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Effect of irradiation temperature on microstructural changes in self-ion irradiated austenitic stainless steel

Hyung-Ha Jin [a], Eunsol Ko [a, c], Sangyeob Lim [a], Junhyun Kwon [a], Chansun Shin [b, *]

[a] *Nuclear Materials Division, Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon 305-353, Republic of Korea*
[b] *Department of Materials Science and Engineering, Myongji University, 116 Myongji-ro, Cheoin-gu, Yongin-si, Gyeonggi-do 449-728, Republic of Korea*
[c] *Clean Power Generation Laboratory, Korea Electric Power Research Institute, 105 Munji-ro, Yuseong-gu, Daejeon, 305-760, Republic of Korea*

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ABSTRACT

We investigated the microstructural and hardness changes in austenitic stainless steel after Fe ion irradiation at 400, 300, and 200 °C using transmission electron microscopy (TEM) and nanoindentation. The size of the Frank loops increased and the density decreased with increasing irradiation temperature. Radiation-induced segregation (RIS) was detected across high-angle grain boundaries, and the degree of RIS increases with increasing irradiation temperature. Ni–Si clusters were observed using high-resolution TEM in the sample irradiated at 400 °C. The results of this work are compared with the literature data of self-ion and proton irradiation at comparable temperatures and damage levels on stainless steels with a similar material composition with this study. Despite the differences in dose rate, alloy composition and incident ion energy, the irradiation temperature dependence of RIS and the size and density of radiation defects followed the same trends, and were very comparable in magnitude.

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1. Introduction

Internal components of nuclear reactors are installed to support the nuclear fuel assembly core in a reactor pressure vessel. These are among the most harshly irradiated components in a nuclear power plant. Since the material degradation in irradiation environments is closely related to the radiation-induced changes in the microstructures [1,2], an understanding of the evolution of radiation-induced defects and segregation in the internal components is recognized as an important task in order to maintain a material's service integrity.

Internal components in pressurized water reactor systems have been fabricated with 300-series austenitic stainless steels. The characterization of irradiation-induced phenomena for neutron-irradiated stainless steels using transmission electron microscopy (TEM) has been the subject of a number of research articles [3–5]. It was found that austenitic stainless steels exhibit significant segregation of solute atoms at grain boundaries as well as the formation of radiation defects (Frank loops or voids) and precipitates of various sizes. The radiation defects cause radiation hardening and embrittlement in these types of materials [6–8], especially when a high density of Frank loops is present. Irradiation-assisted stress corrosion cracking (IASCC) is closely related to radiation-induced segregation (RIS) at high-angle grain boundaries [9–11], and is also related to radiation hardening due to the formation of radiation defects.

Recently, there has been progress in both irradiation facilities and analytical characterization techniques. Ion irradiation has been utilized to understand radiation damage processes with the benefits of low activation and ease in changing irradiation conditions, such as temperature, dose level, and dose rate. Detailed understanding on the effects of dose rate and irradiation temperature could be gained for radiation damages in various ferrous and nickel alloys using ion irradiation [12–14]. As for stainless steels, proton irradiation was mainly used, and contributes to understanding of alloy composition and temperature dependence of RIS [15,16]. It was shown that proton irradiation could emulate neutron irradiation effects by comparing proton- and neutron-irradiated 300-series stainless steels [17].

Limited penetration depth of charged ions into a material could pose a difficulty in evaluating mechanical properties. Various small-scale mechanical testing techniques have been developed to probe the mechanical properties from the shallow ion-irradiated layer [18]. The 3D-atom probe tomography (3D-APT) technique

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* Corresponding author.
E-mail address: c.shin@mju.ac.kr (C. Shin).

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Table 1
Chemical composition of austenitic stainless steel (wt%).

Fe	Ni	Cr	Mo	Mn	C	Si	P	S
Bal.	11.1	17.1	2.1	1.3	0.06	0.59	0.04	0.001

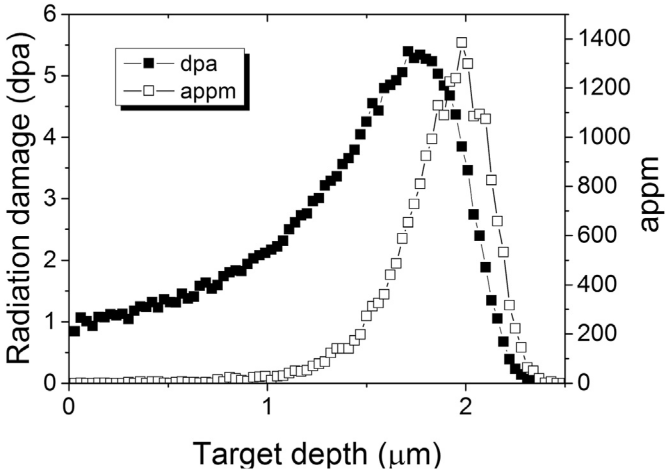

Fig. 1. The ion irradiation-induced damage profile and the stopped ion concentration as a function of depth calculated using the SRIM software.

has been used to acquire chemical information on sub-nanometer features among microstructural changes induced by neutron or ion irradiation [19,20]. In-depth chemical analysis for sub-nanometer-sized defects showed that RIS occurs in the vicinity of not only high-angle grain boundaries, but also of dislocations and radiation defects (Frank loops). New features, such as Ni—Si clusters, were also revealed from these 3D-APT studies. The progress in characterization techniques helps to better understand the process of radiation-induced material degradation in austenitic stainless steels.

While the studies using proton irradiation help to enhance our understanding radiation-induced changes in microstructure and properties of austenitic stainless steels, the number of studies using self-ion irradiation is few [20–22]. In this study, austenitic stainless steel was irradiated with 8 MeV Fe^{4+} ions at three different temperatures. We characterized solute segregation and irradiation defects using TEM, and measured the mechanical properties after irradiation using nanoindentation. We compared the irradiation temperature dependence of the formation of irradiation defects and the solute segregation of self-ion irradiated stainless steel revealed in this study with those of proton- and self-ion irradiation experiments in the literature. Since the RIS and the formation of defects are dependent on various experimental parameters, such as irradiation sources, damage rate, composition and heats of stainless steels, literature data were carefully selected to have a similar damage level, alloy composition and comparable irradiation temperature.

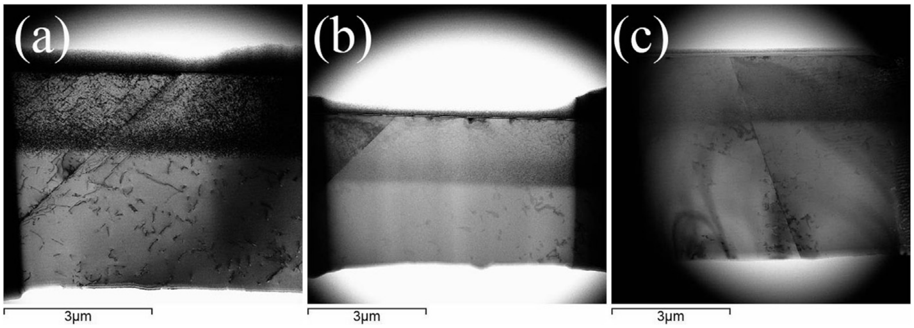

Fig. 2. STEM images of TEM lamellae taken from austenitic stainless steels irradiated at (a) 400 °C, (b) 300 °C, and (c) 200 °C.

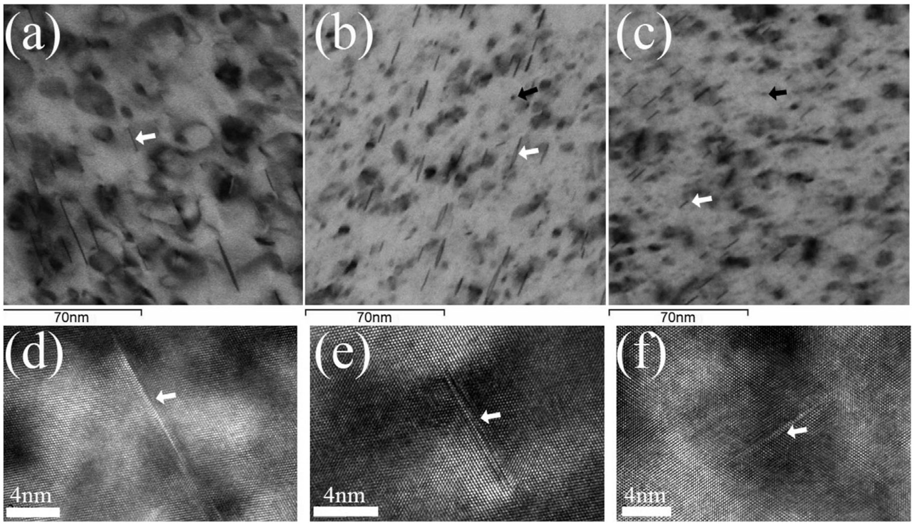

Fig. 3. STEM images of radiation defects of the sample irradiated at (a) 400 °C, (b) 300 °C, and (c) 200 °C. HRTEM images of the edge-on type Frank loop lying on {111} taken from the sample irradiated at (d) 400 °C, (e) 300 °C, and (f) 200 °C.

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