Pak. J. Engg. & Appl. Sci. Vol. 13, July, 2013 (*p.* 1-7)

Failure Analysis of a Compressed Natural Gas Storage Cylinder

Liaqat Ali[1], Khalid M. Ghauri[1] and Faiz ul Hasan[1]

1. *Metallurgical and Materials Engineering Department, University of Engineering & Technology, Lahore, Pakistan. Email" liaqat_kasuri@hotmail.com*

Abstract

In this work the rupture of an 80 liters capacity CNG storage cylinder installed at a CNG sales station was investigated. It was reported that the cylinder had ruptured only a few months after installation. During the initial investigation, the material of the cylinder was found to be in compliance with the specifications of composition and mechanical properties. However, thorough visual examination of the ruptured surfaces indicated the presence of multiple crack initiation sites within a rusted region on the inner surface of cylinder. This observation indicated the potential for stress corrosion cracking. Further macro-examination of the crack established this feature. Metallographic examination of areas adjacent to the fractured surfaces showed the presence of deep draw-marks almost everywhere and a longitudinal fold of unusual depth. These defects might have acted as stress raisers to assist stress corrosion cracking. It is suggested that the defects were present in the failed cylinder due to improper inspection procedures.

Key Words: Rupture, Gas Storage Cylinder, Stress Corrosion Cracking, Surface Folds, Draw-Marks

1. Introduction

This work describes the findings of the examination of an 80 liter capacity natural gas storage cylinder that had ruptured during service at a gas filling station in the eastern part of Lahore Pakistan in November 2006. The following background information was also provided along with the two pieces of the ruptured cylinder.

- That the cylinders at this gas station were installed in a horizontal position.
- That the longitudinal rupture opening corresponded with 6 o'clock position on the horizontally mounted cylinder.
- That the cylinder had ruptured after only a few months of use.

In addition, the following data relating to the mechanical and the operating parameters of the cylinder was also supplied.

Cylinder Diameter (outside)	265 mm
Cylinder Length	1.72 meters
Material and Heat Treatment	Cr-Mo steel 'VCL', Hardened & Tempered
Hardness	350±10 Brinell
Yield/UTS/Elongation	990 MPa min. / 1100-1220 MPa / 12% min.
Normal Operating Pressure	250 bars
Test Pressure	350 bars
Wall Thickness	7.5 mm

2. Mechanical Testing & Material Analysis

The chemical composition and the hardness of the ruptured cylinder were tested in the laboratory. The material was found to be in compliance with the specifications, indicating that the failure of the cylinder was not caused by any shortcoming in the material.

3. Visual Examination

Photographs of the ruptured cylinder are shown in Fig. 1. Visual examination of the fractured surface has shown that the rupture was initiated by the formation of longitudinal cracks on the inside surface of the cylinder, at about the 6 o'clock position on the horizontally mounted cylinder. The region of crack initiation is indicated by an arrowhead in Fig. 1.

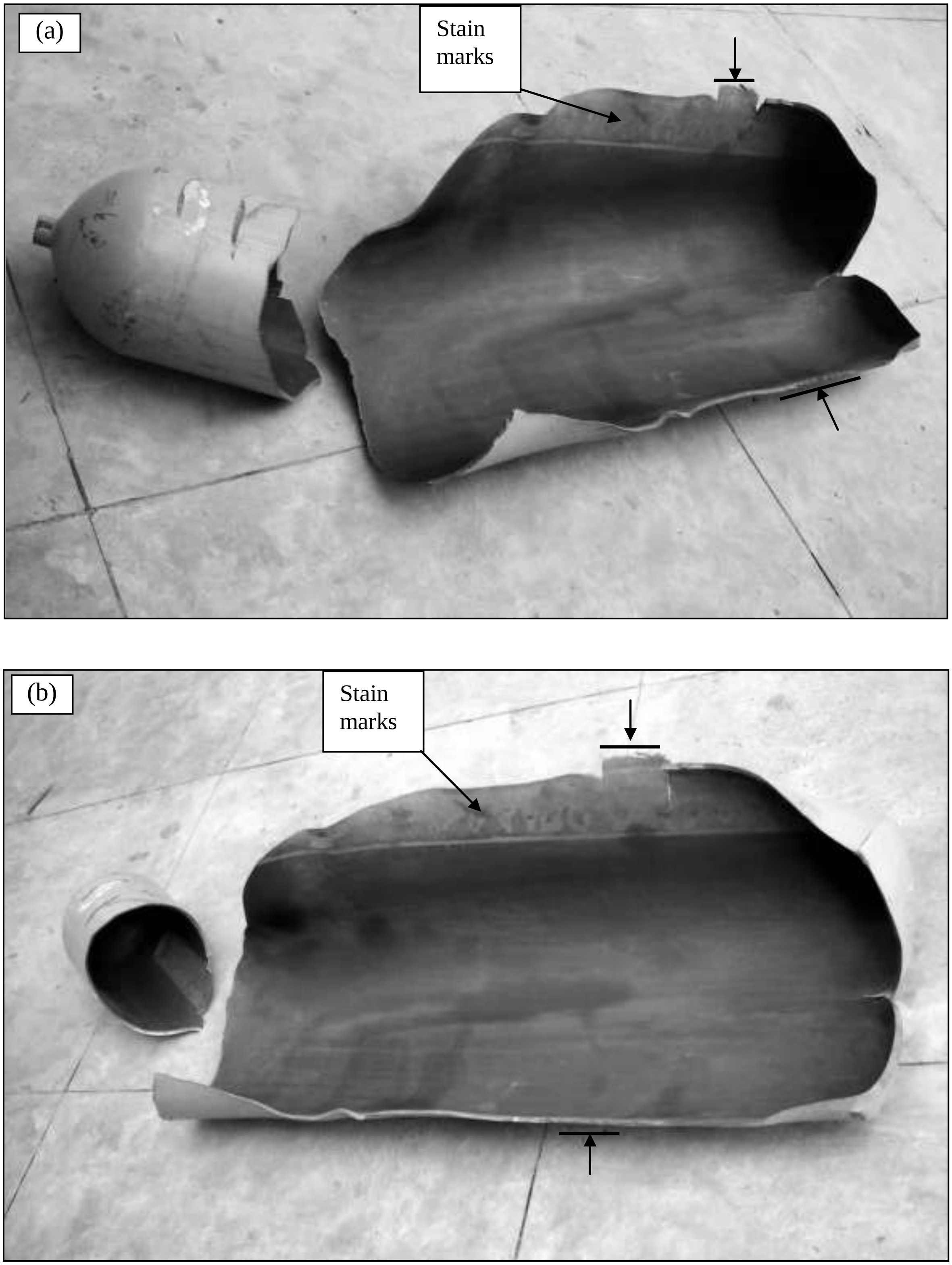

Fig.1(a & b) Photographs of the ruptured cylinder indicating (with an arrowhead) the region of crack initiation, as well as the rusted portions on the inside surface.

A close examination of this region showed that the cracking had actually initiated at many different points, as indicated by 'chevron' markings. As many as eight points of origin could be clearly identified within a distance of about 200 mm along the fractured cylinder wall. The remaining part of the fractured surface showed the typical slant ductile overload fracture.

The area around the 6 o'clock position on the inside surface of the cylinder was visibly 'rusted' when compared with the rest of the internal surface of the cylinder. Further examination of this area, shown in Figs. 1 and 2, indicated that the rusting had been caused by the collection and stagnation of some liquid (presumably water or some condensate) inside the cylinder while it was lying in the horizontal orientation. The rusted region which was about 100 mm wide ran along the entire length of the cylinder, indicating that approximately 2 liters of the stagnant liquid may have been present in the cylinder at the time of rupture. A detailed macroscopic examination of the rusted region also showed signs of sporadic pitting corrosion in these areas (Fig. 2b and c) which indicated that the liquid / water that had been present in the cylinder was of corrosive character. Unfortunately, no sample of the liquid collected from

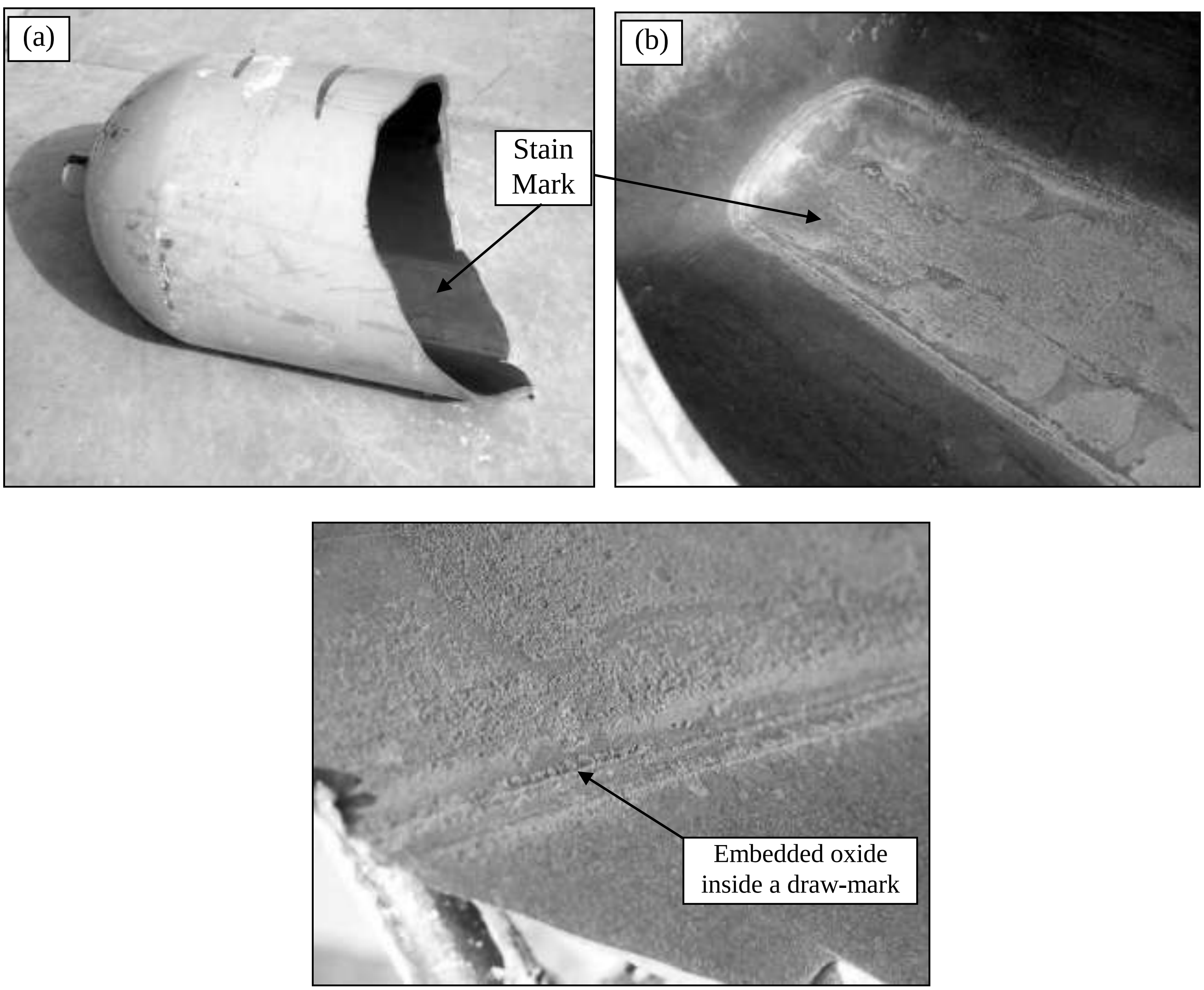

Fig.2 (a &b) Photographs showing the stains caused by the stagnant liquid (presumably water) inside the horizontally mounted cylinder. It was estimated that about 2 liters of liquid was present in the cylinder at the time of rupture. (c) Showing the extent of corrosioncaused by the stagnant water. The arrowhead points at the embedded oxide (dark-grey) inside a longitudinal draw-mark.

one of the cylinders at the affected CNG station was available for analysis.

4. Examination of the Crack

A macroscopic examination of the entire fractured surface showed that the cracking had initiated in an approximately 200 mm long region of the cylinder-wall. This region, as indicated in Fig. 1, was oriented parallel to the axis of the cylinder. It should be noted in Fig. 1 that the initial cracks had formed at the edge of the rusted region on the inside surface of the cylinder. Macro-photographs taken from this region are shown in Fig. 3, from which it is evident that a number of cracks had separately nucleated on the inside surface of the cylinder (Fig.3a) The longitudinal cracks that had initiated the fracture were oriented parallel to the axis of the cylinder and perpendicular to the cylinder wall. These cracks had formed at different planes in close proximity to each other. As many as 8-10 separate longitudinal cracks were present within a length of about 200 mm, indicating that multiple cracking had taken place. It should be noted that when the ruptured cylinder was first examined, about 24 hours after its rupture, there were no signs of any oxidation or corrosion on the surface of the crack.

It was noted that the fracture cracks had formed within the ‘rusted’ region on the inside surface of the cylinder and along a line that was very close to the

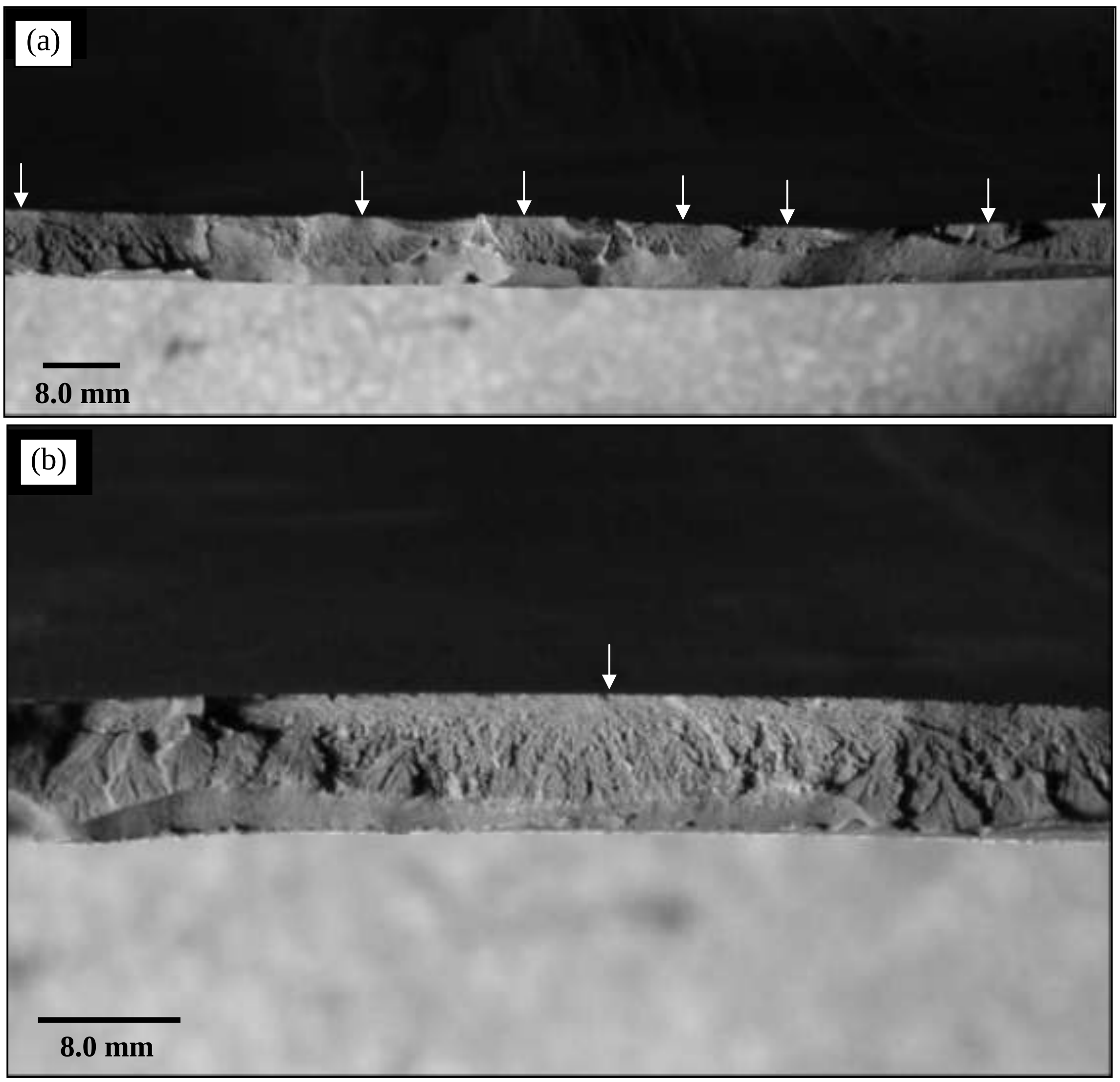

Fig.3 (a &b) Macro-Photographs of the fractured surface showing the points of crack initiation on the inside surface of the cylinder.

edge of the rusted portion of the cylinder surface. This observation suggests that corrosion due to stagnant liquid may have played a role in the initiation of the crack. Considering a hoop stress of 45% (hoop stress ≅ 445 MPa, calculated according to $\sigma_{hoop} = Pd/2t$ [1], P = pressure, d = diameter and t = thickness) of the yield stress (990 MPa) at the operating pressure of 250 bars in the presence of a corrosive environment, the possibility of stress corrosion cracking (or SCC) appears highly likely [2]. Multiple sites of crack nucleation, as seen in Fig. 3a, are also indicative of stress corrosion cracking [3].

5. Metallography

In order to examine whether any further stress-corrosion cracks were present in the areas close to the fracture surface, samples were cut for metallographic examination with surfaces perpendicular to both the plane of the crack and the longitudinal axis of the cylinder; corresponding micrographs are shown in Fig. 4. It can be seen in Fig. 4a that there was a profusion of deep draw-marks on the inside surface of the cylinder. In addition to the draw-marks, a longitudinal 'fold' or 'overlap' (Fig. 4b), was present very close to the line of the fracture.

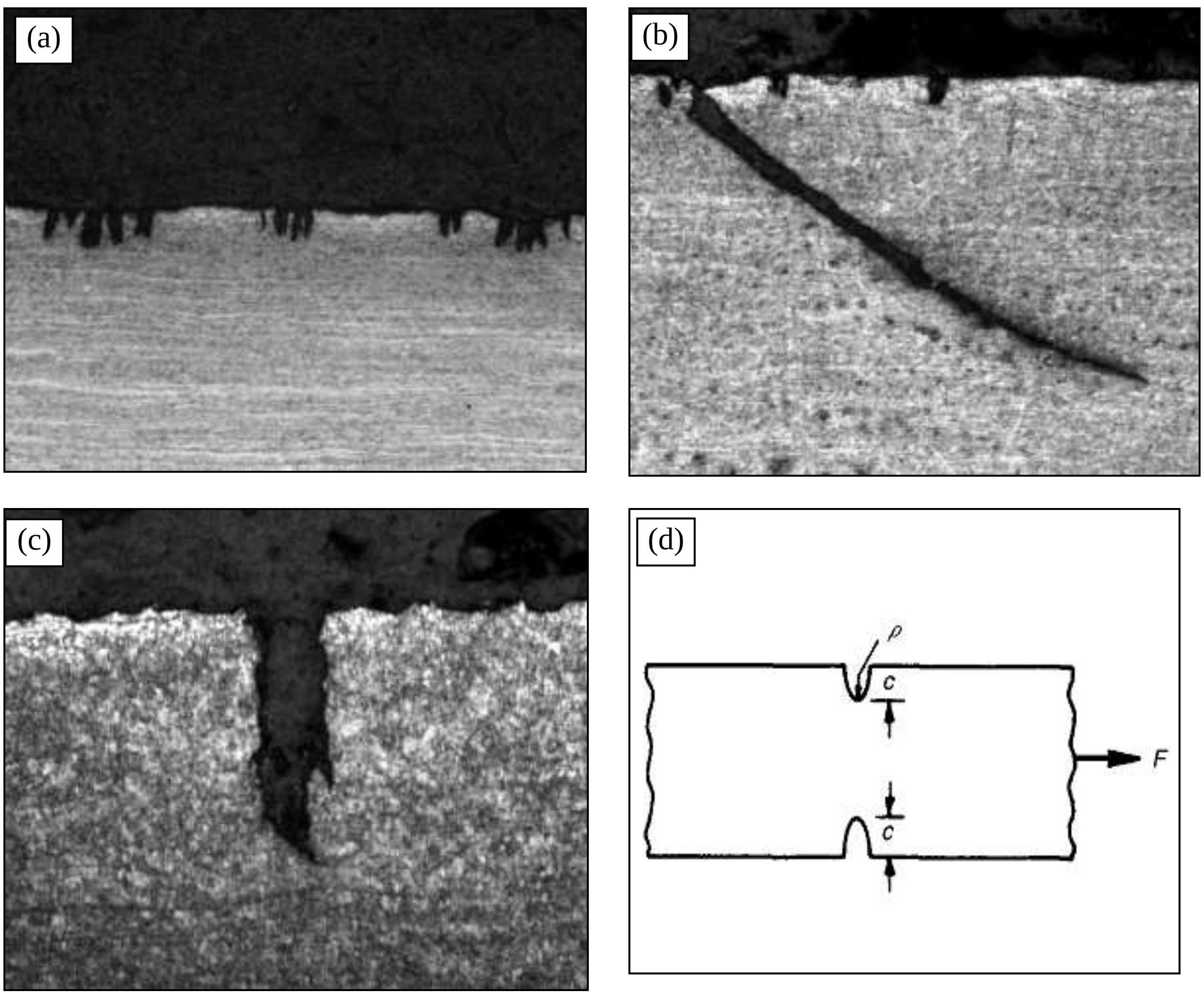

Fig.4 Microphotographs taken from the transverse sections showing the depth of the draw marks (a and c) as well as a surface 'fold' or 'overlap' in (b). It may be noted that no stress-corrosion cracking could be observed to have started at the roots of the draw marks at this stage. (d) Schematic showing the depth and radius of the notch for the calculation of stress concentration factor under tensile force [5].

The depth of the draw-marks, as observed on the sectioned samples (see Fig. 4c), was between 0.35 and 0.4 mm. The observed width of these draw marks was in the range of 0.1-0.16. Such draw-marks can cause stress concentration of sufficient magnitude to become the source of either stress-corrosion-cracking, or fatigue/corrosion-fatigue [3-4]. The stress concentration (SC) factor for some of the draw marks has been calculated according to [5]:

$$\frac{\sigma_{\max}}{\sigma_{\max}} = 1 + a\left(\frac{c}{\rho}\right)^{\frac{1}{2}} \qquad (1)$$

where c = crack length (Fig. 4d), ρ = radius of crack tip (see Fig. 4d) and $\alpha \approx$ 0.5 for tension.

The calculated SC factor values for some of these draw marks are between 2.0 and 2.2, which are in the high range. At this point it can be argued, on the basis of SC factor values, that a high amount of stress can accumulate at the tips of these draw marks and this stress concentration can actively contribute to stress corrosion cracking (SCC)/corrosion-fatigue.

A photograph of the draw-marks as seen on the un-rusted areas is given in Fig. 5. The number (population) and the apparent depth of these draw-marks as seen in Fig. 5 cannot be regarded as a normal and acceptable feature of the deep drawn high pressure cylinders [4].

The 'fold' or 'overlap' shown in Fig. 4b, can also be seen in Fig. 6 as it appears on the inside surface of the cylinder. This fold, which is more than 1 mm deep, extends along almost the entire length of the cylinder. A fold of such depth can act as a highly effective 'stress raiser' in high pressure applications like a CNG cylinder [4-6]. For this fold, the stress concentration (SC) factor has also been calculated using Eq. (1) and the value is > 3.5. This value of SC factor is very high, indicating severe stress concentration with such a fold at the operating pressure. This fault could not have been produced during the deep drawing, but was inherently present in the metal blank that was used for making this particular cylinder [7] and should have been detected during the inspection and quality control stages of manufacturing.

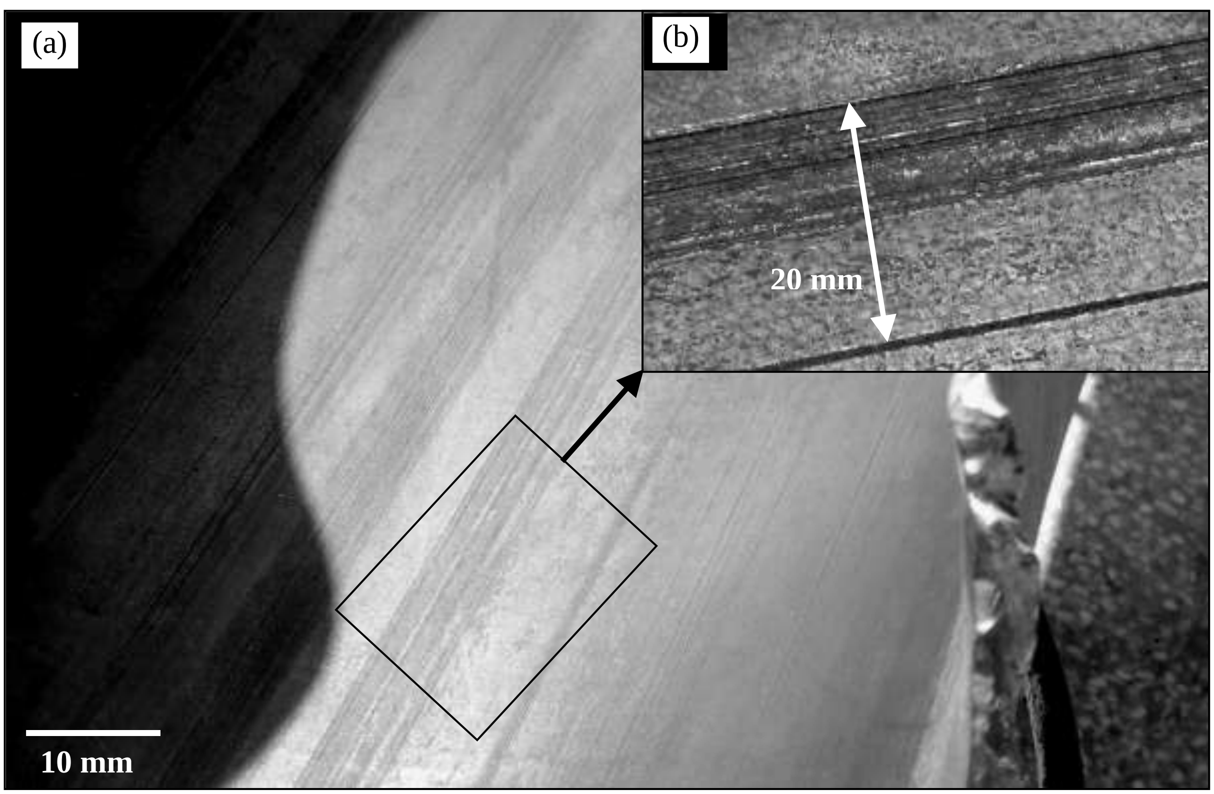

Fig.5 (a) Photograph showing the longitudinal draw-marks on the inside surface of the cylinder. The apparent depth and the sharpness of some of these draw-marks cannot be regarded as a normal feature of deep drawn cylinders to be used for high-pressure applications. (b) A magnified view of the draw marks.

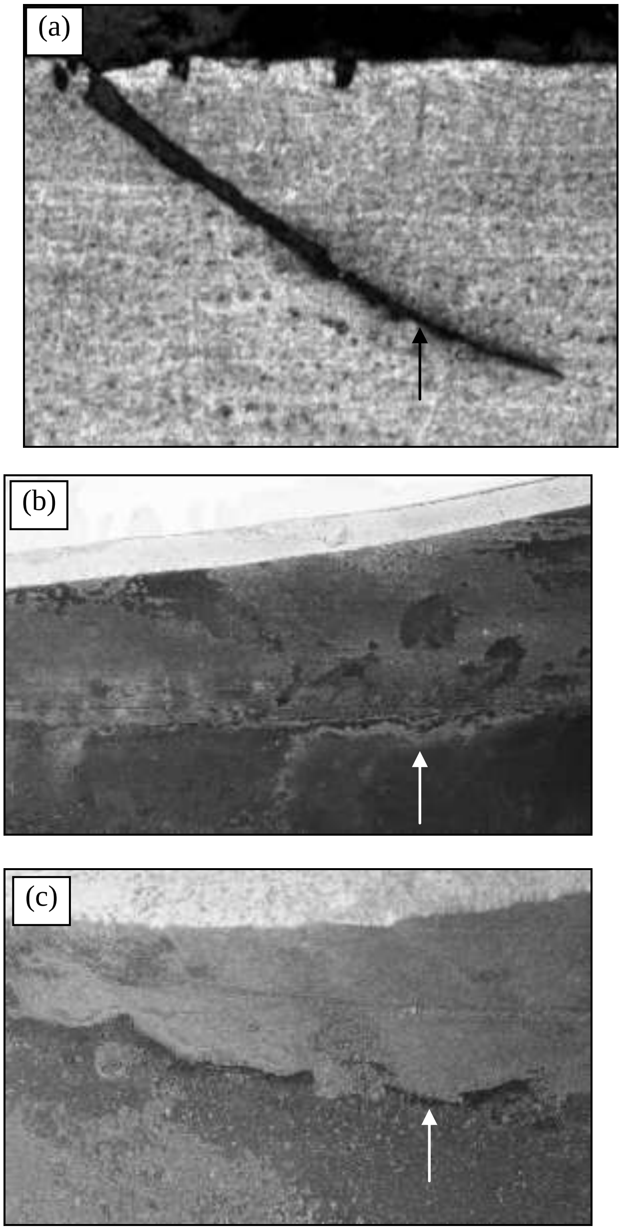

Fig.6 (b&c) Photographs showing the surface fold (or overlap) on the inside surface of the cylinder. Fig. 6a is the same as Fig. 4b.

6. Conclusions

The primary cause of the rupture was the presence of corrosive environments inside the cylinder due to the accumulation and stagnation of the water that must have been acidic in character. The rupture is believed to have been caused through 'Stress Corrosion Cracking' initiated at the longitudinal draw-marks on the inside surface of the cylinder.

The stress corrosion cracking was greatly assisted by the longitudinal draw-marks, which were deep enough to have acted as very effective 'stress raisers'. In the ruptured cylinder, the observed draw-marks could not be regarded as a normal feature of the deep drawn cylinders meant for high pressure usage. The presence of a surface fold clearly suggests that the inspection of the cylinder was negligent. It appears from the findings that quality checks at key manufacturing stages have been ignored by the manufacturer in the CNG cylinders lot supplied/imported for use.

7 References

[1] *Mechanical Metallurgy*, Dieter G. E., A McGraw Hill Book, SI Metric Edition, 1988.

[2] *Fracture Mechanics Analysis of NGV Fuel Cylinders. Part 1: Steel Cylinders***,** Connolly M. P., Hudak S. J., Roy S., *Topical Report, Aug. 1989 - Feb. 1993*, Southwest Research Inst., San Antonio, TX. Materials and Mechanics Department.

[3] *Influence of Interaction Between Multiple Cracks on Stress Corrosion Crack Propagation*, Masayuki Kamaya, Nobuo Totsuka, *Corrosion Science*, Volume 44, Issue 10, October 2002, Pages 2333-2352.

[4] *Failure* of *Engineering Components Due to Environmentally Assisted Cracking*, S.P. Lynch, *ASM International*, PFANF8 (2003) 5: Pages 33-42.

[5] *Materials selection in Mechanical Design*, Ashby M. F., A Butterworth Heinemann Book, 2nd Edition, 1999.

[6] *Failures of Structures and Components by Environmentally Assisted Cracking*, S.P. Lynch, *Engineering Failure Analysis*, Volume 1, Issue 2, June 1994, Pages 77-90.

[7] *Failure of Components and Products by 'Engineered-in' Defects: Case Studies*, C.R. Gagg., *Engineering Failure Analysis*, Volume 12, Issue 6, December 2005, Pages 1000-1026.