20th European Mechanics of Materials Conference - EMMC20
Florence, Italy | May 27th-29th, 2026
www.emmc20.unifi.it

A strain gradient crystal plasticity finite element method to predict irradiation induced damage in martensitic steel

Akash Gupta[1], Ushasi Roy[2]

[1] IIT Kanpur, India. akashg21@iitk.ac.in
[2] IIT Kanpur, India. ushasiroy@iitk.ac.in

Paper ID: 511
Symposium S15: Size-dependent materials modelling

Abstract

Irradiation in martensitic steels promotes radiation-induced segregation, leading to the formation of nanoscale precipitates and dislocation loops preferentially along lath and lath-boundary regions within a martensitic block. These irradiation-induced defects act as strong barriers to dislocation motion, enhance strain localization, and promote embrittlement, manifested as an increase in the ductile-to-brittle transition temperature (DBTT). DBTT is one of the critical properties that govern safe operation of nuclear structural components. To investigate the coupled effects of irradiation-induced nanoscale precipitates, dislocation density evolution, and crystallographic heterogeneity on the mechanical response of martensitic steels, a strain-gradient crystal plasticity framework is developed. Within this framework, sub-micron-scale three-dimensional representative volume elements (RVEs) are constructed to explicitly resolve individual martensitic laths containing spherical nanoscale precipitates located at lath corners and boundaries. Size effects associated with irradiation-induced precipitates are incorporated through separate evolution of statistically stored dislocations (SSDs) and geometrically necessary dislocations (GNDs), enabling a length scale dependent strain gradient plasticity. A thermally activated, Kocks-type slip rate law is used to assess the dependence of plastic flow on each crystallographic slip system as a function of temperature. To account for the hierarchical crystallographic nature of martensitic steels, the Kurdjumov–Sachs orientation relationship is employed at the block level. Additional RVEs comprising two interacting martensitic blocks are constructed to represent both low-angle and high-angle interfaces arising from distinct Kurdjumov–Sachs variants. This enables systematic investigation of block-level plastic strain distribution, misorientation-driven strain localization, and their influence on heterogeneous plastic deformation. Overall, the proposed microstructure-informed framework provides a robust and physically consistent tool for quantifying the coupled roles of nanoscale precipitates, dislocation structures, and crystallographic variants on the strength and deformation behavior of irradiated martensitic steels. The results offer mechanistic insight relevant to microstructural design, embrittlement assessment, and lifetime prediction of nuclear structural materials.

Keywords:

Crystal Plasticity Strain Gradient Plasticity Statistically stored dislocation (SSD) Geometrically necessary dislocations (GND) Microstructure Nano-size precipitates Finite element method