Modelling Irradiated Metastable Materials for Cryogenic Applications

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Metastable materials, such as stainless steels, undergo a plastic strain–induced phase transformation at cryogenic temperatures, transitioning from the parent face-centered cubic (fcc) phase to a secondary body-centered cubic (bcc) phase. Components of superconducting particle accelerators, including high-field magnets, are frequently made of stainless steels. Due to the presence of high-energy particle beams, these components are often subjected to secondary particle flux, which induces nano- and micro-damage resulting from interactions between particles and the crystal lattice. One of the key challenges is predicting the lifetime of these components, considering various dissipative phenomena that occur simultaneously, including inelastic deformation, phase transformation, and the evolution of nano- and micro-damage. To obtain closed-form analytical solutions, constitutive models describing plastic strain–induced phase transformation and micro-damage evolution are needed. In the present work, a constitutive model of metastable austenitic stainless steels operating under combined cryogenic and irradiation conditions is presented. The approach combines plastic strain-induced phase transformation with radiation-induced damage mechanisms to capture the complex evolution of microstructure and mechanical response. The transformation from austenite to martensite is described using a physically based constitutive model referring to a linearized kinetics, based on the classical Olson–Cohen model. Radiation effects are incorporated through the evolution of defect populations, including helium-filled micro-voids, that affect both hardening and softening mechanisms. The growth of porosity is modeled using the Rice–Tracey formulation, enabling the description of void evolution including stress triaxiality. A new model of radiation-induced hardening based on the Orowan mechanism is developed. Building upon the mean-field algorithm, the present work introduces a novel formulation that accounts for the stiffness contribution of helium-filled micro-voids [1] [2]. Unlike conventional approaches that treat voids as compliant defects, the proposed formulation incorporates their internal pressure and effective stiffness, leading to a more accurate representation of the mechanical response. The combined model captures the competing effects of radiation-induced hardening, driven by dislocation–defect interactions, and softening associated with porosity evolution. The resulting framework provides improved predictive capabilities for the behavior of irradiated multiphase materials, and is particularly relevant for the analysis and design of structural components operating in extreme cryogenic environments. The results of the analysis are compared with experimental data to calibrate the models. Furthermore, the evolution of the microstructure accompanying both the plastic strain–induced phase transformation and damage development is thoroughly analyzed. Based on these models, the lifetime prediction of irradiated stainless steel components operating under cryogenic conditions is developed.

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