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TECHNICAL ARTICLE — PEER REVIEWED

Investigation and Recommendations on Bottom-Dented Petroleum Pipelines

Erik Mueller · Xiaohu Liu · Ravindra Chhatre · Adrienne Lamm

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Abstract On September 21, 2015, the National Transportation Safety Board responded to a petroleum leak from a transmission pipeline in Centreville, VA. A small through crack was found leaking at a dent on the underside of the pipe, located away from any welds. The investigation found that corrosion fatigue could initiate at small dents, typically caused by impingement. While top-side dents from excavation and servicing have well-been documented and regulated, bottom-side dents, deemed acceptable per regulations, were found to be susceptible to stress corrosion and fatigue cracking. This investigation explored multiple and fundamental aspects of cracking in steel pipe dents, including nondestructive inspection, electron microscopy, finite element modeling, and long-term cyclic loading tests to characterize the cause of this pipeline accident.

Keywords Pipeline · Corrosion fatigue · NNpHSCC · Dent · Fatigue cracking

E. Mueller (✉) · A. Lamm
Materials Laboratory Division, NTSB, L'Enfant Plaza East, SW, Washington, DC 20594, USA
e-mail: erik.m.mueller@gmail.com

X. Liu
Vehicle Performance Division, NTSB, L'Enfant Plaza East, SW, Washington, DC 20594, USA

R. Chhatre
Pipeline and Hazardous Materials Division, NTSB, L'Enfant Plaza East, SW, Washington, DC 20594, USA

Introduction

On September 21, 2015, a gasoline leak was detected at the location of a petroleum pipeline in Centreville, VA. The National Transportation Safety Board (NTSB) responded to the accident, as the agency investigates pipeline accidents where a fatality, substantial property damage, or significant environmental impact has occurred. As of 2016, there were over 211,000 miles of hazardous liquid pipeline in the USA and Canada, of which over 62,000 miles carry refined petroleum products [1].

Underground infrastructure must be designed to resist a variety of conditions, ranging from corrosion to geological activity [2]. One of the issues studied are dents in pipelines. Dents can create stress risers in the pipe, allowing initiation sites for fatigue and stress corrosion cracking (SCC) [3]. In addition, dents damage the protective coatings on the pipe surfaces, allowing water, microbes, and other contaminants to contact the pipe metal surface [1]. Compromised coatings can enable near-neutral pH stress corrosion cracking (NNpHSCC) [4].

Most dents are created either during installation or during repair, when mechanical equipment makes excessive contact with the pipeline. These pipelines are typically constructed from low-carbon steels, which have high ductility [5] but must be coated to protect them from environmental attack [6].

Upon excavation of this accident pipeline, liquid refined petroleum product was found leaking from a longitudinal through-wall crack at the dent in bottom of the pipe (6 o'clock position). This crack was located away from seam or girth welds. The dent was approximately 23 inches (58 cm) long, 16 inches (40 cm) wide, and 0.75 inches (1.9 cm) deep. During the on-scene investigation, a second dent at a 6 o'clock position was found downstream of the cracked dent, measuring approximately 17 inches (43 cm) long, 26 inches (67 cm) wide, and 0.63 inches (1.6 cm) deep. While this second dent contained corrosion pits, nondestructive testing (NDT) did find any crack indications. Two four-foot long sections of this uncracked dented portion of pipe and the crack dented portion were excised from the pipeline and sent to the NTSB Materials Laboratory.

The pipeline was made of API 5L X52 steel, manufactured in 1963, with a nominal outside diameter of 32 inches (81.3 cm) and wall thickness of 0.281 inches (0.714 cm). The pipe was buried under approximately 6 feet (1.8 m) of clay. The pipeline at this location was coated with asphalt enamel, applied at installation. The nominal operating pressure of the pipe was 325 psig (22.4 bar) with a maximum operating pressure of 657 psig (45.3 bar). The last hydrotest was performed in 1990, and the last in-line inspection (ILI) using ultrasonic shear wave crack detection was performed in October 2014.

Investigation Methods

The on-scene and excavated pipeline segments were photographed with a Canon EOS Rebel T3i digital camera and Keyence VHX-1000 digital microscope. The digital microscope can produce high-dynamic range and composite high depth-of-field images. Dry-particle magnetic particle inspection (MPI) was performed on the surface exterior of the dents.

The two extracted pipeline segments were measured using laser scanners to record dent position and topographical information. The segments were scanned with a FARO Focus 3D rotating ranging scanner and a FARO Freestyle handheld scanner. These data were compiled as point cloud data, later used for finite element analysis.

Sectioned specimens produced from the extracted pipelines were examined using a Zeiss Auriga field emission scanning electron microscope (SEM). This microscope was equipped with a Thermo Scientific UltraDry NORAN System 7 energy dispersive X-ray spectroscopy (EDS).

Several metallographic cross-sectional specimens of the pipeline were mounted, polished to 0.5 µm grit, and etched using a 2% Nital solution. These specimens were inspected using a Zeiss Axio Observer Z1m inverted microscope.

The hardness was inspected per ASTM E18 and was measured on mounted, polished cross sections in the longitudinal and circumferential directions, using a Wilson RB2000-T hardness tester. Additional testing was provided by Lehigh Testing Labs in New Castle, DE. This included optical emission spectroscopy with carbon, sulfur and nitrogen analysis, and mechanical tensile and subsize sample (5 mm × 10 mm) Charpy impact testing per ASTM A370 at 20 °C.

The section of dented, uncracked pipeline was fatigue tested at BMT Fleet Technology, Ltd., in Ottawa, Canada, to determine the time and location of cracks that may have eventually formed in the dent. This fatigue test involved welding end caps to the pipe segment, and then cycling pressurized water to induce loading by hydraulic pressure from 90 to 365 psig (6.2–22.4 bar), which would replicate common service pressure cycles. The pipe segment was cycled until a through-thickness wall crack developed, with regular interruption of the testing to perform magnetic particle inspection of the dent. After testing, specimens from this pipe were examined using SEM and metallography.

Results of the Investigation

The crack was located within an inwardly dented section of the pipeline, as illustrated in Fig. 1. During the initial excavation, there was no rock or other object in direct contact with the pipeline. Reports from a prior excavation in 1994 stated that a rock had been in contact with the pipeline, but it had been removed. The enamel asphalt coating was found compromised at the leak location on the bottom of the pipe.

Figure 2 illustrates a rendering of the laser scan data from the cracked, dented pipe section. This dent depth was calculated as being 2.3% of the pipe diameter, and the uncracked dented pipe segment was measured a 1.9%.

The area surrounding the cracked dent was cleaned using a wire wheel offset grinder, revealing small pits on the surface (Fig. 3). A colony of cracks parallel to the through-wall crack was present, aligned with the longitudinal direction of the pipe. The through-wall crack was backcut and intentionally overstressed (laboratory fractured). Figure 4 shows one of the mating sides of the opened crack face or fracture surface. The oxidized crack measured 5.970 inches long (152 mm) on the outer pipe surface and 4.518 inches (115 mm) on the inner. Adjacent to the crack location, the pipe thickness varied between 0.266 and 0.270 inches (6.76–6.86 mm). The nominal thickness of the pipe was 0.281 inches.

The crack faces exhibited features consistent with progressive cracking, originating at multiple crack initiation sites on the outer pipe surface, propagating inward, as exemplified by crack arrest marks and ratchet marks (Fig. 5). Progressive, sequential ultrasonic cleaning of the fracture surface (using acetone, then a basic solvent, then a rust remover) revealed fatigue striations along the edges of the crack.

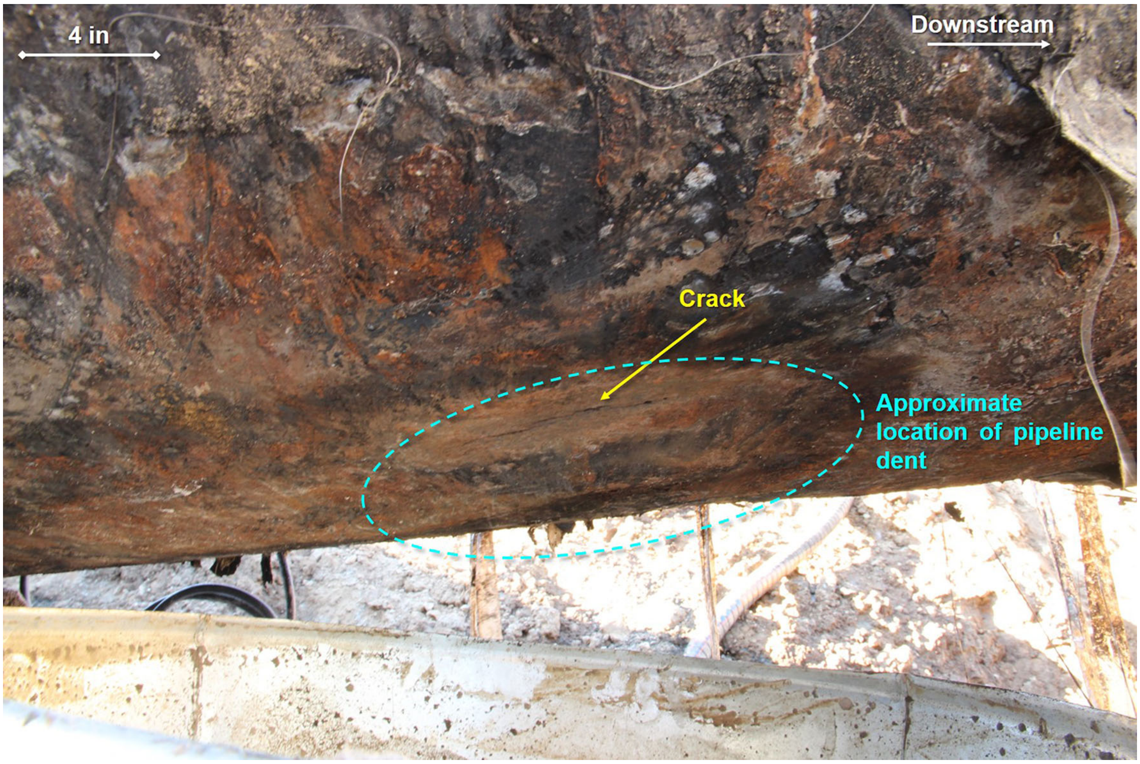

Fig. 1 The 6 o'clock position of the upstream portion of the pipeline from underneath, showing the crack and dent

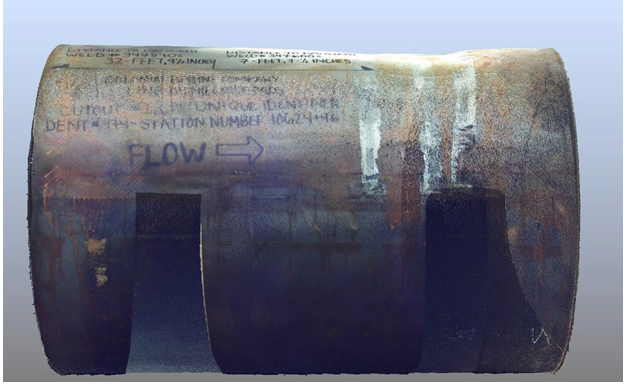

Fig. 2 Rendered data representation of the dented, cracked pipeline from laser scanning, showing the pipe from the side, and the degree of material deformed at the dent

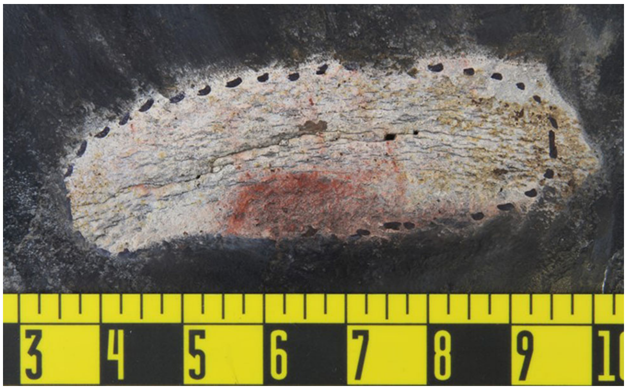

Fig. 3 View of the outside surface of the cracked pipe segment, after sectioning, showing the parallel crack colony about the through-wall crack in the white region

Cleaning of the fracture surface oxide also revealed an underlying faceted morphology, as illustrated Fig. 6, consistent with grains of the microstructure. A mix of fracture features, including fine dimple rupture and faint fatigue striations, was observed along the facets, consistent with a compound propagation mode such as corrosion fatigue. While most of the fracture surface exhibited a general orientation perpendicular to the outer surface of the pipe, secondary cracking perpendicular to the fracture surface was documented (Fig. 6).

Since the initiation sites of the opened primary crack were obliterated by oxidation, the parallel cracks were examined. These cracks were observed propagating from exterior surface pits (Fig. 7). Both the pits and crack interiors exhibited material consistent with iron-based corrosion products (Fig. 8). The cross-sectioned cracks were generally consistent with transgranular propagation, but some perpendicular secondary cracking was observed. These secondary cracks tended to intersect pearlite colonies in the microstructure adjacent the main crack. Figure 9 shows the tip of the largest cross-sectioned crack. The

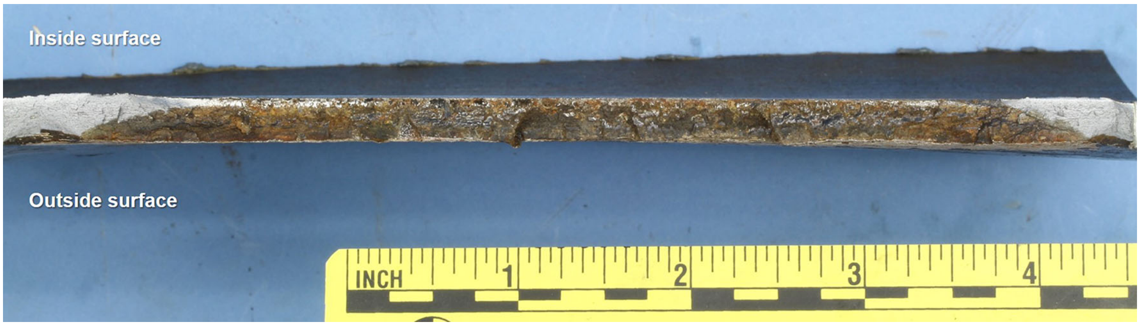

Fig. 4 View of one of the faces of the main crack after laboratory fracture and crack opening

Fig. 5 View of the right edge of the through-wall crack from Fig. 4, showing crack arrest and ratchet marks, consistent with progressive cracking

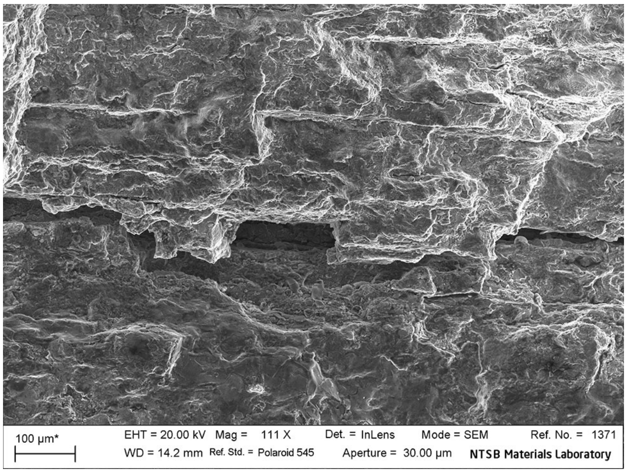

Fig. 6 Secondary electron (SE) micrograph showing branched secondary cracking into the fracture surface at the end of the crack

crack contained compounds consistent with iron oxide, as well as detectable levels of magnesium and silicon. The "darkest" areas of the crack tip oxide also contained silicon, phosphorus, sulfur, and chlorine.

The uncracked, dented pipe segment was fatigue tested over 28 days. The first discernible crack indication, observed at 3100 cycles, became a linear indication at 5830 cycles. These indications were located neither at the dent apex nor at corrosion pits, but rather at a shoulder in the dent. The first indications present at corrosion pits did not appear until after 30,000 cycles. The first detected liquid through a crack was at 41,439 cycles, consistent with crack propagation through the pipe wall [7].

One end of this through-wall crack was cross-sectioned for metallographic inspection, and the other laboratory fractured. The opened crack face revealed a thumbnail-shaped crack that exhibited crack arrest marks and ratchet marks, consistent with the fatigue crack propagation from cyclic loading during the test (Fig. 10). The opened crack exhibited some rust, consistent with contact with the internal pressurized water.

Discernible fatigue striations were observed throughout the cyclic-tested pipe fracture surface (see Fig. 11). In contrast to the accident crack fracture surface, the striations had not been obscured by oxidation, and there was no evidence of other fracture features such as grain boundary facets.

Toward the end of the fatigue crack, secondary branched cracking was present. This was observed in the metallographic cross sections, which revealed branched cracking in a parallel crack (Fig. 12). The branching occurred approximately 4 mm deep from the outer pipe surface. Closer examination of the crack did not find any propagation preference along prior austenite grain boundaries, between pearlite and ferrite, or other features.

The mechanical properties and chemical composition of the pipe material conformed to the requirements of API 5L X52 steel. The microstructure of the pipeline exhibited mostly elongated ferrite with approximately 30% volume fraction of pearlite colonies dispersed throughout. The yield strength, ultimate tensile strength, and elongation (ductility) conformed to the minimum requirements, and the hardness averaged 86 HRBW. The impact energy in the longitudinal direction averaged 46 ft.-lbs. (62.4 J) and 21 ft.-lbs. (28.5 J) in the transverse.

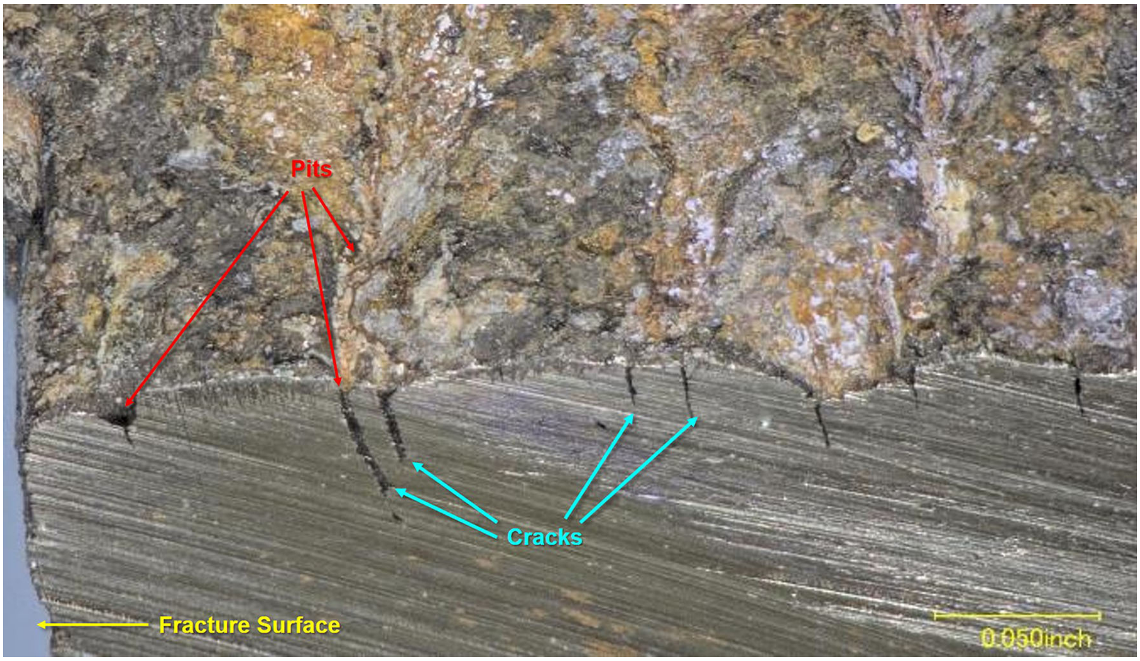

Fig. 7 Angled view of a cross section of through-wall fracture surface, showing parallel cracks propagating from pits on the outer pipe surface

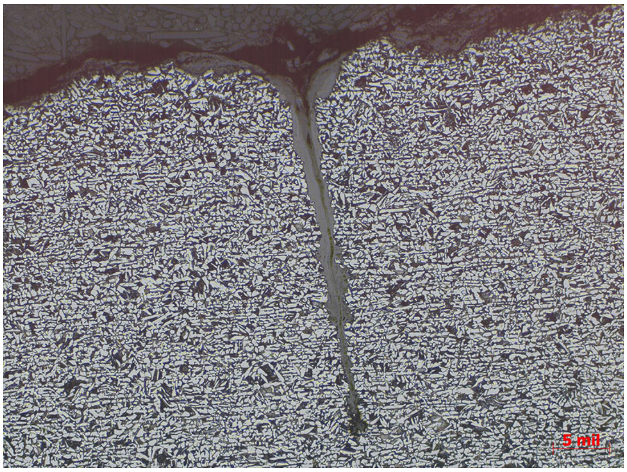

Fig. 8 Bright-field optical micrograph showing oxidation in a crack emanating from a corrosion pit, after etching with 2% Nital solution (~ 100×)

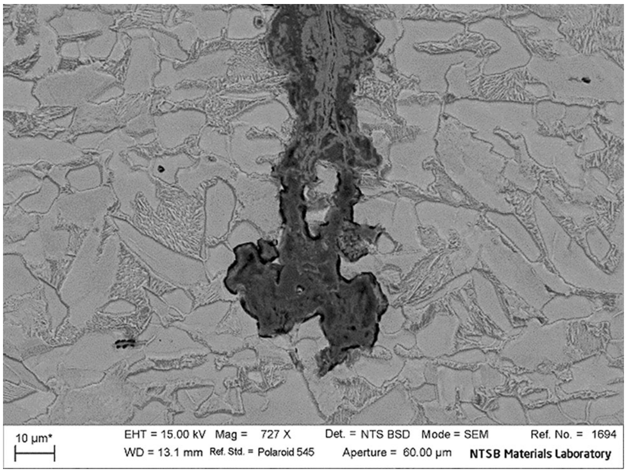

Fig. 9 Backscattered electron (BE) micrograph of the crack tip from Fig. 8

Analysis and Discussion

The petroleum product release occurred when a crack at a bottom-sided dent propagated through the pipe wall. This crack, one of a colony of parallel cracks in the dent, initiated at corrosion pits on the outer surface of the pipe. The crack propagation was consistent with corrosion fatigue that initiated at pitting consistent with near-neutral-pH stress corrosion cracking. These pits and colony of cracks were present at an inward dent in the pipe, which likely formed from an impingement with a rock that had been removed.

Pipeline steels are known to be susceptible to two forms of environmentally assisted cracking: high-pH and near-neutral-pH SCC [8, 9]. In both cases, corrosion tends to initiate at the pipe surface, commonly from groundwater penetration due to coating disbonding [6, 10], manifesting as colonies of longitudinal cracks on the outside surface [8–12].

Field studies of NNpHSCC fractures show that they exhibit transgranular cracks with evidence of mixed dimple rupture and faceted features [13, 14]. NNpHSCC tends to initiate via pitting [8–14]. These features were present on the accident through-wall crack.

Fig. 10 Opened fatigue crack from the dented pipe after cyclic hydraulic testing

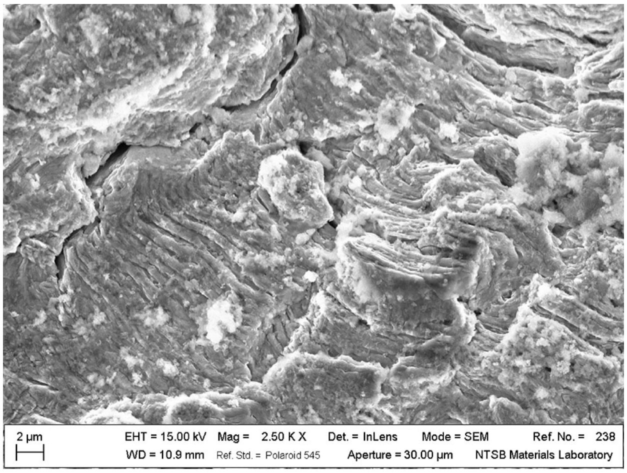

Fig. 11 SE micrograph of fatigue striations at mid-distance of the opened crack in Fig. 10

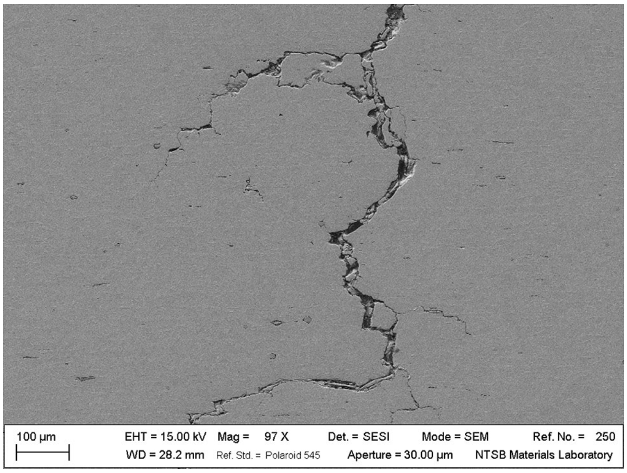

Fig. 12 BE micrograph of a cross section of a crack parallel to Fig. 10, exhibiting crack branching

NNpHSCC typically occurs in a pH range of 5.5–8.5, with small quantities of chloride and sulfate compounds present [13]. Studies of NNpHSCC found that dilute groundwater containing dissolved carbon dioxide, evolving from organic matter decay or soil reactions, drives the reaction [9, 11].

Even with cathodic protection, NNpHSCC can still occur due to localized shielding of the protection current, as well as improper coating, a high-resistivity soil, poor cathodic protection design [15, 16], or seasonal environmental fluctuations [17–19]. However, there were no indications that the cathodic protection on this pipeline was substandard, and no study of shielding effects was performed in this accident.

This pipeline fracture surface also exhibited features consistent with corrosion fatigue. Cracking initiated at corrosion pits and was generally transgranular, with some secondary crack branching. Corrosion fatigue typically occurs at pH conditions closer to neutral [20]. Corrosion fatigue can exhibit both intergranular cracking and fatigue striations on the fracture surface [21]. In carbon steels, corrosion fatigue cracks have been found to initiate at corrosion pits containing corrosion products [2].

This investigation found that different cracking mechanisms can exhibit common features and characteristics. Comparing the cracking in the fatigue-tested dented pipe segment and the cracked accident pipe segment revealed both exhibited colonies of parallel cracks in the dents, and the cracks progressed from the outside surface inward with a thumbnail-shaped morphology, exhibiting crack arrest and ratchet marks. The accident fracture surface exhibited crack branching. The fatigue-tested dented pipe also exhibited crack branching not typical of fatigue crack propagation. Some fatigue crack branching has been observed in highly directional steels, where harder pearlite or cementite deflect fatigue cracks as they grow [22, 23]. In addition, branched cracking was observed in cyclic tests of X65 tested in high hydrogen atmospheres, which can delaminate between microstructural differences near the crack tip [24].

In contrast, the accident fracture occurred at corrosion pits in the apex of the dent. The through-wall crack in the tested pipe initiated at the shoulders of the dent absent corrosion pits. The cracks present at the time of the leak contained corrosive elements common in NNpHSCC and corrosion fatigue [19, 20]. Lastly, the cracking in the fatigue-tested segment showed that (depending on testing conditions) cracking would often occur in the shoulders of the dent, where the highest stress concentration was located [25].

In both cases, cracking of the pipeline occurred at a dent, which increases the susceptibility to failure. The calculated peak stress values for the dent exceeded the measured yield strength for the pipe, and the resulting residual stresses would make the pipeline more susceptible to stress corrosion and fatigue [26]. In addition, the change in geometry has been found to concentrate stresses sufficiently to enable fatigue cracking under cyclic loading conditions [3, 25].

Applied cyclic stresses that result from pressure fluctuations and latent residual stresses can affect susceptibility to NNpHSCC. Cyclic stresses enhance local strain around the pits, increase the rate of initiation and later propagation of these cracks [15, 18, 27]. The pipeline underwent cyclic loading during its lifetime, which has been described or modeled as a form of low-cycle fatigue [3, 28]. The tests on the uncracked dented segment of pipe attempted to replicate this low-cycle fatigue. In addition, finite element modeling of the cracked and uncracked dented segments determined they exhibited residual stresses high enough to be susceptible to both NNpHSCC and fatigue crack initiation [20].

Recent studies on constrained (impinged by a hard object) and unconstrained (free to flex) pipe segments have attempted to model fatigue fracture in pipes [29]. Fatigue studies on dented pipes have been shown to develop colonies of parallel cracks that visually appear to be SCC, but are only fatigue. The unrestrained dented pipe segments in tests have been found to fail faster, due to the lack of constraint (e.g., rock removal).

The dent in this accident was likely caused by an object (such as a rock) impinging on the underside of the pipeline. Unconstrained dents have been shown to fail faster due to higher local hoop stresses present, since the dent can flex more absent an adjacent object [29]. The pipeline had been recently inspected, but the inspection did not locate the cracks at the accident location. This means either the crack was not at a detectable size or the inspection was incapable of locating the crack.

According to current regulations by the US Pipeline and Hazardous Materials Safety Administration (PHMSA), an operator must schedule repair of any dents located at the 6 o'clock position with reported depths greater than 6% of the pipe diameter or with any indicated metal loss or corrosion [30]. The cracked and uncracked dents in this accident pipeline were located on the 6 o'clock position, with 2.3% and 1.9% depths relative to the pipe diameter. A post-accident third party review of the inspection data calculated depths of 1.6% and 1.57%, respectively. Since this accident, three more pipeline leaks were reported at through-wall cracks in dents less than 2% of the pipe diameter. Therefore, according to PHMSA regulations, it was acceptable for the operator to leave these dents be following inspection.

According to finite element analysis, the highest stress values were at dent shoulders with small radii of curvature due to the nonsmooth nature of the dent not at the dent apex. These findings were consistent with a previous study on dents [25]. The curvature appears to be more critical because of local stress concentrations, plasticity, and surface corrosion. Pipeline dents caused by a rock impingement with the rock present (a constrained condition) will have a different stress magnitude and distribution than dents where the rock is later removed (unconstrained conditions). These dents can also damage the external coating. Based on these findings, the 6% dent depth requirement should not be the threshold criterion for repair.

Therefore, the NTSB recommended that PHMSA work with trade and standards organizations to modify dent acceptance criteria to account for all the factors that lead to pipe failures caused by dents, including dent shape, curvature, and depth as well local variations in the steel, coating type, coating adhesion, soil type, seasonal soil conditions, and impingement constraint. Also, because this myriad of factors influences when a dent will leak, the NTSB believes the safest approach is to repair all dents found when a pipe is excavated. If an operator chose not to excavate a detected dent, the NTSB recommended local leak detection equipment be installed at that location.

Conclusions

The National Transportation Safety Board determined that the probable cause of the release of gasoline and other refined petroleum liquids from the pipeline was a through-wall corrosion fatigue crack that developed at a dent in the pipeline due to residual and operational stress and exposure to the underground environment. Contributing to the accident was vague regulations that allowed the dent to remain in the pipeline [31].

The NTSB made several recommendations because of the investigation. Among these were for PHMSA to work with pipeline trade and standards organizations to modify the dent acceptance criteria to account for all the factors that lead to pipe failures caused by dents, and to require incorporation of these new criteria into integrity management programs. In addition, the NTSB recommended that PHMSA change the federal regulations to require operators to either (a) repair all excavated dents or (b) install a local leak detection system at each location where a dent is not repaired, to continuously monitor for hydrocarbons, taking prompt corrective action to stop a detected leak.

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