CAAP Quarterly Report

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Project Title: Fundamental Understanding of Pipeline Material Degradation under Interactive Threats of Dents and Corrosion

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Business and Activity Section

(a) Generated Commitments – Due to the COVID-19 pandemic, the Iowa State University was under strong restriction for access of facilities. Undergraduate student have severe restrictions to be on campus and actively participate in the experimental work. These restrictions have resulted in sever delay in our progress towards our promised milestone. A request of no cost extension will be requested from the CAAP program to carry out all conducted tasks.

(b) Status Update of Past Quarter Activities - The main objective of the proposed work is to enrich the knowledge base for evaluating interactive threats of external mechanical dents and secondary features, through and integrated lab-scale experimental and numerical framework to characterize and better predict the remaining safe life and operating pressures, while projecting the needs for mitigation measures.

The proposed experimental-computational framework will address the interacting threats of external mechanical damage, coupled with secondary feature as corrosion or cracking on the integrity management decision. The proposed methodologies utilize: (i) A high throughput lab-scale testing apparatus for simulating the combined threats of external damage induced plastic deformation combined with exposure to corrosion, (ii) A lab-scale experiments to assess the synergistic interaction between different threats and their effects on strength and toughness of corrosion degraded pipeline steel, (iii) Utilization of electrochemical impedance spectroscopy (EIS) as a path way for ILI-implementation to characterize the severity of the corrosion near an

external mechanical damage, (iv) A detailed FEM analysis of the different geometric constraints on the variance of local stress and strain state (concentration), and (v) Systematic numerical sensitivity analysis in FEM to quantify metrics for material strength and toughness degradation with corrosion and under the interacting threats of external mechanical damage, and stochastic interpretation of the variation in reported full scale fatigue testing of dents (PRCI MD 4-2, 4-9).

While we were under strong restriction of access to research labs and experimental facilities, the main activity during this period focused on sample preparation and synergistic corrosion and mechanical testing.

1. Developed testing configuration for prolonged corrosion experiment, while allowing subsequent mechanical testing.
2. Conducted a set of testing on an X70 steel pipelines samples for prolonged corrosion experiments, and followed by tensile test to fracture to compare the initial yield strength of the samples and its degradation due to the corrosion process.

(c) Details of the Tasks:

Task 2- Lab-scale investigation of dent-corrosion interactive threats (Month1-18)

This is an extended task to reveal the role of over-stressing by external mechanical damage (dent or gouge), to lower the threshold stress for crack initiation below the mean operating stress. The main aspect of this work is to (i) study the role of initial corrosion on lowering the residual strength of the pipeline (measured in terms of strength and toughness), and (ii) study the effect of pre-stress on the initiation and progression of the corrosion process (measured in terms of total corrosion charges, and depth and morphology –grooving and subsurface cracks- of the corroded surface).

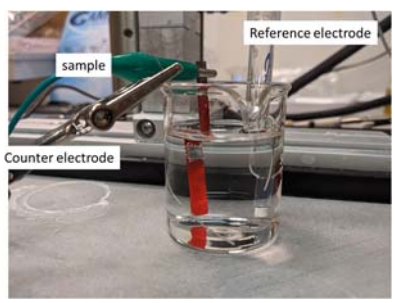

Fig. 1: The micro-cell corrosion setup with the loading mechanism to mimic IGSCC conditions with variable stress levels. Electrochemical Experimental setup showing the tensile corroded sample with a well-defined window for corrosion. (1 M $NaHCO_3$ solution with pH 8.1-8.2 and applied potential in the range of -0.4 to -0.6V).

The employed electrochemical cell for the corrosion experiment is shown in Fig. 1. All corrosion experiment were carried out in a high pH electrolyte solution of 1 M $NaHCO_3$ with pH 8.1-8.2 and applied potential in the range of -0.4 to -0.6V relative to vs. Ag/AgCl. Tensile sampled of X70 steel stock are machined with a length of a 100mm, width of 5mm and 1mm thickness. The corrosion samples are coated with a lacquer to define the corrosion window across the tensile sample gage length. Figure 2 shows the sample preparation and testing steps. The original configuration of the tensile sample is defined with a window for corrosion as shown in Fig. 2(a). The sample is then corroded for 24hrs under constant voltage, removed from the solution and dried. A cleaning step is followed to remove the defining lacquer coating, so as not to interfere

with testing protocol. Subsequently, the corroded sample is tested under tensile loading to failure, under a crosshead displacement control of 50μm/s. Four marks are deposited on the sample gage-length to allow for optical transducer monitoring of the axial and transverse strain components. Figure 2(c) shows the final failure gage section with the marks indicated.

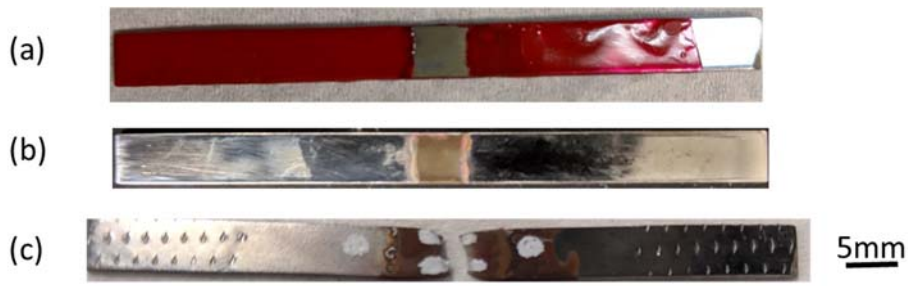

Fig. 2: Sequence of corrosion-tensile failure testing. (a) The defined corrosion window with lacquer coating. (b) Corroded sample with the corrosion region within the gage length. (c) The final failure of the corroded sample after the tensile testing step.

Summary of the preliminary testing result of the remaining strength after corrosion are shown in Fig.3, along with the strength of version sample for comparison. It is clear that the initial yield strength of the corroded sample is statistically lower by about 10% in comparison with the reference sample (the average of several tests showed variability of the yield strength of about ±2%). This is a critical evidence of the effect of the corrosion on the yield strength of the pipeline steel. However, one might also conclude that the ductility limit, and thereby toughness might have increased due to corrosion. However, the extent of deformation after the ultimate tensile strength is critically dependent on the geometry of the localization, as well as the possibility of nucleation of cracking from the corrosion process. This will be the focus of work in the next quarter.

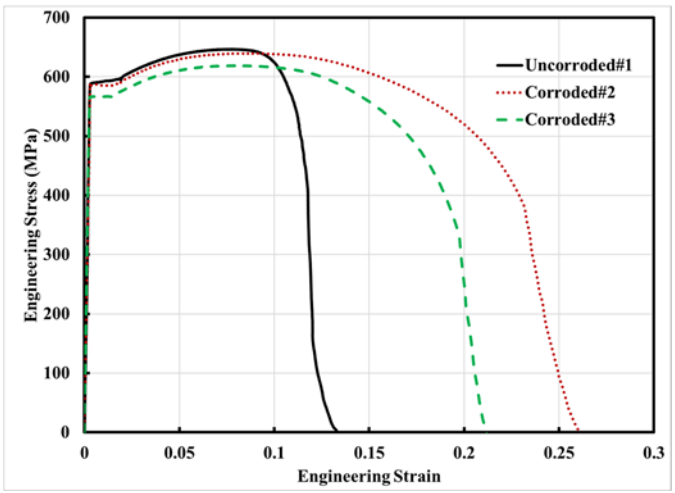

Fig. 3: Comparison of the stress-strain curve for the corroded sample with the reference uncorroded sample. The initial results imply reduction of the tensile yield strength, though unexpectedly, an increase in ductility may be identified.

Typically, toughness and thereby ductility are measured by sharpy test. However, identify the ductility or toughness from the curve is slightly ambiguous as the peak stress, may not correspond to the critical strain for homogeneous deformation before the localization process. Beyond the homogeneous deformation, the details of the stress-strain curves are function of the details of the geometric details of localized deformation. However, in our measurements, we have another parameter, which is the transverse strain. The ratio between the transverse and axial strain is the Poisson's ratio for the incompressible homogeneous plastic flow, and approximately =0.5. Figure 4 clearly show the transition from macroscopic homogeneous deformation to localized necking on the axial vs transverse strain plot. Such transition can not be clearly identified on the stress-strain curve.

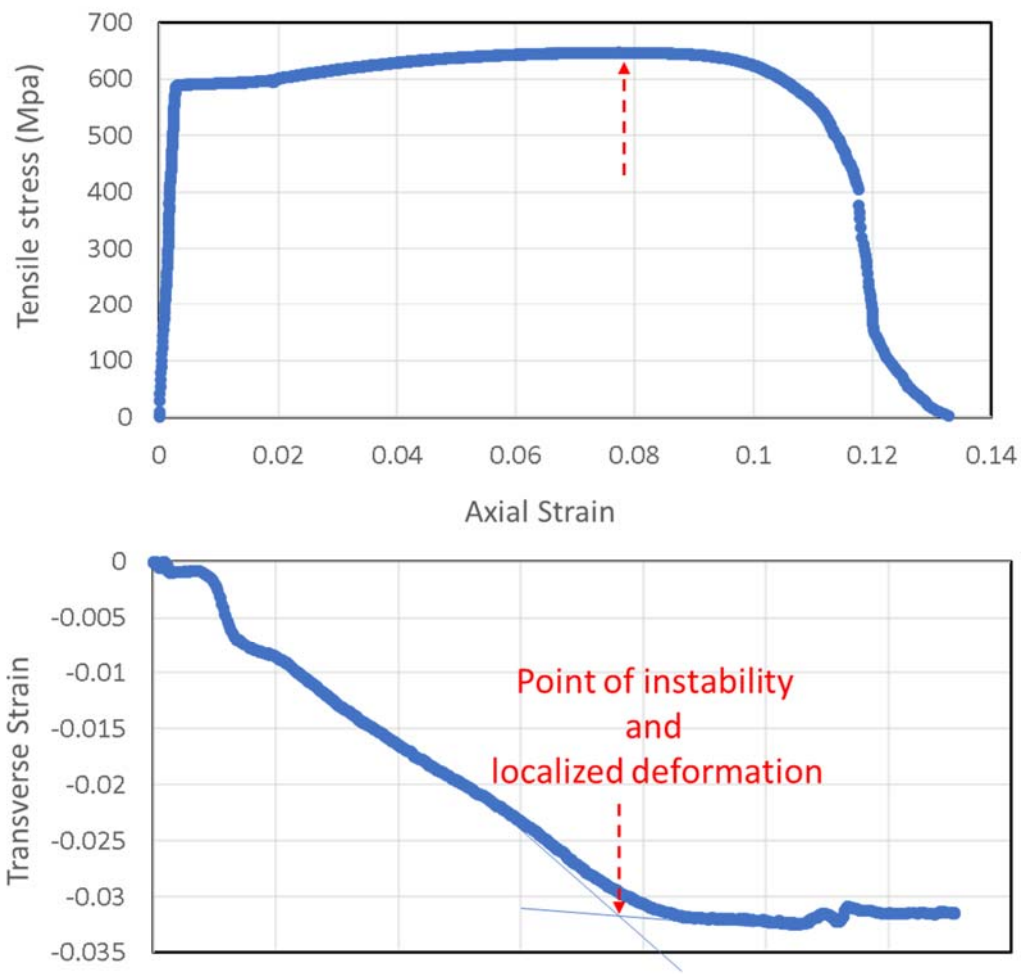

Fig. 4: Utilization of the axial vs. transverse strain distribution to identify the start of the localized necking process.

Outcome: The testing protocol is undergoing to identify the role of interactive threats of residual stress arising from external dent and combined with corrosion. The preliminary results clearly identify the role of corrosion on the reduction of the minimum reported yield strength of the alloy.

In addition, the unique utilization of the transvers to axial strain ratio has facilitated the identification of the start of localized necking and the limit of ductility.

(d) Planned Activities for the Next Quarter – The progress in the next quarter will be tied to the level of access to different laboratory and testing facilities. With the hope of reduced restriction, the focus of the next phase of work will be on identification of the deformation mechanisms responsible for the mechanical degradation of strength and toughness of pipeline steels. In particular we will continue to carry out:

1. Preloading of set of samples to various plastic strains ranging between 0.5 to 5%.
2. Perform electrochemical corrosion experiments on these samples and observe the subtle changes in the current-voltage characteristics as well as the corrosion morphology
3. Perform a tensile stress test to failure to characterize the remaining strength of the samples.

These measurements would provide some of the material parameters for the numerical framework.