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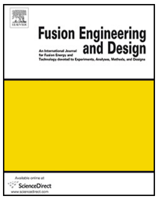

# Evaluation of strain-rate sensitivity of ion-irradiated austenitic steel using strain-rate jump nanoindentation tests

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## HIGHLIGHTS

- We examined strain-rate jump nanoindentation on ion-irradiated stainless steel.
- We observed irradiation hardening of the ion-irradiated stainless steel.
- We found that strain-rate sensitivity parameter was slightly decreased after the ion-irradiation.

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## ABSTRACT

The present study investigated strain-rate sensitivity (SRS) of a single crystal Fe–15Cr–20Ni austenitic steel before and after 10.5 MeV $Fe^{3+}$ ion-irradiation up to 10 dpa at 300 °C using a strain-rate jump (SRJ) nanoindentation test. It was found that the SRJ nanoindentation test is suitable for evaluating the SRS at strain-rates from 0.001 to 0.2 $s^{-1}$. Indentation size effect was observed for depth dependence of nanoindentation hardness but not the SRS. The ion-irradiation increased the hardness at the shallow depth region but decreased the SRS slightly.

## 1. Introduction

Fusion reactor blanket structural materials suffer from strong electro-magnetic force at a wide range of strain-rate due to transient phenomenon such as current disruption [1]. Previously, we investigated the strain-rate dependence of the tensile properties of reduced-activation ferritic steel F82H up to high strain rates of $\sim 10^3\ s^{-1}$ [2]. However, there is limited data of strain-rate sensitivity (SRS) of structural materials, especially after neutron irradiation.

Ion-irradiation is a useful method to evaluate the irradiation effect on materials at high dose rate, with no induced-radioactivity, high-usability, and high cost performance. While the depth range of irradiation is limited to several microns (μ), we successfully obtained the nanoindentation hardness after evaluating the irradiation hardening of ion-irradiated materials [3–5]. However, there seems to be very little reported about the SRS of ion-irradiated materials. Recently, Maier et al. developed a novel method to evaluate the SRS of nanocrystalline Ni and Al by using strain-rate jump (SRJ) nanoindentation [6]. Here we examine the SRJ nanoindentation of ion-irradiated materials in order to investigate the SRS of austenitic stainless steel before and after Fe-ion irradiation.

## 2. Experimental procedure

### 2.1. Materials

Fe(bal.)–15 wt.%Cr–20 wt.%Ni was used as a single crystal austenitic stainless steel. This chemical composition was used to avoid data scattering of nanoindentation hardness due to microstructural non-uniformity.

### 2.2. Ion-irradiation

The ion-irradiation experiments were performed at the TIARA facility, Japan Atomic Energy Agency. A single-ion beam of 10.5 MeV $Fe^{3+}$ was irradiated on to the surface of the single crystal specimen.

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Irradiation temperature was controlled and measured at 300 °C. Displacement damage and damage rate at 1000 nm sample depth were 10 dpa and $1 \times 10^{-3}$ dpa $s^{-1}$, respectively.

### 2.3. SRJ nanoindentation

Nanoindentation tests were carried out using a NanoIndentor G200 (Agilent Technologies) equipped with a three-sided Berkovich diamond tip at room temperature. Constant stiffness measurement (CSM) mode, which adds an oscillatory signal about the main loading rate at 45 Hz with 2 nm amplitude oscillations, was applied for obtaining depth-dependent nanoindentation hardness [7]. Tip rounding and flame compliance were calibrated using the Oliver-Parr method [7]. The SRJ nanoindentation method developed by Maier et al. [6] was applied for evaluating the SRS of nanoindentation hardness. In nanoindentation, strain rate can be estimated as

$$\dot{\varepsilon} = \frac{\dot{h}}{h} = \frac{1}{2}\left(\frac{\dot{P}}{P} - \frac{\dot{H}}{H}\right) \cong \frac{1}{2}\frac{\dot{P}}{P} \qquad (1)$$

where $h$ is the indentation depth and $\dot{h}$ is the indenter descent rate [6,8]. The CSM controls the value of loading-rate based strain-rate $\dot{P}/P$ to be a constant in order to achieve a constant strain rate $\dot{\varepsilon}$. This prospect is valid for materials showing $\dot{H} \cong 0$, e.g. nanocrystallines examined by Maier et al. [6] and ceramics. However, many metallic materials deformed by dislocation gliding show indentation size effect (ISE), which causes depth–dependent hardness [8]. Furthermore, ion-irradiation can cause depth–dependent hardness due to the damage gradient effect and the softer substrate effect [3]. Therefore, the method for controlling strain-rate based on Eq. (1) is suitable for the measurement of austenitic stainless steel. According to previous work [6,9], the SRS parameter $m$ of nanoindentation hardness is defined as

$$m = \frac{d\ln H}{d\ln \dot{\varepsilon}}. \qquad (2)$$

## 3. Result and discussion

Fig. 1 shows an example of the depth dependences of (a) nanoindentation hardness and elastic modulus, (b) loading-rate-based strain-rate $\dot{P}/P$, and (c) strain-rate of an unirradiated single crystal austenitic stainless steel obtained by SRJ nanoindentation. The magnified graph of the depth range 350 to 550 nm is shown in Fig. 1(a)'–(c)'. As well-known, ISE on nanoindentation hardness was seen in the depth dependence. While the value of $\dot{P}/P$ was well

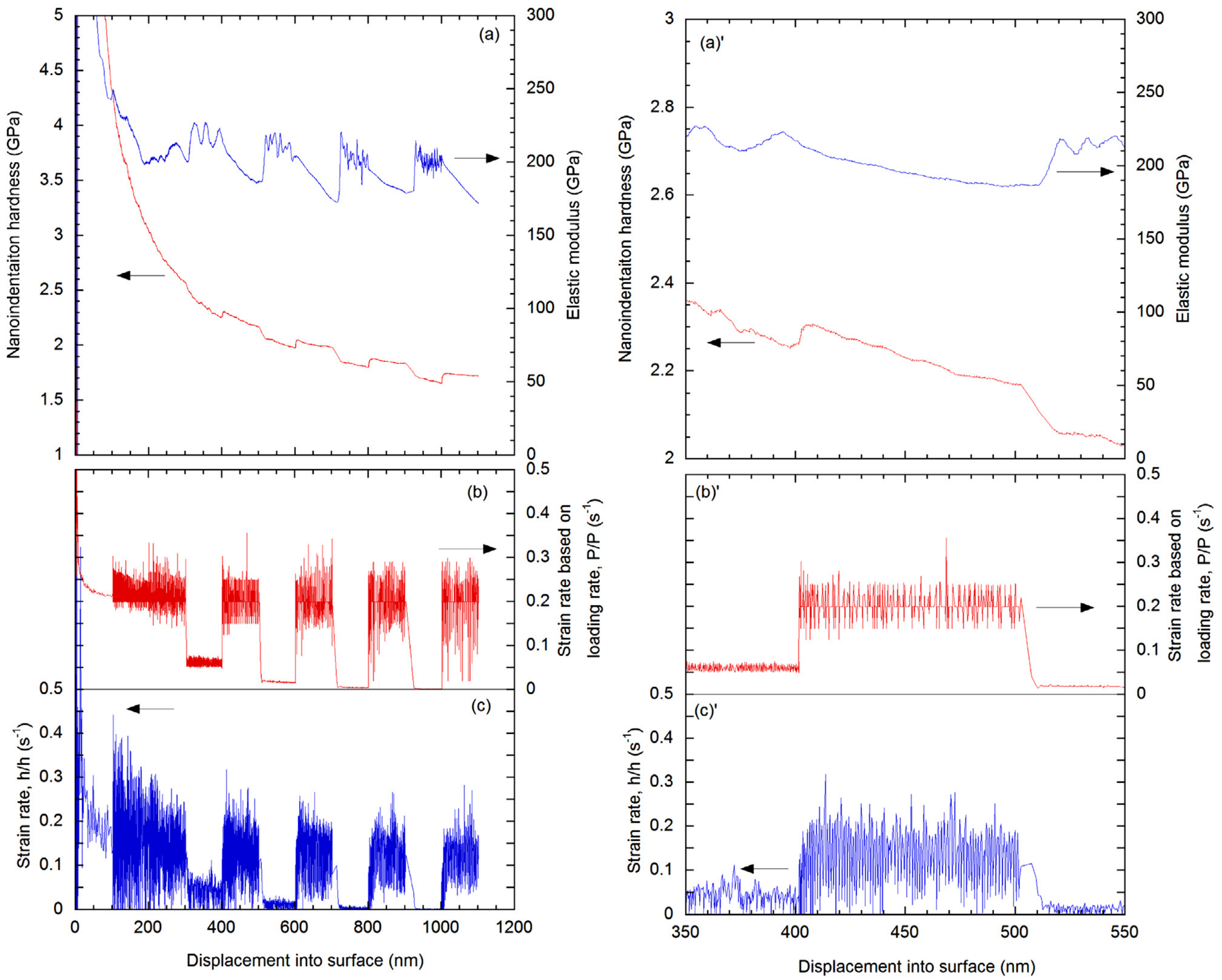

**Fig. 1.** An example of the depth dependence of (a) nanoindentation hardness and elastic modulus, (b) loading-rate based strain rate and (c) strain rate of an unirradiated single crystal austenitic stainless steel obtained by SRJ nanoindentation test. The graphs of (a)', (b)' and (c)' are magnified images of the depth range between 350 and 550 nm.

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