A Monolithic Finite Element Framework for Fully-Coupled Chemo-Mechanics and the Non-Local Gurson-Tvergaard-Needleman Model

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Abstract

The transition from fossil fuels to sustainable energy sources across various sectors elevates the risk of hydrogen embrittlement in ductile materials, such as steel, used for hydrogen storage and transportation. Due to its small size, hydrogen easily diffuses into the metal lattice when exposed to various environments, inducing a ductile-to-brittle transition (1, 2). Ductile damage in steel is characterized by the nucleation, growth, and coalescence of microvoids-a process that is further accelerated in the presence of hydrogen. Theories explaining the hydrogen-induced reduction of strength in steels include hydrogen-enhanced decohesion (HEDE), hydrogen-enhanced localized plasticity (HELP), and hydrogen-enhanced strain-induced vacancies (HESIV) (3). The HEDE mechanism results in a principal stress-controlled brittle failure mode, while the HELP and HESIV mechanisms are driven by plastic deformation, accelerating void growth and coalescence. To address the latter aspect of this complex stress-diffusion process, we propose a mesh-independent finite element framework by combining coupled chemo-mechanics and the well-known non-local Gurson-Tvergaard-Needleman (GTN) damage model (4, 5). This fully-coupled framework is motivated by Fick's law for standard diffusion and the mixed rate-type potential approach introduced in (6), which accounts for the influence of hydrogen concentration on the material's mechanical response. Furthermore, the effects of hydrogen on damage are incorporated by extending the original non-local GTN model to account for hydrogen-enhanced void nucleation and growth, as suggested in (1, 3, 7). The stress-diffusion coupled system of equations is solved using a monolithic approach. The mutual interactions are explored in various representative boundary value problems to assess the impact of hydrogen on material degradation and the stress state on diffusion.

References

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