New Method Combining Nanoindentation and Finite Element Modeling (FEM) for Estimating Helium Ion Irradiation-Induced Eigenstrain/ Residual Stress in SiC

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Abstract

The advancement of next-generation reactors, focusing on improved safety and reduced waste production, relies on the development of innovative materials. Understanding the degradation of materials used as structural components in reactor cores is a critical aspect of this process. However, studying irradiation effects through test reactors is often constrained by limited access, high costs, and the risks associated with radioactivity. To address these challenges, research frequently employs ion beam irradiation as a safer and more accessible alternative to investigate the impact of radiation on material properties (1).
The ion irradiation process induces microstructural changes, including defect generation and accumulation, leading to mechanical deformation in a material leading to residual stresses (RS) field. Residual stress has a significant impact on the mechanical behavior and service life of materials under extreme conditions. Silicon carbide (SiC), a key candidate for advanced nuclear reactors, experiences a changes in its mechanical properties due to helium ion irradiation. Accurate quantification of these irradiation-induced residual stresses is essential for predicting the material's performance and failure mechanisms.

Experimentally estimating the irradiation-induced eigenstrain profile presents significant challenges, requiring the use of coupled advanced technological setups such as focused ion beam (FIB) techniques and transmission electron microscopy (TEM). However, this destructive approach, which involves slicing the sample, can induce relaxation of residual stresses within the material, potentially leading to underestimated measurements. This limitation highlights the need for developing alternative approaches.
This study proposes an innovative methodology for estimating residual stress in helium-irradiated SiC. The approach relies on minimizing the error between force-displacement curves obtained from experimental nanoindentation tests and corresponding simulations conducted using the finite element method (FEM) in Abaqus. The methodology provides an accurate assessment of the compressive residual stress. This novel technique offers a robust alternative for characterizing irradiation-induced stresses, contributing to the design and evaluation of advanced reactor materials.

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