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Introduction

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has established the Natural Gas Infrastructure Reliability Program in order to provide research and technology development for ensuring safe and efficient operational reliability of the Nation's natural gas transmission and distribution network. Maintaining the highest levels of integrity and reliability regarding design, construction and operation of the Nation's natural gas infrastructure is of primary importance. Of particular importance is the accurate prediction of the lifetime of damaged pipelines due to outside force. In order to accurately predict the remaining life it is essential to accurately determine the stress and strain in the damaged region. Currently there is a significant technological gap inhibiting accurate diagnostics and prognostics for pipeline life assessment. Specifically, there is no accurate quantitative connection between nondestructive measurements and the state of stress and strain in a damaged region.

There are several categories of outside force incidents that can lead to the failure of otherwise sound pipe. These include: 1) third-party mechanical damage, usually caused by construction damage; 2) secondary loads imposed on a pipeline, usually due to soil movement; and 3) dents due to the pipe resting on rocks. Third-party damage, sometimes referred to as "dig-in's" by the industry, accounts for the vast majority of outside force incidents in pipelines.

Either immediate or delayed failure can occur due to mechanical damage. Immediate failure occurs when construction equipment punctures the pipe and produces a leak at the time of damage. However, mechanical damage more frequently provides an initiation site for crack formation and eventual failure. Unreported damage can result in delayed failure due to either slow crack growth through the thickness or hydrogen-stress cracking of the cold worked and strain-aged steel. Recent failures in Edison, New Jersey and Bellingham, Washington serve as examples of damage to pipelines that resulted in delayed catastrophic failure.

Mechanical damage is normally divided into two categories, dents and gouges, which are deformations in the wall of a pipe that serve as crack initiation sites. Dents typically result from a purely radial deformation whereas a gouge has a component of deformation along the surface of the pipe. For example, a pipe impinging on a rock will result in a dent. If the pipe also slides on the rock a dent with a gouge will result. Third-party

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mechanical damage, usually caused during construction and excavation, is a common cause of gouges. A gouge normally results in a highly deformed, work hardened surface layer and may involve metal removal. Mechanical damage can result in immediate failure of the pipe, delayed failure or no failure over the design life of the pipeline. Distinguishing between damage that can result in either delayed failure or no failure is the major concern of damage characterization. Immediate failures are of more concern from a design standpoint. When predicting the remaining life of the pipeline, there are two steps, the first is detecting and locating the damage and the second is characterizing it. Detecting damage can routinely be performed with common nondestructive evaluation (NDE) techniques. However, characterizing the degree of stress and strain in dents and gouges is a particularly challenging task because the damage creates spatial and through thickness stress and strain gradients.

The detection and analysis of mechanical damage has been an ongoing interest for the pipeline industry for many years. Due to its brevity, this description is not meant to be complete. It is meant to give an indication of the present state of research in the area, to identify gaps in the application of NDE techniques to characterize damaged pipelines and indicate how current research by the authors fit into this body of work. In the remainder of the document the state of the art of traditional damage detection and characterization methods will be discussed. This discussion will be followed by a discussion of the state of the art of ultrasonic damage characterization and will highlight the limits of current capabilities.

Detection of mechanical damage

At the present time In Line Inspection (ILI) tools are the most commonly used technique to detect mechanical damage.[1] In Line Inspection tools (or smart pigs) are instrumented pigs that are placed in the pipeline and moved from one location to another along the line by traveling with the product in the pipe. Almost any type of instrumentation can be mounted on a pig. The most common techniques for pipeline integrity assessment are electromagnetic, ultrasonic or dimension measurements. Magnetic Flux Leakage (MFL) tools use an electromagnetic technique that has been shown to be sensitive to both geometric and mechanical changes that result from mechanical damage. Caliper tools measure the pipe radius at multiple locations around the circumference and have been used to detect dents and estimate their geometry.[2] Direct assessment is a surface based technique primarily used to detect coating problems related to corrosion. Some direct assessment methodologies are also capable of detecting mechanical damage, but they are unable to distinguish damage from coating holidays.[3] Some pigs use a ring of acoustic sensors to measure the inside profile of the pipeline in liquid filled lines. Ultrasonic methods have also been used to detect dents and cracks, however, implementation on pigs is complicated because of the need to couple the sound to the pipe. Therefore, measurements which utilize alternate forms of transduction are attractive such as, gas coupling or the use of Electromagnetic Acoustic Transducers (EMATs), which require no coupling.[4]

Regulatory requirements

Currently CFR 192[5] requires the removal of dents in transmission pipelines operating at pressure that results in a hoop stress of 20 percent or more of the Specified Minimum Yield Strength (SMYS) if the dent contains a stress concentrator such as a scratch, gouge, groove, or arc burn, or affects a weld. If the pipeline is operating at greater than 40 percent SMYS, there is the additional requirement that the dent must be removed if it is more that 0.25 inch deep in pipe 12.75 inches or less in diameter; or more than 2 percent of the nominal pipe diameter for pipe greater that 12.75 inches in diameter. The CFR requirements only take the dent depth into consideration and in some cases these regulations can be very general and inaccurate, and in most cases the pipe has rerounded due to the internal pressure of the gas and this criteria is not conservative, especially if an axial gouge is present.[6,7,8] In other cases where the pipe has not rerounded, the criteria may be very conservative. While these regulatory mechanisms are adequate in some cases there is a need to have a more quantitative measure of the degree of damage to the pipeline in order to predict the remaining life.

Qualitative Characterization of mechanical damage

Once mechanical damage is detected and located, the degree of degradation to the pipeline properties must be assessed and the remaining life predicted. Currently there is a significant technology gap with regard to the characterization of mechanical damage. Specifically the quantitative determination of stress and strain to accurately provide diagnostic and prognostic capability is needed to accurately predict the remaining life of the damaged pipeline. Current techniques involve measurements obtained from pigs and both pigging and pipeline companies have algorithms for characterizing mechanical damage based on dent dimensions. The pigging companies usually have 2-3 levels of defect severity that serve as a basis for digging up the defect.[9] In some cases the pipeline companies use the raw data from the pig runs in their own damage algorithms. Ultimately, the final judgment is made by digging up the pipeline to visually inspect the defect. Depending on the companies operating procedure, a subjective judgment based on inspector experience, field measurements combined with damage algorithms are used to assess the severity of the damage. Some of the measurements that are made include dent geometry (length, depth, profile, wall thickness, etc.), gouge geometry, magnetic particle, eddy current and ultrasonic NDE for cracking and hardness. This process is highly inaccurate and can be subject to inspector bias. In addition, the dimensions do not accurately represent the physical state of the damage because the shape changes due to rerounding as the dent is pushed out due to the internal pressure of the gas.

The parameters used to calculate the structural integrity of a pipe with mechanical damage are a subject of ongoing research. In most analysis methods, information on both geometric changes (residual dent depth, amount of wall thinning and shape) and mechanical changes (residual stresses, plastic deformation and cold working) are important. Due to the complexity of mechanical damage, most damage algorithms are empirically based. Two commonly used algorithms include one developed by the Pipeline Research Council (PRC) of the American Gas Association (AGA) and one developed by British Gas.[10] Both of these algorithms include pipe geometry, defect geometry and material properties to estimate the remaining strength of damaged pipe. They tend to involve complicated equations with many parameters further decreasing the accuracy.

The PRC model tends to give a lower bound for the remaining strength whereas the British Gas model tends toward the mean of the remaining strengths and needs to be used with a safety factor. More recent work has extended a Ductile Flaw Growth Model developed by the Pipeline Research Council International (PRCI) from gouged pipe to pipe with a dent and gouge.[11] This elasto-plastic fracture mechanics based model yields good predictions for both the remaining strength and the remaining life under cyclic loadings. The difficulty with this model is that it requires knowledge of the residual stress in the dented area, which is not readily available from field measurements.

The onset of failure in damaged pipe can be accurately predicted if the state of stress and strain can be determined in a dented pipe and coupled with fracture mechanics based models. Currently there is a technology gap to implementing this type of procedure; specifically there are no current NDE techniques for accurate determination of stress and strain in dented pipelines. Filling this gap is the primary objective of work currently being performed by the authors for the NETL, Natural Gas Infrastructure Reliability Program.

Ultrasonic Characterization of Mechanical Damage

Commonly used techniques for nondestructively determining the stress and strain in damaged materials typically rely on ultrasonic velocity measurements. Ultrasonic velocity is very sensitive to damage induced stress and strain and offers the potential for accurate quantitative determination of stress and strain as inputs into fracture mechanics models. This powerful combination offers a prognostic capability that is not currently available to pipeline inspection companies and utilities because of the lack of ability to accurately measure stress and strain. In addition, the main drawbacks include the fact that velocity is affected by competing sources of velocity shifts due to microstructural effects such as texture, temperature variations, the necessity for very precise time measurements, and low spatial resolution. Despite these drawbacks, ultrasonic measurements are valuable because they allow one to obtain information about the stress and strain in the interior of the materials as a function of depth. Typical ultrasonic measurement equipment is relatively inexpensive, portable, quick to set up, and the ultrasonic velocity data is rich with information. For these reasons the use of ultrasonic measurements to determine stress and strain has been an active area of research for many years.

When considering applications to characterizing dents and gouges in pipes it is important to realize that the stress and strain exhibit spatial variations and depth gradients. There are several different ultrasonic methods that are appropriate for this application, including through thickness measurements to characterize spatial gradients and waves with penetration depths that can be varied to characterize depth gradients. Thompson et al.[12]

thoroughly reviewed the past several decades of research that utilized ultrasonic velocity measurements to characterize the stress and strain of materials. They reviewed the considerable progress in developing the scientific foundation underlying the techniques and highlighted specific results that have promise for various applications.

One such result that is promising for characterizing inhomogeneous through-plate stress distributions is the work by King and Fortunko based on the velocity measurements of horizontally polarized shear waves that were incident to the surface at shallow, grazing angles.[13] The theoretical development exploits the relative insensitivity of the grazing shear wave propagation mode to texture and other microstructural anisotropies, compared to other wave propagation modes including bulk and Rayleigh modes. Experimental measurements were made of 25 mm thick 6061-T6 aluminum under a variety of conditions including unstressed, under tensile stress, and under a four-point bending stress. Using two EMATs separated by about 35 mm on the same surface, velocity difference measurements were combined with the model to provide surface residual stress values within 5% of the accepted values. These results help to establish the fundamental scientific foundation and point to the need to improve spatial resolution for practical applications.

One way to improve spatial resolution is by utilizing immersion measurements with focused transducers to characterize areas on the order of millimeters by measuring the Rayleigh wave velocity where the effective wave penetration depth is inversely related to the frequency. Lavrentyev and Veronesi[14] have shown that significant factors that contribute to the surface wave velocity measurements include surface roughness, near-surface grain orientation (texture), dislocation density changes, and residual stress. The authors contend that the immersion method has the potential to provide the stress-depth profile of a specimen with improved spatial resolution and a high degree of measurement precision. The study found that in Waspaloy and Al-7075, the Rayleigh wave velocity decreased with shot peening intensity, with a larger decrease observed at higher frequencies. From a quantitative standpoint, the study concluded that the velocity changes caused by stress are significantly smaller than those observed experimentally. This translates into an important practical consequence that a near-surface residual stress measurement in shot peened materials is difficult to achieve. One other drawback is that this technique requires relatively sophisticated ultrasonic equipment and careful measurement capabilities of the operator.

Results by Thompson et al.[15] applied many different types of waves generated by EMATs to accurately characterize the texture in aluminum and copper plates. Their experimental results agreed well with theoretical predictions for these plates under stress free conditions. In addition, the texture parameters obtained ultrasonically agreed well with x-ray determinations. Thompson et al. presented the theory and applications of the measurements of stress and texture in biaxially stressed specimens.[16] Their measurements agreed well with theoretical predictions and form the scientific basis for characterizing biaxial stress states.

Initial measurements performed by the authors have shown that through thickness measurements were strongly correlated with the strain in pipeline steels and experiments were performed which indicate that the stress and texture may have separable contributions to the velocity measurements. [17,18] Results were obtained while uniaxially loading a pipeline steel sample, which showed systematic changes in the shear wave birefringence during and after loading, which increased with increasing strain. Compression tests were also performed on the pipe and showed systematic differences in the birefringence between compression and tension that could easily be distinguished.[17]

The difficulty with numerically extracting the stress and strain from experimental data further complicates the quantitative determination of stress and strain. Degtyar et al. described a method for determining absolute stresses in an anisotropic material and simultaneously determining the stress-dependent elastic constants from inversion of the wave equation, where the bulk wave velocities as a function of their measured angular dependence are used as inputs.[19] The authors argue that this method is applicable for stress measurements in materials that have undergone a complicated history (plastic deformation) of loading and unloading, and can be used to determine both applied and residual stresses. They presented experimental results that provide a means for conducting high precision ultrasonic velocity measurements. In order to measure the angular dependence of the ultrasonic bulk wave velocity, the authors used a self-reference bulk wave (SRBW) method for determination of elastic moduli, where the effects of geometric imperfections were significantly reduced.

Summary

While there has been much progress in qualitatively characterizing mechanical damage, a significant technological gap inhibiting accurate diagnostics and prognostics for pipeline life assessment exist that regulatory requirements do not alleviate. Specifically, there is no accurate quantitative connection between nondestructive measurements and the state of stress and strain in a damaged region. Ultrasonic measurements are promising for characterizing damage in pipelines and several applications are currently being developed or are already in place. However, considerable work needs to be undertaken in improving the resolution of the techniques, in suppressing the influences of competing microstructural effects, especially inhomogeneities in density and texture and in understanding the effects of plastic deformation.

The large body of work in the field provides a strong possibility for providing quantitative ultrasonic measurement methodologies for determining residual stresses and strains in damaged pipelines. Furthermore, quantitative ultrasonic measurements could be integrated with FEM models to completely characterization stress and strain fields of damaged pipelines. In work being performed by the authors for the NETL Natural Gas Infrastructure Reliability Program we are extracting the potentially practical measurements from the science foundation to fill the technology gap that exists to nondestructively characterize dents and gouges in pipelines.

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