Journal of Nuclear Materials 441 (2013) 674–680

Contents lists available at SciVerse ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Study of irradiated mod.9Cr–1Mo steel by synchrotron extended X-ray absorption fine structure

Meimei Li [a,*], Dan Olive [b], Yulia Trenikhina [b], Hasitha Ganegoda [b], Jeff Terry [b], Stuart A. Maloy [c]

[a] Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439-4838, United States
[b] Illinois Institute of Technology, 3101 South Dearborn, Chicago, IL 60616, United States
[c] Los Alamos National Laboratory, MST-8, MS-H816, Los Alamos, NM 87545, United States

ARTICLE INFO

Article history:
Available online 12 October 2012

ABSTRACT

Synchrotron extended X-ray absorption fine structure (EXAFS) spectroscopy measurements were performed to study the dose dependence of and alloying effects on irradiation-induced changes in the local atomic environments in a mod.9Cr–1Mo ferritic-martensitic steel. The measurements were carried out at room temperature on non-irradiated and irradiated specimens exposed to 1, 4, and 10 displacement per atom (dpa) at 40–70 °C. The EXAFS data for Fe, Cr, Mo, and Nb K-edges were recorded, and the local structure close to the X-ray absorbing atom was determined. Irradiation caused significant reductions in peak amplitude in the Fe, Mo and Nb K-edge Fourier transformed EXAFS. The data showed a systematic decrease in coordination number of neighbor atoms with increasing irradiation dose, and the dose dependence of the coordination loss was dependent on the specific element. The measured damage around Fe sites can be correlated with the dpa value, while the loss of near neighbors around Mo saturated at ~1 dpa. The coordination in the Fe matrix was reduced less by irradiation than either the coordination of Mo in solution or Nb in carbides. It was demonstrated that EXAFS can provide a detailed, atomic level description of radiation damage in complex alloy systems.

1. Introduction

Ferritic–martensitic steels are the lead structural materials for various types of advanced fission and fusion energy systems. These alloys have excellent resistance to irradiation-induced swelling, good thermal properties, and low cost. Modified 9Cr–1Mo ferritic–martensitic steel is a prime candidate for structural applications in advanced sodium-cooled fast reactors [1]. Mod.9Cr–1Mo is a Fe-9%Cr–1%Mo steel modified with addition of V and Nb. The high temperature strength of mod.9Cr–1Mo relies on tempered martensite stabilized by $M_{23}C_6$ carbides and a fine distribution of vanadium/niobium carbon-nitride (MX) precipitates; molybdenum in the solution contributes to the strength through solid solution strengthening [2]. Irradiation can significantly change the initial optimum microstructure and degrade the mechanical performance of the alloy. A previous electron microscopy study on specimens of mod.9Cr–1Mo irradiated by mixed high-energy protons and neutrons showed that irradiation at low temperatures produces a large number of dislocation loops, carbide amorphization, and/or nanocrystallinity [3]. For such a complex alloy a variety of advanced characterization tools are required to fully understand irradiation defect production and accumulation and irradiation-induced/enhanced precipitation or dissolution processes.

The use of X-ray scattering and X-ray absorption spectroscopy has provided valuable insight into radiation damage in nuclear materials [4,5]. Extended X-ray absorption fine structure (EXAFS) spectroscopy has been used to probe irradiation-induced changes of local atomic environments in several classes of alloys, e.g. dilute Al alloys, steels, zirconium alloys, etc. [6–15]. The EXAFS oscillations of the X-ray absorption spectrum begin approximately 40 eV above the absorption edge and continue to higher photon energy. The oscillations arise from the interference of the outgoing photoelectrons with the scattered waves from neighboring atoms. The measurements of the oscillations can probe the local atomic environment of the absorbing atom, providing chemically-specific, local structural parameters such as atom types, coordination number and position of neighboring atoms. The element-specific nature of the technique makes it particularly useful for study of complex alloy systems [16]. EXAFS was employed to investigate interstitial-solute interactions in electron-irradiated dilute Al(Zn) and Al(Ag) [6,7]. It was demonstrated that the EXAFS is a useful tool to probe detailed structure of interstitial-solute complexes and to study defect trapping and detrapping reactions. Edwards et al. [8] characterized thermally-aged and neutron-irradiated Fe–Cu and

* Corresponding author. Tel.: +1 630 252 5111.
E-mail address: mli@anl.gov (M. Li).

0022-3115/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jnucmat.2012.09.039