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The generation of corrosion under insulation and stress corrosion cracking due to sulphide stress cracking in an austenitic stainless steel hydrocarbon gas pipeline

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ABSTRACT

This paper describes a root cause failure investigation of a corroded AISI 304L stainless steel pipeline used to carry hydrocarbon gas. The corrosion was originally identified due to a leakage observed after removal of a section of lagging insulation. The investigation revealed however a three stage mechanism of attack had occurred; both intergranular cracking and transgranular cracking was present originating from both the internal and external surfaces. The process of attack occurred due to SSC from the internal surface resulting in CUI; the attack to the external surface then initiated SCC. A complex process of corrosion mechanisms was initially attributed to CUI, it was however due to internally initiated corrosion due to the combination of water carryover and the presence of corrosive species highlighting the importance of forensic examinations in oil and gas failures.

1. Introduction

It has been estimated that one third of all metallic failures are due to environmentally assisted cracking corrosion such as hydrogen assisted cracking and stress-corrosion cracking (SCC) [1]. Such mechanisms are a particular problem in the oil and gas industry with an estimated annual cost of £1.372 billion [2]. Corrosion of steels arises from the exposure to corrosive media such as sour gas or hydrogen sulphide (H_2S), carbon dioxide (CO_2) and free water. Often relatively high operating temperatures and pressures are involved which can further exacerbate the rate of corrosive attack.

Furthermore, due to the possibility of a 'cocktail' of corrosive media being present, a combination of corrosion mechanisms may be acting simultaneously. This paper describes the failure investigation performed on an austenitic stainless steel pipeline used to carry hydrocarbon gas. The investigation revealed the presence several corrosion mechanisms; pitting corrosion, corrosion under insulation (CUI), stress-corrosion cracking (SCC) and sulphide stress cracking (SSC).

1.1. Corrosion mechanisms

Pitting corrosion is a well-researched and understood highly localised form of corrosive attack that leads to the loss of material in the form of pits. In some cases if left to continue then pitting may increase to full wall thickness perforation [3].

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Nomenclature

CUI	corrosion under insulation
EDX	energy dispersive X-ray analysis
ESEM	Environmental Scanning Electron Microscopy
IG	intergranular
HAZ	heat affected zone
HE	hydrogen embrittlement
SSC	sulphide-stress cracking
SOES	spark optical emission spectroscopy
SCC	stress-corrosion cracking
TG	transgranular
XRD	X-ray diffraction

Corrosion under insulation (CUI) is a form of localised corrosion caused by the presence of moisture in pipeline insulation materials. The moisture can enter the insulation directly through the jacketing or may already be present within the insulation layer upon installation [4]. Subsequent dry/wet cycles increase the availability of aggressive corrosive species such as chlorides. The species then migrate towards the insulation/pipe interface. The problem is further exacerbated due to poultice effects retaining the species. Temperature cycles also contribute to an increased rate in corrosion attack. Research has shown that the mechanism of CUI can then lead to the initiation of other forms of attack such as SCC [4].

A well-documented and understood phenomenon is SCC. This corrosion process requires the simultaneous presence of a susceptible material, a tensile stress (residual or applied) and the presence of a corrosive environment. Often the environment may be considered mild with the level of stress required for failure well below the yield point of the material. SCC can often result in catastrophic failure as it is typically undetectable from the surface [3]. Intergranular (IG) branched cracking is the most common form of crack propagation in SCC.

The final corrosion related mechanism of interest within this study is the less well known phenomenon of sulphide-stress cracking (SSC), also termed hydrogen sulphide-stress cracking, due to it being one of the known forms of hydrogen embrittlement (HE).

A cathodic mechanism commonly found in oil and gas applications operating around ambient temperatures. The natural gas and crude oil media contain considerable amounts of H_2S which reacts with the metallic surface, resulting in the formation of both sulphides and atomic hydrogen. The atomic hydrogen may either simply 'sit' at the surface, or, diffuse through the grain structure. The sulphur can also affect the formation of the molecular H_2 atoms, which can lead to increases in the availability and rate of diffusion of atomic hydrogen. Diffusion of the atomic hydrogen can then form molecular hydrogen throughout the grain structure, reducing the ductility and load-bearing capacity of the steel, which causes cracking and catastrophic brittle failures at stresses below the expected yield stress.

An increase in hardness of a stainless steel increases the risk of SSC, along with composition and microstructure also affecting susceptibility for SSC attack [5]. Cracking is typically internally initiated and propagates through an IG mechanism exhibiting very little crack branching, although some reports of transgranular (TG) cracking have been observed in SSC, but TG is more likely not related to HE [6]. Externally driven SSC tends to be from sulphate reducing bacteria in soil water coming into contact with the pipe wall.

This study describes the failure of a hydrocarbon stainless steel (304L) pipe which exhibited through wall leakage, initially attributed solely due to CUI. Forensic examination however revealed the leakage was initiated by SSC attack from the internal surface which subsequently lead to both CUI and SCC attack from the external surface.

2. Experimental procedure

The failed section of pipeline was removed from the plant and examined in the laboratory using various experimental techniques. Visual identification of cracks was achieved through liquid dye penetrant testing (DPI). The chemical composition of the material was assessed using SOES and the hardness measured using a Vickers macro-indenter. Scanning electron microscopy (SEM) was performed to examine the internal and external surfaces of the pipe and the morphology of opened cracks. Energy dispersive X-ray analysis (EDX) was used to determine elemental composition of the insulation materials, substrate materials and corrosion products. To assess corrosion, cracking mechanisms and microstructures optical microscopy of metallurgically prepared samples was employed. Assessment for the susceptibility of the material to sensitisation was carried out in accordance with ASTM A262 [7]. X-ray diffraction (XRD) was used to determine the crystallographic structure and chemical information of the internal surface of the pipeline. Copper kα radiation (λ = 0.15406 nm) was employed with and a secondary monochromator with a step size of 0.05°2θ between the range of 5°–75°2θ and a count time of 12 s per step.