EFFECT OF PRE-ACCUMULATED PLASTIC STRAIN ON STRESS CORROSION CRACKING AND FATIGUE LIFE OF STEELS; EXPERIMENT AND MODELING

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Abstract

Steel structures may experience localized plastic strains, arising from wide range of service anomalies. Regions of accumulated plastic strain are more prone to accelerated stress corrosion cracking and reduced fatigue life. In this work, we systematically analyzed the intergranular corrosion (IGC) under combined oscillatory mechanical loading and active electrochemical environment in a specially designed experimental apparatus. Loading cycles were design to mimic both the low amplitude high frequency vibration loads and the low frequency-high amplitude structural duty cycles. Electrochemical potentials were maintained for active dissolution in moderately alkaline carbonate-bicarbonate solutions and under pre-accumulated plastic strain of 0-4%. We observed grain boundary softening, directly arising from vacncies formed by silicon oxidation. Triangular wedges were formed and correlated with the level of the accumulated plastic strains and the load profile. A three-dimensional elasto-plastic continuum damage mechanics model is developed to account for both, the pre-accumulated plastic strain, and the induced elasto-plastic fatigue strains to accelerate the evolution of damage accumulation. Upto 90% of life reduction is observed with 4% of pre-accumulated plastic strain. These findings can be used to advance the understanding of the combined effect of damage and corrosion on the remaining fatigue life of energy materials.

1. Introduction

Ductile alloys fail in corrosive environments by intergranular stress corrosion cracking, through interactions between mechanical and chemical processes that are not yet understood. IGSCC of pipeline steels is preceded by an initiation stage of selective grain boundary attack or intergranular corrosion (IGC). We investigate formation and mechanical effects of metal defects produced by grain boundary corrosion of low-alloy pipeline steel, at conditions of high susceptibility to stress corrosion cracking in the absence of hydrogen evolution. We employed a multiple scale investigation, to understand (1) the nanoscale processes that leads to crack nucleation at the triple junctions. Combined nanoindentation and molecular dynamic simulation were performed in attempt to identify the defects responsible for near-GB softening and elucidate the chemical mechanism of their formation. (2) macroscale effect of such local loss of GB cohesion on the fatigue life of structural steels. And (3) the synergistic effect of dents and gauge generating plastic damage on accelerating the corrosion process. Summary of electrochemical testing, nanoindnetaion, MD simulation and continuum damage modeling, and summary of the critical results are given.

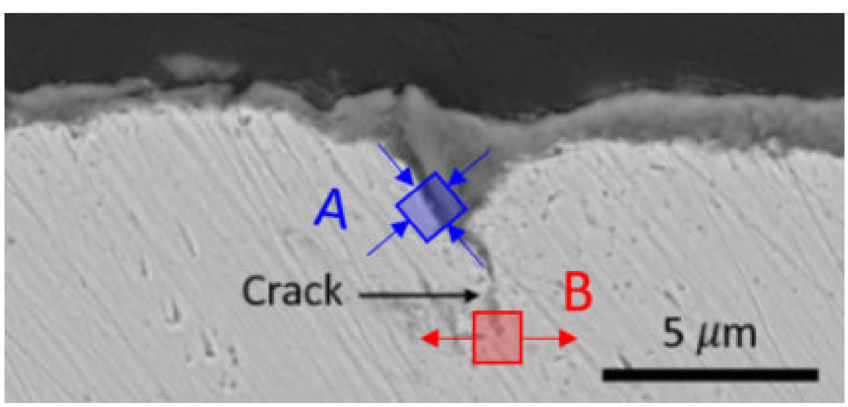

Fig.1 – $FeCO_3$ corrosion product layer grows at the metal interface by inward diffusion of CO_3^{-2} ions. Point A: volume expansion, compressive out-of-plane stress in the steel, Point B: tensile stress concentration at the GB ahead of the wedge.

2. Results

A X70 pipeline steel is electrochemically exposed to high-pH IGC with different level of initial plastic strains. Time-depenedent evolution of GB-edging is monitored and compared to electrochemical diffusion model. Nanoindentation (NI) were perfomed on shallow sections near the corroded GB-triple junctions. Observations were reconciled with molecular dynamic simulation to identifying the nanoscale softening mechanisms. These results were the bases for an interactive threat analysis of the remaining fatigue life of the structure, perfomed by a three-dimensional elasto-plastic continuum damage mechanics model for multiaxial fatigue. The modeling framework employs the thermodynamic formulation for the elastic and plastic continuum damage evolution laws proposed by LeMaitre and Chaboche and implemented into an ABAQUS user material subroutine (UMAT). The model accounts for both, the pre-accumulated plastic strain, and the induced elasto-plastic fatigue strains to accelerate the evolution of damage accumulation. An analysis of time-dependent corrosion product-induced stress, incorporating the effect of groove shape change, can potentially predict the time of crack initiation. The main findings are:

a. Nanoindentation (NI) measurements show local softening near corroded grain boundaries, indicated by significantly reduced critical loads for dislocation nucleation.
b. Molecular dynamics simulations of nanoindentation of bulk iron showed that metal vacancies and not interstitial hydrogen atoms explain the observed critical load reduction.
c. NI observed GB-softening arises from synergistic interactions between dislocation nucleation and a “softening agent”; vacancies generated by oxidation of reactive Si solute atoms in X70 steel.
d. Large volume expansion in GB grooves formed by IGC, should stimulate tensile wedging stresses at GB, thus explaining observations of GB cracks during extended corrosion exposures.
e. Wedging stress also helps explain initiation of intergranular SCC under external stress at active dissolution potentials typical of cathodically protected pipeline steel.
f. A reduction in GB cohesive strength led to marked reduction in the overall fatigue life.
g. Residual plastic strain increase the density of nucleation sites with arehnius dependence.
h. Risdual platic strain results in near 90% lose of fatigue life.

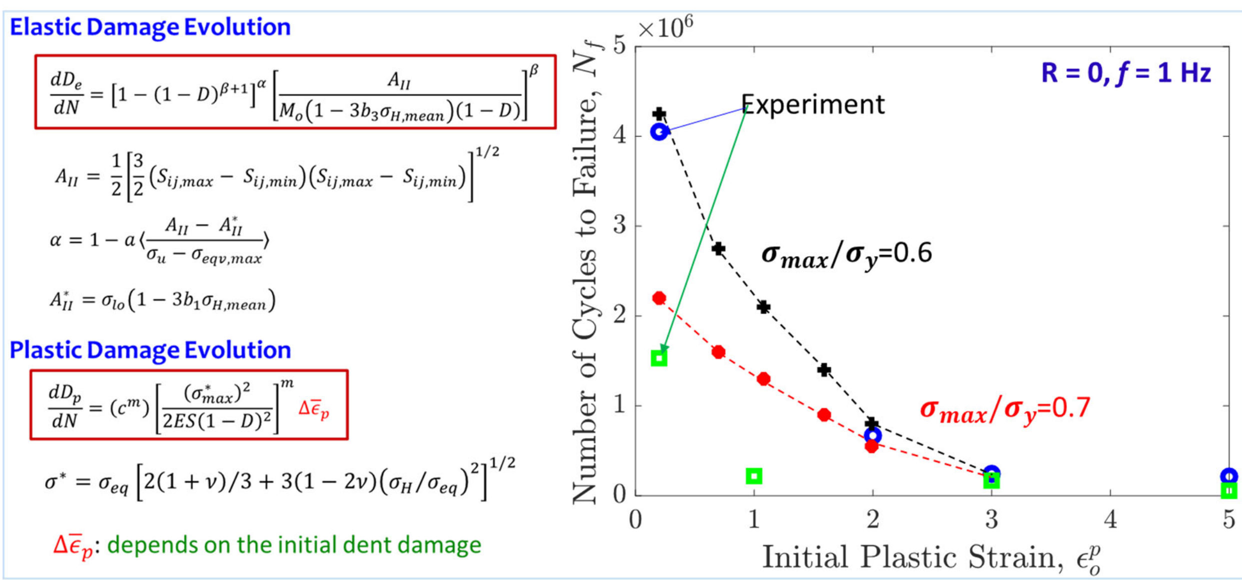

Fig. 2 – Summary of the employed elastoplastic damage model, accounting for initial plastic damage, and summary of the model prediction compared to reported experimental fatigue results.

Acknowledgements

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