



Radiation damage in nanostructured materials



Xinghang Zhang^{a,*}, Khalid Hattar^b, Youxing Chen^c, Lin Shao^d, Jin Li^a, Cheng Sun^e, Kaiyuan Yu^f, Nan Li^c, Mitra L. Taheri^g, Haiyan Wang^{a,h}, Jian Wangⁱ, Michael Nastasi^{i,j}

^a School of Materials Engineering, Purdue University, West Lafayette, IN 47907, USA

^b Department of Radiation-Solid Interactions, Sandia National Laboratories, Albuquerque, NM 87185, USA

^c MPA-CINT, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

^d Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843-3128, USA

^e Materials and Fuels Complex, Idaho National Laboratory, Idaho Falls, ID 83415, USA

^f Department of Materials Science and Engineering, China University of Petroleum-Beijing, Beijing 102246, China

^g Department of Materials Science and Engineering, Drexel University, Philadelphia, PA 19104, USA

^h School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA

ⁱ Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583-0857, USA

^j Nebraska Center for Energy Sciences Research, University of Nebraska-Lincoln, Lincoln, NE 68583-0857, USA

ARTICLE INFO

Article history:

Received 30 December 2016

Received in revised form 4 March 2018

Accepted 13 March 2018

Available online 15 March 2018

Keywords:

Radiation damage

Nanomaterials

Modeling

In situ radiation

Defect sinks

Materials design

ABSTRACT

Materials subjected to high dose irradiation by energetic particles often experience severe damage in the form of drastic increase of defect density, and significant degradation of their mechanical and physical properties. Extensive studies on radiation effects in materials in the past few decades show that, although nearly no materials are immune to radiation damage, the approaches of deliberate introduction of certain types of defects in materials before radiation are effective in mitigating radiation damage. Nanostructured materials with abundant internal defects have been extensively investigated for various applications. The field of radiation damage in nanostructured materials is an exciting and rapidly evolving arena, enriched with challenges and opportunities. In this review article, we summarize and analyze the current understandings on the influence of various types of internal defect sinks on reduction of radiation damage in primarily nanostructured metallic materials, and partially on nanoceramic materials. We also point out open questions and future directions that may significantly improve our fundamental understandings on radiation damage in nanomaterials. The integration of extensive research effort, resources and expertise in various fields may eventually lead to the design of advanced nanomaterials with unprecedented radiation tolerance.

© 2018 Elsevier Ltd. All rights reserved.

Abbreviations: BCC, body-centered cubic; CG, coarse-grained; CTB, coherent twin boundary; DDZ, defect denuded zone; dpa, displacements-per-atom; ECAP, equal channel angular pressing; FCC, face-centered cubic; GB, grain boundary; HCP, hexagonal close-packed; HRTEM, high-resolution transmission electron microscopy; ITB, incoherent twin boundary; IVEM, intermediate voltage electron microscopy; KS, Kurdjumov–Sachs; MD, molecular dynamics; MDI, misfit dislocation intersection; NC, nanocrystalline; NP, nanoporous; NT, nanotwinned; NV-NT, nanovoid-nanotwinned; ODS, oxide dispersion strengthened; OKMC, object kinetic Monte Carlo; PED, precession electron diffraction; PKA, primary knock-on atom; PPM, parts per million; RT, room temperature; SAD, selected area diffraction; SFE, stacking fault energy; SFT, stacking fault tetrahedron; SIA, self-interstitial atom; SITB, symmetric incoherent twin boundary; SRIM, stopping and range of ions in matter; SS, stainless steel; STEM, scanning transmission electron microscopy; TB, twin boundary; TBAZ, twin boundary affected zone; TEM, transmission electron microscopy; TJ, triple junction; UFG, ultra-fine grained; VDZ, void denuded zone; XTEM, cross-sectional transmission electron microscopy; 0/1/2/3 D, zero/one/two/three dimensional.

* Corresponding author.

E-mail address: xzhang98@purdue.edu (X. Zhang).

<https://doi.org/10.1016/j.pmatsci.2018.03.002>

0079-6425/© 2018 Elsevier Ltd. All rights reserved.

Contents

1.	Introduction	219
1.1.	Motivation, scope and architecture	219
1.1.1.	Motivation	219
1.1.2.	Scope	219
1.1.3.	Architecture	220
1.2.	Radiation induced defects in metals with various crystal structures	221
1.2.1.	Radiation induced defects in metals with face-centered-cubic (FCC) structures	221
1.2.2.	Radiation induced defects in metals with body-centered-cubic (BCC) structures	224
1.3.	Radiation induced defects in metals with HCP structures	225
1.4.	Radiation induced cavities: Voids and gas bubbles	228
1.4.1.	Voids and void swelling	228
1.4.2.	Radiation induced He bubbles	230
1.5.	Classical models of sink strength for various types of defects	230
1.6.	Defect sinks and some general philosophies for alleviation of radiation damage	232
2.	Radiation damage in nanocrystalline metals and ceramics	233
2.1.	Sink strength of grain boundaries	233
2.2.	Defect-GB interactions	234
2.2.1.	Experimental observations of the defect-GB interactions in NC metals	234
2.2.2.	MD simulations showing defect absorption/capture by GBs	234
2.3.	Effect of grain size on radiation tolerance – microstructure and mechanical properties	235
2.3.1.	Radiation damage in pure NC metals	235
2.3.2.	Radiation damage in NC alloys	237
2.3.3.	Radiation damage in non-metallic NC materials	238
2.4.	Need to refine the GB sink strength model	245
2.4.1.	Complexity of GB nature on radiation damage in NC metals	245
2.4.2.	Modified GB sink strength model	245
2.4.3.	Application of the modified model for interpreting experimental findings	247
2.5.	Stabilities of NC metals in radiation environments	248
2.6.	Challenges and future outlook	251
3.	Radiation damage in metallic and ceramic nanolayers	252
3.1.	Sink strength of nanolayers	252
3.2.	Phenomena of defect-interface interactions	254
3.2.1.	<i>In situ</i> studies on absorption of radiation-induced defects by layer interfaces	254
3.2.2.	Layer interface effect: distance dependent defect concentration profile	254
3.2.3.	Layer-thickness-dependent defect concentration	255
3.2.4.	He bubble denuded zones near layer interfaces	255
3.3.	Size effect on mitigation of radiation damage in nanolayers	255
3.4.	Nature of interface on irradiation response of nanolayers	258
3.4.1.	Incoherent immiscible interfaces: The influence of misfit dislocation arrays	258
3.4.2.	Immiscible coherent interfaces: The Influence of coherency stress	261
3.4.3.	Miscible layer interfaces: radiation-induced intermixing	263
3.5.	Alternative mechanisms of reducing defect densities in nanolayers	263
3.6.	Radiation damage in ceramic nanolayers: Amorphization and nanocrystallization	263
3.7.	Size effect on hardening in irradiated nanolayers	267
3.8.	Challenges and future outlook	273
4.	Radiation damage in nanotwinned metals	273
4.1.	Twin boundaries in FCC metals	274
4.1.1.	Defective CTBs	274
4.1.2.	Dislocation structures of ITBs	275
4.2.	Radiation effects of CTBs	276
4.2.1.	Defect-CTB interactions	276
4.2.2.	The formation of ITB steps due to dislocation-CTB interactions	278
4.3.	Effects of ion irradiation on ITBs	280
4.3.1.	Point defect-ITB interactions	280
4.3.2.	Irradiation-induced ITB migration and dislocation-ITB interactions	280
4.4.	3D defect-TB interactions	282
4.4.1.	SFT-TB interactions: mechanisms and experiments	282
4.4.2.	Helium bubbles in nanotwinned metals	286
4.5.	Anomalous defect distribution in nanotwinned metals	287
4.6.	Healing of nanovoids and alleviation of irradiation damage by nanovoid-nanotwinned architecture	288
4.7.	Summary and future outlook	288
5.	Radiation damage in nanoporous materials, nanowires and nanoparticles	288
5.1.	The sink strength of nanoporous materials	289

Download English Version:

<https://daneshyari.com/en/article/8023011>

Download Persian Version:

<https://daneshyari.com/article/8023011>

[Daneshyari.com](https://daneshyari.com)