STRESS CORROSION CRACKING: A CANADIAN PROSPECTIVE FOR OIL AND GAS PIPELINE

Mimoun Elboujdaini and Mahmoud T. Shehata
CANMET Materials Technology Laboratory
Natural Resources Canada, Government of Canada
568 Booth Street, Ottawa, Ontario K1A 0G1
Email: {melboujd@NRCan.gc.ca}

CANADIAN NATIONAL ENERGY BOARD INQUIRY

Stress corrosion cracking (SCC) is a form of environmentally assisted cracking (EAC) that is of great significance to Canadian oil and gas pipelines. In these pipelines when ground water penetrates under the pipe coating, longitudinal cracks develop and grow at a maximum through-wall rate of about 0.6 mm/year. Over the last decades, thousands of colonies of these cracks have been found all across pipelines in Canada (Figure 1). These cracks frequently go dormant at depths of about 1 mm. Occasionally, for reasons as yet not understood, the cracks continue to propagate and this can lead to pipe rupture. This phenomenon led to several serious ruptures within the Canadian pipeline system between 1985 and 1995 and the phenomenon was the subject of two National Energy Board (NEB) inquiries in the 1990's [1].

Pipeline steels are often susceptible to SCC in two basic forms of cracking, namely Intergranular and Transgranular. Intergranular cracks initiate and propagate at grain boundaries and usually form at high-pH (8.5-10.5). They are initiated at the outer surface of pipe and the cracking results from the generation of a carbonate-bicarbonate solution under disbonded coatings. On the other hand, transgranular cracks cut through the grain and is usually manifested at near-neutral-pH SCC (5.5-8.5). Transgranular cracks in high-pressure gas pipelines has been found to be associated with dilute solutions of near neutral pH in regions where coatings are disbonded. This environment could develop from ground water in the presence of carbon dioxide (CO_2). However, it is not understood how cracks initiate under such a coating disbondment environment, and whether there are any microstructural features responsible for the initiation process. A characteristic of both types of cracks is the presence of colonies of longitudinal surface cracks in the body of the pipe that link up to form small flaws (or shallow cracks).

Near-neutral pH EAC is now reasonably well controlled from an integrity management point of view and there have been, at most, one or two ruptures a year in Canada since 1995. Although soils models were developed to help assess risk, these are rather imprecise, and predicting the occurrence of minor SCC rather than significant SCC. Thus, at present, significant portions of pipeline are managed by in-line inspection for oil pipelines or by hydrostatic testing for gas pipelines. Either of these techniques provides protection from in-service failures for a number of years and then the process has to be repeated. The testing cycle is particularly troublesome for gas pipelines since only quite large flaws that fail at SMYS (specified minimum yield strength) are detected by the hydrostatic testing technique. These procedures are enormously expensive. The present monitoring methods for EAC cost a lot of money to pipeline industry. Indeed, a better knowledge of the mechanism of SCC crack initiation and propagation leading to more accurate prediction of the locations of significant SCC would enormously reduce the cost. This knowledge would also reduce the rupture rate and hence prevent the associated large gas fires (releasing clouds of carbon dioxide and smoke) and the oil fouling (threatening ground and river water supplies) that accompany these failures. Near-neutral pH EAC is now reasonably well controlled from an integrity management point of view and there have been, at most, one or two ruptures a year in Canada since 1995. Although soils models were developed to help assess risk, these are rather imprecise, and predicting the occurrence

Figure 1: Small 'SCC' cracks, that are widespread in tape-coated line pipe.

of minor SCC rather than significant SCC. Thus, at present, significant portions of pipeline are managed by in-line inspection for oil pipelines or by hydrostatic testing for gas pipelines. Either of these techniques provides protection from in-service failures for a number of years and then the process has to be repeated. The testing cycle is particularly troublesome for gas pipelines since only quite large flaws that fail at SMYS (specified minimum yield strength) are detected by the hydrostatic testing technique. These procedures are enormously expensive. The present monitoring methods for EAC cost a lot of money to pipeline industry. Indeed, a better knowledge of the mechanism of SCC crack initiation and propagation leading to more accurate prediction of the locations of significant SCC would enormously reduce the cost. This knowledge would also reduce the rupture rate and hence prevent the associated large gas fires (releasing clouds of carbon dioxide and smoke) and the oil fouling (threatening ground and river water supplies) that accompany these failures.

STRESS CORROSION CRACKING PHENOMENON

SCC in steels for oil and gas pipelines is a very complex and challenging phenomenon. The complexity of SCC is reflected in the changes, with time, of the diverse parameters influencing the cracking phenomenon, whereas, the biggest challenge is in obtaining field-relevant reproducible laboratory data. SCC encompasses major effects from metallurgical, mechanical, and environmental parameters, all of which can be dominant under specific conditions. Adding to the complexity are the loading conditions in operating pipeline that define the mode of failure as SCC or corrosion fatigue (CF). While SCC and CF are sometimes regarded as different modes of failure, the distinctions between them in mechanistic or engineering terms are becoming less sharply defined. Thus, to consider SCC and CF as involving static and cyclic loads, respectively, appears increasingly arbitrary, since in many cases SCC is found in operating pipelines where the loads are not static.

In any EAC process, whether SCC or CF, there are generally three stages for the cracking process: (i) generation of an environment that causes cracks to initiate; (ii) initiation of cracks; and (iii) propagation of cracks until failure occurs. This present study is focused on crack initiation, types of cracks, crack behavior, role of crack initiation sites, inclusions, factors governing crack growth, and the crack coalescence process in the context of low-pH SCC in linepipe steel. For the current research, the validation of the results under accelerated test conditions is based on the assumption that the micro-processes, microstructural features, and specific sites associated with initiation of cracks in laboratory tests are those associated with the initiation of SCC in operating pipelines. In this context, the following aspects were studied for SCC initiation:

1. The site of where cracks are initiated in relation to metallurgical factors, such as nonmetallic inclusions, grain boundaries, specific phases, or other forms of surface discontinuities or surface defect;
2. The role of applied mechanical loading conditions, including: the effects of stress level (for static and cyclic loading), strain rate (for dynamic loading), stress ratio, R, and loading frequency, f;
3. The time dependence of crack development, including: (i) existence of an incubation time, (ii) changes in crack number density, crack size with time, dormancy, and (iii) the crack growth rate;
4. The spatial distribution of cracks. Spacing affects crack interaction and coalescence and significantly influence the overall cracking behavior and hence, the lifetime of a pipeline.

CRACK INITIATION AND EARLY-STAGE GROWTH

A fatigued single-phase pure alloy, when exposed to an aggressive environment, often produce a high number of microscopic cracks that are initiated following slip traces and other surface stress concentrators resulting from plastic deformation. However, in some occasions the effect can be the opposite, in that preferential dissolution along active slip bands can tend to dissolve out microcracks and decelerate the initiation of a macroscopic crack. On the other hand, in alloys containing two or more phases, crack initiation can be accelerated in one of the phases, as influenced by the plastic strain amplitude and the relative deformability of the two phases.

In commercial alloys, corrosion pitting is often the cause of crack initiation, as cracks preferentially initiate at corrosion pits that often start at nonmetallic inclusions. In steels, sulphide inclusions at the external surface often act as sites at which corrosion pits form and cracks initiate as well as it provide sites around which, accelerated hydrogen-assisted cracking can be facilitated.

Near-neutral pH environmentally assisted cracking should be regarded as a process occurring in distinct stages. Cracking begins with the formation of shallow cracks at pits, inclusions or persistent slip bands at the metal's surface. There are two aspects in the growth of these starter cracks that may lead to crack arrest. It has been observed in the laboratory [2] that microstructurally short cracks often are arrested at the grain boundary or pearlite boundary. This process is not very important practically, because these tiny cracks (<10 μm) are below reasonable inspection levels so their existence is not recognized as an integrity threat. Of more significance are the mechanically short cracks, typically from 0.1 to 1 mm deep and up to a few mm long. Such short cracks are found in very large numbers in operating pipelines and can be produce due to fatigue in air. They are usually sharp and crack more readily than long cracks. In near-neutral pH environmentally assisted cracking, however, most of these cracks are found to become dormant and hence are innocuous. Significantly, they are always found near the site of ruptures (Figure 2), so it is felt that these cracks are sometimes precursors to rupture [3]. It is not known why the vast majority of small cracks are innocuous, but only very few go on to become ruptures. Of paramount concern to pipeline companies are identifying and avoiding the conditions that sometimes cause short cracks to continue to grow. Once this short crack surpasses a critical threshold, they grow by the "normal" growth process for near-neutral pH. This is presumably because the driving force for growth is above some threshold value, which for SCC has traditionally been denoted as K_{ISCC}. This has been widely recognized [4,5] as a critical issue for pipeline integrity.

IMPLICATIONS TO PIPELINE OPERATION

We will start by noting that EAC in near-neutral pH solutions has traditionally been referred to as SCC, but it is increasingly being accepted that normal crack growth, especially in oil pipelines, is actually a form of "corrosion fatigue", since crack growth does not occur without a significant variation in stress, which is the hallmark of a fatigue process [6]. It is fairly well established [7] that both crack tip dissolution and hydrogen embrittlement contribute to the normal cracking process,

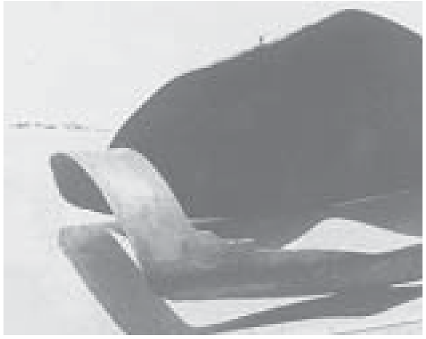

Figure 2a: SCC failure as root cause.

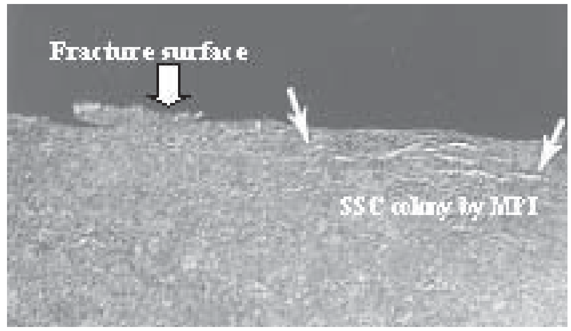

Figure 2b: Magnetic Particle Inspection (MPI) picture of SCC colony found next to a pressure failure. The outside pipe surface shows additional, longitudinal cracks adjacent to the fracture origin.

but the exact mechanism has so far not been delineated. It is also observed [7] that more corrosive conditions tend to eliminate starter cracks; whereas, higher mechanical driving force (higher ΔK or higher frequency) tend to promote initiation. We can argue that the initiation process is not as dependent on hydrogen ingress as the crack growth process. Since the radius of the plastic zone is proportional to K_I^2/σ_{ys}^2, small cracks possess only a small region of high stress that will accumulate hydrogen. Smaller brittle regions are more difficult to crack. It has been experimentally observed [8] that cathodic polarization (that tends to increase the production of hydrogen and suppress dissolution) will slow the growth of small cracks but will accelerate the growth of larger cracks. It has been observed, however, that in cracks over 0.5 mm deep there were tiny cracks ahead of the main crack that may be associated with HIC [9] so the critical depth may be about this size. Another facet of the different growth mechanism of cracks below the threshold comes from the observation that tiny cracks in soil box tests can grow in size with virtually no variation in stress [10]; while, in contrast, various efforts have been made to grow larger cracks without varying the stress and all have failed in spite of the large applied forces [11,12]. Considering all these differences it is clear that growth during initiation must be considered as distinct from “normal” crack growth.

Recent studies on SCC [13-15] showed that fatigue loading or other processes that accumulate dislocations along a line, produce mechanically small cracks suitable as starter cracks. The most likely cracking process is anodic dissolution of the higher energy region of the dislocation networks. Chen *et al*. [9] have studied starter cracks up to 800 µm deep in two regions in X-65 line pipe from near a rupture region. They showed that cracks could be characterized as either linked or independent with somewhat different characteristics. All these cracks were relatively wide at the tip. For example, a 600-µm deep crack showed a variation in crack tip width from 75 µm to 300 µm. It is believed that the crack-like characteristics come from processes of fatigue and/or plastic flow that cause accumulation of dislocations along a narrow region followed by the preferential dissolution of this deformed region. Corrosion fatigue nucleation studies on steel in 3.5% NaCl showed that early growth is related to dissolution and that pearlite colonies can be one obstacle to stop crack growth [16]. The starter cracks are not believed to grow by either a straight fatigue cracking or a corrosion fatigue cracking process. These starter cracks would continue to accumulate dislocations and grow, whenever there is sufficient stress variation because the cracks act as stress raisers. There is, however, a competing process, the corrosion of the starter cracks to produce shallow pits. These starter cracks appear at inclusions, persistent slip bands and at pits. As this corrosion occurs and the tip blunts, the ability of this region to support plastic deformation declines. Additionally, as the cracks deepen, the electrolyte in the crack becomes altered from that of the bulk solution. This process is sometimes referred to as acidification. It would appear that there is a competition between the starter crack growth processes and the starter crack blunting processes. In summary, the cracking process depends on:

1. The size and frequency of the pressure variations in the linepipe and the modification of this operating stresses caused by residual stresses and stress raisers;
2. The characteristics of the near-neutral pH solution including especially its corrosivity and its ability to otherwise affect the cracking processes such as through hydrogen ingress;
3. The linking or coalescence process for neighbouring growing cracks (Figure 3) that was proposed [2,14] as a means to encourage growth, but which was shown by measurements to be more likely associated with crack tip dormancy [9].

The implications of the above factors on the operation of a pipeline are to consider the cause of stresses that are exerted on the pipe during its operation. For example, the operating pressure in the pipeline and more importantly is the pressure variation during the operation. Other implications are concerned with the type of soil surrounding the pipe and expectations of soil movements and permafrost that could exert pressure and external stresses on the pipe. The type of soil and how it could affect the acidity around the pipe is also important. Metallurgical factor relates to nonmetallic inclusions in the steel from which the pipe is made and what steel making practices was used in its production. Other metallurgical factors relates to the various welds in the pipe and what kind of problems that could be expected from welds. However, it is not easy to cover in details all these factors affecting SCC in line-pipe steels in one paper, but it is hoped that the paper provided some valuable insights on the initiation process of SCC and some understanding of the competing processes in the development of SCC in steels for oil and gas pipelines.

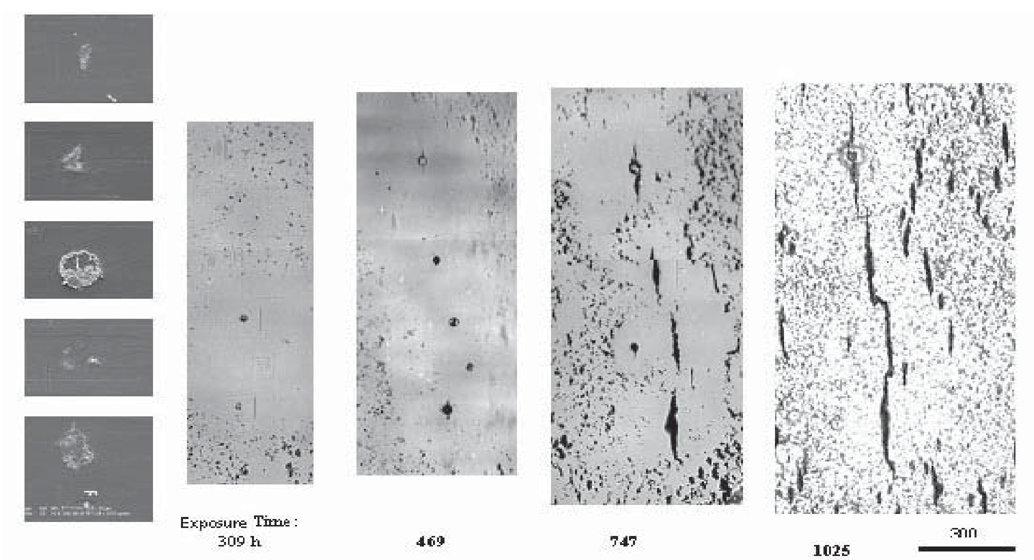

Figure 3: Development of 5 cracks, a, b, c, d and e, after the total exposure time shown in a X-65 specimen at smax = 70% YS, R = 0.6 and f = 0.1 Hz in NS4 solution saturated with CO_2, showing the correlation of crack initiation, pits and non-metallic inclusions and the interaction and coalescence of cracks. (Observations were made on replicas) Ref. 7

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