Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

A new modeling approach to predict hydrogen embrittlement induced ductile-to-brittle transition in high strength steels

Sidharth Sarmah[1*], Tuhin Das[1], Salim Brahimi[1,2], Stephen Yue[1], Jun Song[1]
[1]Department of Materials Engineering, McGill University, Montreal, H3A 0C5, QC, Canada
[2]Industrial Fasteners Institute, Cleveland, 44131, OH, USA
*sidharth.sarmah@mail.mcgill.ca

Abstract

Hydrogen embrittlement (HE) has been a long-standing challenge for high-strength metals, particularly in high-strength steels. The present work focuses on developing a modeling approach that accurately captures and predicts the hydrogen embrittlement induced ductile-to-brittle transition in high-strength steels. A stress-coupled diffusion model is formulated and implemented within the finite element modeling framework to evaluate hydrogen distribution under different loading and charging conditions. Benchmarking the model against the experimental results obtained from incremental step load testing on AISI 4340 notched specimens under varying charging scenarios, the threshold maximum hydrogen concentration and load values corresponding to failure have been identified. The results have shown that although the threshold load exhibits a monotonic function of the global, equivalent boundary hydrogen concentration, it is not so with respect to the maximum local hydrogen concentration. This refurbishes the concept of critical hydrogen concentration required to induce hydrogen embrittlement by establishing a strong dependency of hydrogen concentration on the history of loading and stress development. Contrary to previous works on such consideration of hydrogen concentration along with stress triaxiality influencing failure due to hydrogen embrittlement in isolation, a new combinatorial approach is proposed here. The loci of the maximum local hydrogen concentration and stress triaxiality are incorporated as modeling parameters into a cohesive zone model to define a hydrogen-informed material degradation criterion. Furthermore, the hydrogen induced ductile-to-brittle transition behavior observed in high-strength steels is incorporated into the cohesive zone model by representing the two fracture modes separately. The results demonstrated its excellent capability in capturing the material's hydrogen embrittlement susceptibility trend curve and predict the ductile-to-brittle transition threshold. The model is then further validated by varying the charging concentration and loading rate. Integration of local characteristics in the proposed model administers its applicability to other hydrogen embrittlement susceptibility tests.