Journal of Nuclear Materials 479 (2016) 48–58

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Observations of defect structure evolution in proton and Ni ion irradiated Ni-Cr binary alloys

Samuel A. Briggs [a,*], Christopher M. Barr [b], Janne Pakarinen [a,c], Mahmood Mamivand [a], Khalid Hattar [d], Dane D. Morgan [a], Mitra Taheri [b], Kumar Sridharan [a]

[a] University of Wisconsin-Madison, 1415 Engineering Drive, Madison, WI 53706, United States
[b] Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, United States
[c] SKC•CEN Belgian Nuclear Research Centre, Boeretang 200, B-2400 Mol, Belgium
[d] Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, United States

HIGHLIGHTS

- Binary Ni-Cr alloys were irradiated with protons or Ni ions at 400 and 500 °C.
- Higher irradiation temperatures yield increased size, decreased density of defects.
- Hypothesize that varying Cr content affects interstitial binding energy.
- Fitting CD models for loop nucleation to data supports this hypothesis.

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form
25 June 2016
Accepted 27 June 2016
Available online 29 June 2016

Keywords:
Radiation damage
Frank loops
Voids
Nickel alloys
Scanning/transmission electron microscopy

ABSTRACT

Two binary Ni-Cr model alloys with 5 wt% Cr and 18 wt% Cr were irradiated using 2 MeV protons at 400 and 500 °C and 20 MeV Ni^{4+} ions at 500 °C to investigate microstructural evolution as a function of composition, irradiation temperature, and irradiating ion species. Transmission electron microscopy (TEM) was applied to study irradiation-induced void and faulted Frank loops microstructures. Irradiations at 500 °C were shown to generate decreased densities of larger defects, likely due to increased barriers to defect nucleation as compared to 400 °C irradiations. Heavy ion irradiation resulted in a larger density of smaller voids when compared to proton irradiations, indicating in-cascade clustering of point defects. Cluster dynamics simulations were in good agreement with the experimental findings, suggesting that increases in Cr content lead to an increase in interstitial binding energy, leading to higher densities of smaller dislocation loops in the Ni-18Cr alloy as compared to the Ni-5Cr alloy.

1. Introduction

Ni-based alloys are commonly used in high-temperature applications due to their superior high temperature creep strength and were considered for nuclear reactor systems during fast reactor development programs in the '70s and '80s [1–6]. High-Cr Ni-based alloys are currently used primarily in systems in which there is no neutron flux, such as steam generators, as they have been found to be susceptible to irradiation-induced embrittlement [6]. However, there is a renewed interest in radiation damage effects in Ni-based alloys due to their excellent corrosion resistance, especially in molten salt reactor environments [7,8]. In these environments Cr-content, usually added to increase oxidation resistance, is considered detrimental as it is preferentially leeched by the fluoride salts [9]. As such, an understanding of radiation damage effects in low-Cr Ni-based alloys is desired.

Many prior radiation effects studies on Ni-based alloys focused on the Nimonic PE16 Ni-Fe-Cr alloy [1–5] and there is considerable literature on composition effects in austenitic stainless steels and ternary model alloy systems [3,10–13]. However, only a few fundamental studies have been performed to study Cr content effects on the radiation response of Ni-based alloys. Hudson and Ashby showed that increases in Cr content tended to reduce swelling in Ni-irradiated Ni-Cr binary systems and swelling rates for Ni-Cr continued to increase for higher damage doses, rather

* Corresponding author.
E-mail address: sabriggs2@wisc.edu (S.A. Briggs).

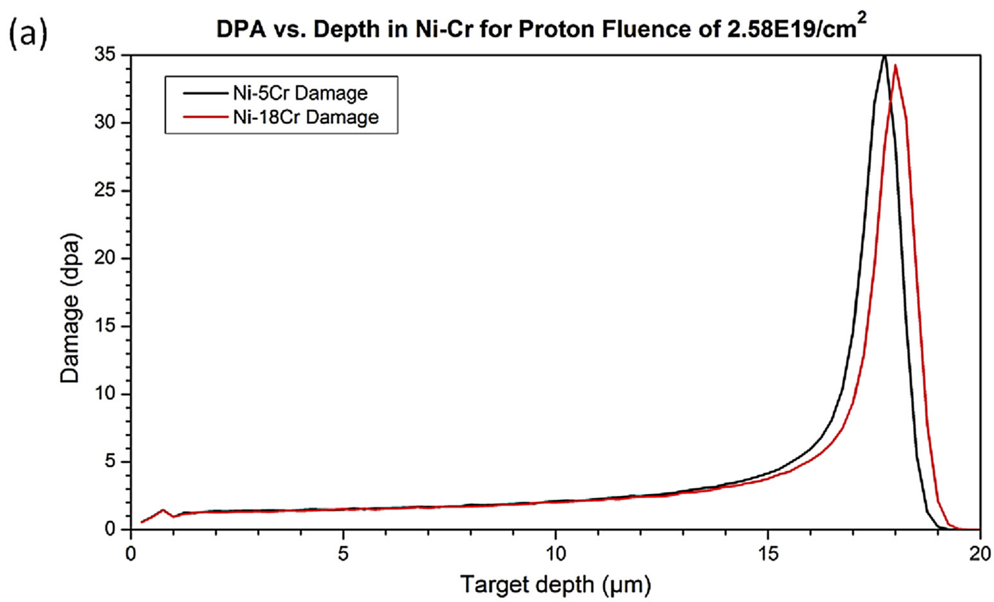
http://dx.doi.org/10.1016/j.jnucmat.2016.06.046
0022-3115/

than saturate as for pure Ni [14]. Garner has postulated that atomic ordering effects may influence void swelling [15], and Robinson and Jenkins have demonstrated weak dependence of dislocation loop formation on Cr content [16]. Finally, Barr et al. investigated the effects of grain boundary character on the radiation-induced segregation response in a Ni-5Cr alloy [17]. Extrapolation of data from these analogous systems can help to develop Ni-based alloys for the next generation reactor applications. However, more work is required to understand the fundamentals of the radiation response of these alloys.

Ion irradiation experiments have long been used to simulate neutron radiation damage in reactor environments; comparable damage levels are achieved much more rapidly and the resulting samples are typically non-radioactive, making the logistics of sample handling post-irradiation much easier. In this study both protons and Ni ions have been used to induce damage with the purpose of comparing the effect of dose rate on the induced microstructure, though other factors such as the efficiency of producing mobile point defects and gradients in induced damage must be considered in the context of the presented results. While no neutron irradiation experiments have been performed in the current work, the insights gained can be extrapolated to predict in-core radiation response, though the best way to reconcile the

Table 1
Summary of bulk alloy compositions for Ni-5Cr and Ni-18Cr in weight percent.

Alloy	Cr	Ni	C	Si	Co	P	S	Other minors
Ni-5Cr	5.00	94.94	0.007	0.01	0.01	<0.005	0.005	<0.01
Ni-18Cr	17.90	82.02	0.016	0.01	0.01	<0.005	0.006	<0.01



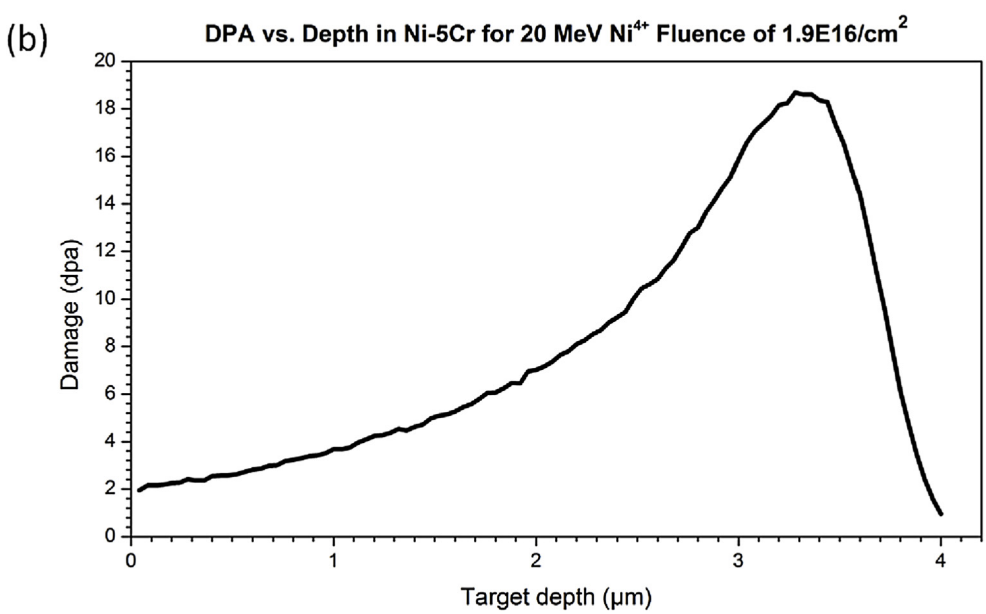


Fig. 1. (a) Damage profile for 2 MeV proton irradiations in both Ni-Cr alloys. Damage profiles are extremely similar and are assumed to be equivalent for the purpose of this experiment (studied region from 0 to 10 μm). (b) Damage profile for 20 MeV Ni^{4+} irradiations in Ni-5Cr. Microstructural investigation took place at a target depth of 1 μm, corresponding to a nominal damage dose of 3.4 dpa. Damage profiles generated using the SRIM-2008 software [27].