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Coupled mechanical–diffusion models to understand the role of shot peening in mitigating hydrogen embrittlement

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Hydrogen embrittlement (HE) represents a major concern for steels, as hydrogen-assisted degradation significantly accelerates crack initiation and propagation. The mechanisms governing HE are multifactorial and remain challenging to fully understand due to the complex interactions between hydrogen and material microstructures. Several strategies are available to mitigate HE, including the use of protective polymeric or metallic coatings such as chromium or copper. However, coating adhesion and mechanical integrity often limit their applicability to load-bearing structures. Within this context, the present work investigates the ability of shot peening (SP) to mitigate HE, as an alternative to coatings. The focus is on the X60 steel, using an experimental approach supported by numerical modelling.

The experimental campaign includes permeation tests, thermal desorption analysis, X-ray diffraction, EBSD characterisation, and Slow Strain Rate Tensile (SSRT) tests performed under continuous hydrogen charging. These tests provide the mechanical, microstructural and trapping parameters needed for modelling, including yield and ultimate strengths, residual stress distribution, diffusion coefficients, trap types, densities and binding energies. Analysis of the load–time curves from SSRTs on unpeened and peened specimens shows that the compressive residual stresses and increased trap density introduced by SP can effectively delay hydrogen-assisted fracture.

In parallel, a fully coupled mechanical–diffusion numerical model was developed in Abaqus, complemented by dedicated routines to simulate hydrogen uptake, stress-assisted diffusion, trapping mechanisms and crack propagation via a cohesive zone layer. The model aims to clarify the evolution of local hydrogen concentration fields, e.g., in the lattice and in the traps, and their accumulation in the fracture region, thereby shedding light on the beneficial mechanisms introduced by SP. Model parameters are calibrated using hydrogen-free mechanical tests and validated against SSRTs performed on unpeened specimens under hydrogen charging. The numerical approach successfully reproduces the mechanical behaviour and crack evolution of these specimens, capturing the progressive hydrogen accumulation at the crack tip and the associated transition to brittle fracture. A subsequent sensitivity analysis is conducted by varying the diffusion coefficient, the imposed surface concentration and trap density.

The SP condition is then simulated by introducing residual stresses, modified boundary concentrations, and a trap distribution consistent with the experimentally observed SP layer. However, this direct implementation did not lead to delayed fracture; instead, the increased trap density and higher imposed concentration resulted in elevated local hydrogen content and premature crack propagation. It was found that only a significant reduction in the lattice diffusivity within the SP layer can realistically capture the decreased hydrogen mobility and produce a delayed fracture behaviour consistent with experimental observations. These results indicate that the beneficial effect of SP is governed primarily by the reduced hydrogen diffusion rate in the peened layer, whereas residual stresses provide only limited protection due to their early relaxation.

In conclusion, the study provides a validated numerical framework for analysing HE mitigation and identifies key parameters—particularly diffusivity modifications in the SP layer—that control the beneficial impact of shot peening.

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