Irradiation Dose Dependence of Deformation and Fracture Characteristics for SA533B Steel

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1. Introduction

The analysis of necking deformation of tensile data is helpful to understand the failure characteristics of irradiated materials because the fracture toughness of material might be related to the fracture strain and significant true necking strain is often measured in the irradiated specimens. Thus, our previous study developed a procedure, which is iterative finite element (FE) simulation technique, for determining full equivalent true stress(σ_T) - strain(ε_T) curve including unstable necking deformation in tensile data and investigated the irradiation effect on the deformation behavior and fracture properties from tensile data for irradiated austenitic stainless steels [1]. It was seen that the iterative FE simulation technique is useful for evaluating equivalent σ_T-ε_T curve from the tensile data given by flat specimen and can reliably provide deformation and fracture characteristics for irradiated materials. The present study evaluated the deformation behavior and fracture characteristic of irradiated SA533B steel from tensile data using iterative FE simulation technique and investigated the irradiation effects on these mechanical properties.

2. Finite Element Simulation

2.1 Tensile Data

Tensile data for irradiated SA533B steel obtained from earlier study [2] were analyzed in the present study using iterative FE simulation technique. The material was irradiated to doses of 0.0001, 0.01, 0.1, and 0.89dpa, and tested at ambient temperature. Irradiation was conducted at the hydraulic tube facility of the high flux isotope reactor (HFIR) at the Oak Ridge National Laboratory. Irradiation temperature was estimated to be in the range 60-100^{o}C. Small-sized flat specimen, whose gage section dimension is 8mm×1.5mm×0.25mm, was employed for tensile tests.

Figure 1 presents the engineering stress(σ_E)-strain(ε_E) curves of irradiated SA533B steel analyzed in the present study. It shows that the σ_E-ε_E curves are considerably changed by irradiation; the strength increases and ductility decreases as the irradiation dose increases. For the two higher doses of 0.1 and 0.89dpa, moreover, there is no uniform plastic deformation and prompt necking begins at yield followed by continuous softening to failure. Thus, it is expected that the analyzed tensile data apparently represent the irradiation effects on the deformation behavior and fracture properties of SA533B steel.

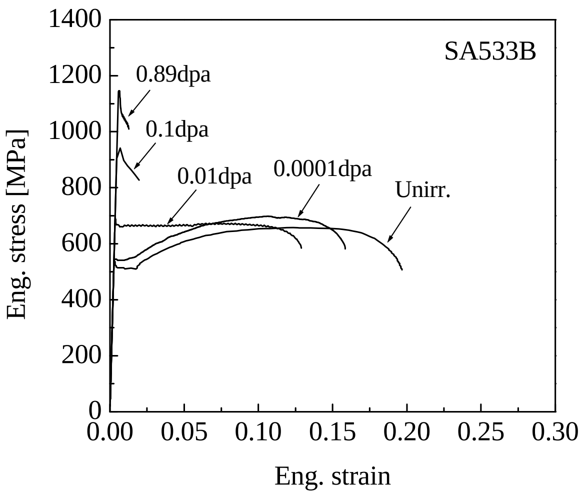

Fig. 1 Engineering stress-stress curves for irradiated SA533B steel

2.2 Finite element model

A procedure applied to determine full equivalent σ_T-ε_T curve including unstable necking deformation in tensile data was the same as that described in the previous study [1]. In the procedure, the equivalent σ_T-ε_T curve after onset of necking was determined by iterative FE simulations until the numerical calculation of the load and unstable deformation corresponded well with the experimental data.

FE simulation was performed using a general-purpose finite element program, ABAQUS [3]. The FE model used in the analysis is three-dimensional one-eighth model that consists of 20-nodes solid element with reduced integration (C3D20R in ABAQUS). Material and geometrical nonlinearities were considered in the analysis to properly simulate the necking of specimens. A geometrical imperfection in a form of localized reduced width and thickness of an amount 0.25% of their dimensions was embedded in the model to allow the initiation of necking.

3. Results and Discussion

3.1 Deformation behavior

Figure 2 presents full equivalent σ_T-ε_T curves including unstable necking deformation region for SA533B steel

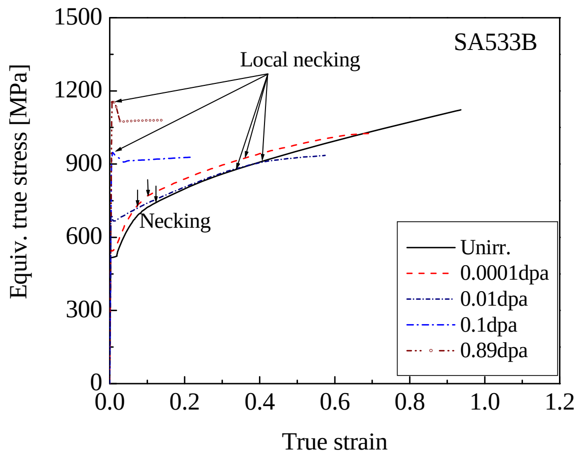

Fig. 2 Equivalent true stress-strain curves for irradiated SA533B steel obtained from tensile data using FE simulations

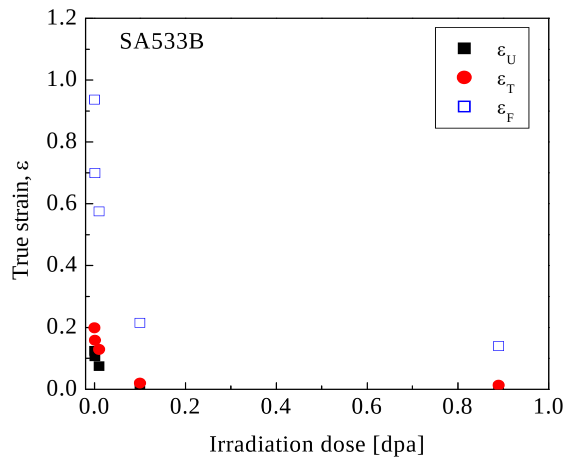

Fig. 3 Dose dependence of equivalent fracture strain for SA533B

irradiated to various doses. At dose of 0.0001dpa, the equivalent σ_T-ε_T curve is almost identical over the whole strain range to that before irradiation. The curve at the intermediated dose of 0.01dpa is also almost the same as that of unirradiated condition, except that the slope of the curve is reduced in the higher strain region above 40%. At higher doses of 0.1 and 0.89dpa, however, the equivalent σ_T-ε_T curves are much higher than those at doses below 0.01dpa. The curves are initially dropped and then increase with increasing true strain to final failure, and the slope of the curves is lower than that at lower dose cases. It is indicated that the strain hardening rate of SA533B steel irradiated at lower doses below 0.01dpa, which exhibited uniform plastic strain in σ_E-ε_E curves, is almost the same as that before irradiation. For the higher doses above 0.1dpa where the σ_E-ε_E curves showed continuous softening after a prompt necking at yield, the strain hardening rate is also still positive even though the value is less than that at lower doses below 0.01dpa.

3.2 Fracture properties

To investigate irradiation dose dependence of tensile fracture properties for SA533B steel, the equivalent fracture stress, fracture strain, and tensile fracture energy were obtained from the equivalent σ_T-ε_T curves. The equivalent fracture stress decreases with increase in dose level up to 0.01dpa and slightly increases above dose level: thus, the equivalent fracture stress at 0.89dpa is almost the same as that before irradiation. As shown in Fig. 3, the equivalent fracture strain significantly decreases with increasing dose level up to 0.1dpa and then decreases at lower rate. But, at 0.89dpa the fracture strain is about ε_F=16%, which is much high compared to uniform and total strains that are about 0% and 0.3%, respectively. The variation of tensile fracture energy with irradiation dose is nearly the same as that of fracture strain. The tensile fracture energy is exponentially reduced by irradiation up to 0.01dpa, and then it is slowly saturated above 0.1dpa. The saturated tensile fracture energy is about 20% of unirradiated specimen. Therefore, it is indicated from these data that the fracture properties were sensitive to irradiation dose level in the range 0-0.1dpa, but it is less sensitive above dose level of 0.1dpa. This is related to the saturation of point defect clusters, which was observed at doses range 0.01-0.1dpa.

4. Conclusions

1) Strain hardening rate in the equivalent true stress-strain curve was still positive during the unstable necking deformation, and it varied with necking mode change rather than with irradiation dose.
2) Equivalent fracture stress decreased with increase in dose level up to 0.1dpa and slightly increased above irradiation dose level.
3) Equivalent fracture strain and tensile fracture energy significantly decreased with increasing dose level up to 0.1dpa and then decreased at lower rate. But, it was still high after high dose irradiation exposure even if uniform ductility was almost zero.

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