Evaluation of Dose Dependence on Tensile Deformation and Failure in Austenitic Stainless Steels

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1. Introduction

A number of studies have been conducted to clarify the change in the mechanical properties of austenitic stainless steels under intense radiation environments [1, 2]. However, most of these radiation-induced changes were observed for the uniform deformation regime only based on the engineering stress-strain curves, and consequently the radiation effects on the unstable deformation, which is often larger than the uniform deformation in the stainless steels, were often ignored. To understand the radiation effects on deformation and fracture phenomena in detail, therefore, it is necessary to produce full stress-strain data covering yielding, uniform deformation, unstable deformation, and final failure. This study aimed at the detailed characterization of irradiation effects on the full range of deformation including unstable deformation and final failure based on the equivalent true stress and true strain relation. Thus, the full equivalent true stress-true strain curves were determined from tensile data for annealed 316 SS and EC316LN SS irradiated to various doses using finite element simulation technique. The tensile fracture properties, *i.e.*, equivalent fracture stress, fracture strain, and tensile fracture energy, were evaluated from the calculated true stress-true strain curves.

2. Analyzed Materials

Two tensile datasets for irradiated 316 SS and EC316LN SS obtained from earlier studies [3,4] were analyzed in this study. The materials were irradiated to various doses and tested at RT. These datasets were selected to well represent the radiation effect on the deformation and facture behaviors of the austenitic stainless steels. Table 1 summarized the irradiation and test conditions, respectively.

3. Finite Element Simulation Procedure

The equivalent true stress-true strain curve beyond the onset of necking was determined by an iteration method until the numerical calculation of the load and unstable deformation corresponded well with the experimental data. Three-dimensional one-eighth model that consists of twenty-node solid element with reduced integration was used for finite element simulations. In this simulation, the end of true stress-true strain curve, *i.e.*, the fracture strain, was determined from the simulated cross-section area at the displacement corresponding to final failure in the load-displacement curve. The equivalent fracture stress was also determined as a stress value corresponding to the fracture strain on the equivalent true stress-true strain curve.

Finite element simulation results were verified by comparing the simulated and experimental curves for irradiated stainless steels and by examining the strain contour and deformation pattern at final failure. It is seen that the finite element model successfully simulates the load-displacement responses of tensile tests including the failure phenomena such as the initiation of localized necking.

4. Results and Discussion

4.1 Equivalent true stress-true strain curves

Figure 1 presents full equivalent true stress-true strain curves including unstable deformation region for 316 SS and EC316LN SS irradiated to various doses, which were determined by the iterative finite element simulations. The curves have continuously decreasing slopes in uniform deformation region. The continuity of the curves was kept at the onset of necking; there was no sign of transition in the equivalent true stress-true strain curves regardless of irradiation dose and the equivalent true stress still increased with increasing true strain at similarly high rates throughout the unstable deformation. It was also observed that the slopes of the curves little varied with irradiation dose before the significant slope change appeared, even though the specimen at a higher dose exhibited higher equivalent true stress-true strain curve. The comparison of equivalent true stress-true strain curve and strain contour revealed that the significant slope change after

Table 2 Irradiation and test conditions [3,4]

Data I.D.	Materials	Irradiation facility	Dose range (dpa)	Irradiation temperature (^oC)	Test temperature (^oC)	Specimen type
IR1	[a]316-annealed	HFIR	0-0.78	60-100	20	BES/NERI
IR2	EC316LN	LANSCE	0-10.7	60-160	20	SS-1

a certain amount of unstable deformation is associated with the necking mode transition. Therefore, it is seen that in the austenitic stainless steels after significant irradiation high positive strain hardening rate is still retained during unstable deformation before localized necking initiates. Further, it is indicated that the strain hardening rate is independent of irradiation dose.

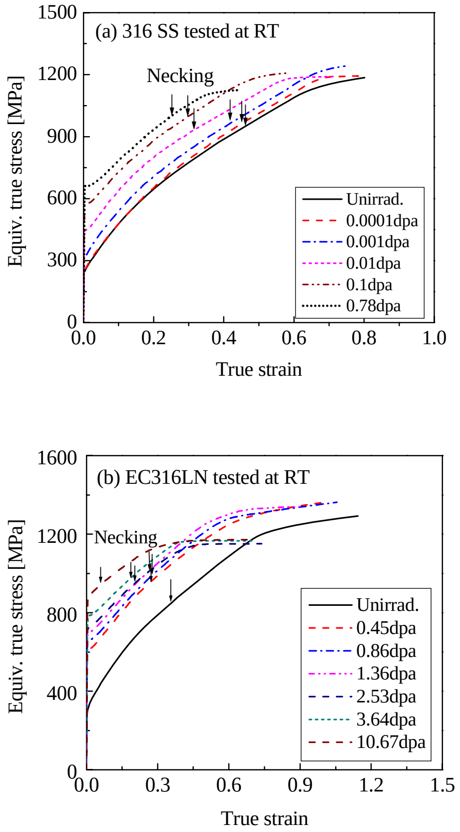

Fig. 1 Equivalent true stress-true strain curves for austenenite stainless steels irradiated to various doses

4.2 Dose dependence of fracture properties

To investigate dose dependence of tensile fracture properties for austenitic stainless steels, the equivalent fracture stress and fracture strain were obtained from the equivalent true stress-true strain curves. For the 316 SS both σ_{nL} and σ_{FE} , which are equivalent fracture stresses defined at initiation of localized necking and final fracture, respectively, slightly increased at lower doses and then decreased with increasing irradiation dose. But their variations with dose were minor; the values of σ_{nL} and σ_{FE} at 0.78dpa were nearly identical to those at unirradiated condition, $\sigma_{nL,unir}$ and $\sigma_{FE,unir}$. For the EC316LN SS, the variations in σ_{nL} and σ_{FE} with irradiation dose were also negligible up to around 2dpa, but the σ_{nL} and σ_{FE} abruptly dropped about 10% above 2dpa. This result indicates that the equivalent fracture stress defined at either initiation of localized necking or final fracture is insensitive to irradiation dose up to, at least, 0.78dpa in 316 SS and 10.7dpa in EC316LN SS, except for the 10% drop of fracture stress around 2dpa in EC316LN SS that is associated with a change in the irradiation damage and associated failure mechanism.

On the other hand, for 316 SS the ε_{nL} and ε_F, which are fracture strains defined at initiation of localized necking and final fracture, respectively, were relatively little changed over a lower dose below 0.01dpa and then decreased exponentially with dose above 0.01dpa. However, the values of ε_{nL} and ε_F at 0.78dpa were still higher than 50% of those in unirradiated condition, $\varepsilon_{nL,unir}$ and $\varepsilon_{F,unir}$. The ε_{nL} and ε_F for EC316LN SS rapidly decreased with dose in the range 0 ~ 2 dpa and then decreased at lower rates after a small drop around 2dpa. At a dose of 10.7dpa, the values of ε_{nL} and ε_F were approximately 35% of $\varepsilon_{nL,unir}$ and 60% of $\varepsilon_{F,unir}$, respectively. The reduction in fracture strain with irradiation dose was relatively small compared to the uniform strain. It is recognized from this result that the fracture strain of austenitic stainless steels is still high after irradiation exposure even if uniform ductility is considerably reduced.

5. Conclusions

The conclusions from the analysis results are:

(1) Before the localized necking started, the strain hardening rate during the unstable deformation was retained at a high level similar to that in the end of uniform deformation, and it was nearly independent of dose.

(2) The variation in equivalent fracture stress with irradiation dose was negligible for the austenitic stainless steels unless irradiation damage mechanism changed.

(3) The fracture strain of austenitic stainless steels decreased rapidly with dose in the low dose range < 2dpa and at higher doses they approached saturation values, which were still significantly high.

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