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Development of a finite element model for simulation and prediction of mechanoelectrochemical effect of pipeline corrosion

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ABSTRACT

In this work, a finite element model was developed to study mechanoelectrochemical effect of pipeline corrosion through a multiphysics field coupling technique. The modeling results, i.e., corrosion potential and corrosion current density, are well consistent with experimental measurements on pipeline steel in a near-neutral pH solution. It is demonstrated that, while a tensile strain enhances stress uniformly through pipe wall, an increasing depth of corrosion defect results in a concentrated stress at the defect center only. When the corrosion defect is under an elastic deformation, there is no apparent effect of mechanical–electrochemical interaction on corrosion. However, when the applied tensile strain or the geometry of corrosion defect is sufficient to cause a plastic deformation at the defect, the local corrosion activity is increased remarkably. Corrosion at the defect is composed of a series of local galvanic cells, where the region with a higher stress, such as the defect bottom, serves as anode, and that under lower stress, such as the defect sides, as cathode. The locally accelerated corrosion at the defect center can be further enhanced as the corrosion defect deepens.

1. Introduction

High-strength steel pipelines operating in Arctic and sub-Arctic areas experience complex stress/strain conditions. In addition to hoop stress resulted from internal operating pressure, ground movement generates significant longitudinal strains on the pipe [1–4]. It has been established [5–7] that an applied stress and/or strain enhance corrosion of steel remarkably. In authors' previous work [8,9], it was demonstrated both experimentally and theoretically that the mechanoelectrochemical effect of pipeline corrosion is small in the elastic deformation region. A plastic strain would increase the mechanoelectrochemical effect at a much appreciable level. Moreover, while both anodic and cathodic reactions are enhanced by plastic strain, the effect on anodic reaction is more apparent.

In reality, in addition to the hoop stress and soil strain applied on pipelines, local stress and strain raisers usually exist on the pipe surface, such as corrosion defects and mechanical dents. These surface irregularities can contribute to local plastic deformation [10]. A synergism of internal pressure and soil strain at corrosion defects on local stress/strain concentration and the resulting defect propagation is quite complex. To date, there have been a number of industrial codes/standards, such as American Society of Mechanical Engineers (ASME) B31G standard [11], modified B31G code [12–14] and DNV-RP-F101 standard [15], that can be used to evaluate remaining strength and failure pressure of pipelines under complex stress/strain conditions. However, these industry models were developed to primarily address low grades of steel and relatively smooth corrosion defects. Modifications are required to consider factors such as increasing grade of pipe steels and the longitudinal soil strain applied. Furthermore, these models usually provide prediction of failure pressure of pipelines at a relatively high tolerance [10,16].

In this work, a finite element (FE) model was developed upon previous version [10] to study the mechanoelectrochemical effect of corrosion of a high-strength pipeline steel, i.e., X100 steel, under synergistic effects of soil strain and internal pressure at corrosion defects in a near-neutral pH bicarbonate solution. The initial parametrical conditions for FE modelling were derived from experimental tests. The reliability of the model was validated by various mechanical and corrosion measurements. The simulating parameters included stress distribution, corrosion potential, and anodic and cathodic current densities as a function of the defect size and longitudinal tensile strain. It is anticipated that this research provides a sufficiently reliable method for simulation and prediction of localized corrosion on pipelines under complex stress and strain conditions, and develop recommendations to industry for risk assessment and integrity management.

2. Experimental testing

Tensile specimens used in this work were cut from a sheet of X100 steel pipe wall along circumferential direction, with a

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chemical composition shown in Table 1. The specimen was machined into dumbbell shaped, as shown previously [9]. The specimen surface was ground up to 1000 grit silicon carbide paper, and then rinsed with deionized water and degreased in acetone.

The test solution was a near-neutral pH bicarbonate solution, i.e., NS4 solution, which has been used widely to simulate electrolyte trapped under disbonded coating in the field [17]. The solution contained 0.483 g/L $NaHCO_3$, 0.122 g/L KCl, 0.181 g/L $CaCl_2 \cdot H_2O$ and 0.131 g/L $MgSO_4 \cdot 7H_2O$, and was made from analytic grade reagents and ultra-pure water (18 MΩ cm in resistivity). Prior to test, the solution was purged with 5% CO_2 balanced with N_2 gas for 1 h to achieve an anaerobic and near-neutral pH condition (pH = 6.8). The gas flow was maintained throughout the test. The conductivity of the solution was 0.096 S/m.

All tests were performed at ambient temperature (~22 °C).

The engineering stress–strain curve of X100 steel was obtained by tensile testing through a Bose Electroforce dynamic materials test system with a strain rate of 1×10^{-4}/s, as described previously [8]. Potentiodynamic polarization curve was measured on steel electrode through a Solatron 1280C electrochemical workstation after a steady-state corrosion potential was achieved upon immersing in NS4 solution for 1 h. The potential scanning rate was 0.3 mV/s, and potential polarization started at −0.9 V(SCE) and ended at −0.6 V(SCE). A saturated calomel electrode (SCE) was used as reference electrode, and a platinum sheet as counter electrode.

Mechanical properties of the steel and various electrochemical corrosion parameters derived from the polarization curve were used as initial conditions for FE. These included corrosion potential, corrosion current density, Tafel slope and exchange current density.

3. FE simulation

3.1. Initial and boundary geometrical parameters

The FE simulation of mechanoelectrochemical effect of corrosion of X100 pipeline steel was performed using a commercial COMSOL Multiphysics 4.2a software. The geometrical model of the steel pipe containing a corrosion defect is shown in Fig. 1, where the pipe wall thickness is 19.1 mm and the outer diameter of the pipe is 812.8 mm (32 in.). The length of the pipe segment for FE simulation is 2 m. The corrosion defect is elliptically shaped, with a length of 200 mm, and depths of 20%, 40%, 60% and 80% of the pipe wall thickness, i.e., 3.82 mm, 7.64 mm, 11.46 mm and 15.28 mm, respectively. In reality, the aspect ratio of corrosion defects may change during corrosion. This work assumes an unchanged length with growing depth for corrosion defect in order to investigate propagation of the corrosion defect along the pipe wall direction.

The boundary condition of solution is that the solution boundary is electrically isolated, except the solution/steel interface that is set as a free boundary. While the left end of the steel pipe is fixed, the right end is loaded with prescribed tensile strains as described below. The bottom of the pipe is set as electric grounding. The mesh type used is triangular. A complete mesh consists of 9240 elements. The maximum and minimum element sizes are 5 mm and 0.1 mm, respectively, with a maximum element growth rate of 1.3. A solver of MUMPS (multi-frontal massively parallel sparse) is selected for solution.

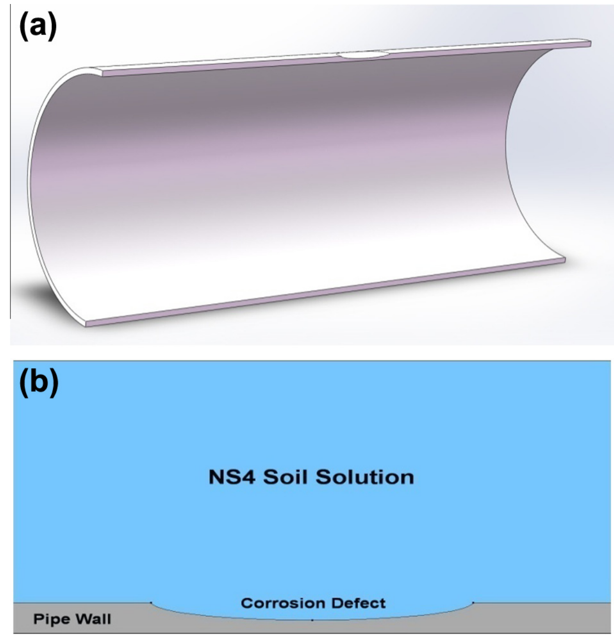

Fig. 1. The geometrical model of the steel pipe containing a corrosion defect for FE simulation (a) 3D model, (b) 2D model.

The 3D geometry of pipe segment is simplified into a 2D model due to the symmetrical property, as shown in Fig. 1b. The FE simulation contains three aspects, i.e., (i) mechanical elasto-plastic solid stress analysis of the steel pipe, (ii) electrochemical potential and current density analyses in solution and at the steel/solution interface, and (iii) simulation and analysis of mechanoelectrochemical effect of pipeline corrosion, i.e., the interaction of mechanical stress/strain and electrochemical corrosion behaviour of the steel in solution.

3.2. FE simulation of mechanical stress developed on pipelines

All energy pipelines carry pressurized fluids, such as natural gas and oil. Stress on pipelines primarily comes from internal pressure. An elasto-plastic solid stress simulation was performed on pipe steel. The isotropic hardening model is selected, and the hardening function, σ_{yhard}, is defined as [9]:

$$\sigma_{yhard} = \sigma_{exp}(\varepsilon_{eff}) - \sigma_{ys} = \sigma_{exp}(\varepsilon_p + \frac{\sigma_e}{E}) - \sigma_{ys} \quad (1)$$

where σ_{exp} is experimental stress function derived from the measured engineering stress–strain curve of X100 steel, ε_{eff} is total effective strain, σ_{ys} is yield strength of the steel, i.e., 806 MPa, ε_p is plastic strain, σ_e is effective stress, E is Young's modulus of 207,000 MPa, and σ_e/E is elastic strain. Von Mises yielding criterion is used for the elasto-plastic simulation. A variety of tensile strains, i.e., 0%, 0.1%, 0.2%, 0.3% and 0.4%, are applied on the steel pipe along the longitudinal direction to simulate soil strain. It is realized that the tensile strain applied is total strain, and is equal to the total

Table 1
Chemical composition of X100 steel (wt%).

C	Mn	S	Si	P	Ni	Cr	Mo	V	Cu	Al
0.07	1.76	0.005	0.1	0.018	0.154	0.016	0.2	0.005	0.243	0.027

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