X42 pipe transverse view showing weld and typical straight stress corrosion cracks.

2. Materials and methods

2.1. Material

The samples were cut out of pipe sections made of API 5L X42 steel (Fe bal., C 0.23 wt%, Mn 0.64 wt%, Si 0.01 wt%, S 0.03 wt%, P 0.01 wt%, Ni 0.01 wt%, Cr 0.01 wt%) extracted from the field after 39 years of operation and showing stress corrosion cracking (Fig.1). The nominal wall thickness and the external diameter of the pipe were respectively 4.37 and 168.3 mm. The pipe was manufactured from centre slit strip and via the electric resistance welding (ERW) process and coated with an adhesive PVC tape wrap on the top of a rubber type layer. The pipe sections were extracted at approximately 40 km downstream from a compressor station, where the soil temperature was estimated to be between 15 °C and 25 °C through the year. The maximum allowed operating pressure (MAOP) of the line was 8.24 MPa.

2.2. Microstructural characterizations

The samples were sectioned transversely to the pipe longitudinal direction, embedded in epoxy resin, polished down to 1 µm diamond paste using a semi-automatic TegraPol polishing machine (Struers) and etched with 2% Nital for metallographic analysis. A Zeiss Axio imager optical microscope was used to examine the microstructure of the samples and the stress corrosion crack path characteristics.

For electron backscatter diffraction (EBSD) analysis the final polishing step was achieved using a porous neoprene disc with a colloidal silica suspension (0.04 µm). The EBSD scans were collected using a FEI Helios Nanolab 600-SEM equipped with an EBSD detector (EDAX Hikari™). The acceleration voltage and the electron beam current of the SEM were 30 kV and 2.7 nA, respectively. The step size was 1 µm with a hexagonal scan grid (scans were approximately 450 × 450 µm [2]). TSL-OIM software was used for the data collection and analyses.

2.3. Residual stress measurements

The residual stress profiles were measured with neutron diffraction (ND) using a strain scanning diffractometer (KOWARI, ACNS, ANSTO, Lucas Heights, Australia) through the thickness of the pipe section. A monochromatic beam with $\lambda = 1.67$ Å from Si{400} monochromators reflection was used in this analysis. This choice of wavelength resulted in a scattering angle of 90° of the sample Fe (211) reflection. A nominal gauge volume of $0.3 \times 0.3 \times 8\ mm^3$ was used to measure two principal stress directions (normal and hoop) and to reconstruct the hoop stress component (under assumption of the zero normal stress). The measurements were done with 0.2 mm steps through thickness and started 0.2 mm below the outer surface. Given the significant microstructural differences on both sides of the weld (Fig.1), residual stresses through the thickness of the pipe were measured on both sides of the weld and at a distance of 50 mm from the weld centreline.

The surface residual stresses were measured by X-ray Diffraction (XRD) using the sine-squared method, with a StressTec -3000 equipment (ANSTO). The surface was pickled in 50% sulphuric acid to remove mill scale, no mechanical methods were employed to remove mill scale. Measurement positions were based on the apparent weld centreline, taken as the centre of the internal trim line. This position was given as 0, with measurements being made at ± 4, ± 8, ± 12, ± 16 and ± 50 mm from the weld centreline. The surface residual stress distribution was measured in the axial and hoop directions.

ND and XRD measurements were made on the same sample of $150 \times 150\ mm^2$ dimension cut from the pipe section.

2.4. Texture measurements

The KOWARI diffractometer was also used to perform texture measurements in the pipe through wall thickness (at seven locations) on both sides of the weld at a distance of 10 mm from the weld centreline. Samples were prepared by cutting a slice at certain depth measured from the outer surface of the pipes of about 0.26 mm thick, 6 mm wide (between 10 and 16 mm from the weld centreline) and 60 mm length. The slice was then cut into small coupons and coupons were glued together to form a cube of about 6 mm side. The orientation of each coupon was preserved when cutting and gluing them together. A monochromatic beam with $\lambda = 1.67$ Å was used to measure three pole figures, (110), (200) and (211) on a grid close to 5 × 5°. Orientation distribution functions (ODF) at $\varphi_2 = 45°$ were then plotted from the three obtained pole figures [8].