ANALYSIS OF NECKING DEFORMATION AND FRACTURE CHARACTERISTICS OF IRRADIATED A533B RPV STEEL

JIN WEON KIM^{1†*} and THAK SANG BYUN²

¹Department of Nuclear Engineering, Chosun University
375 Seosuk-dong, Dong-gu, Gwangju, 501-759, Republic of Korea

²Oak Ridge National Laboratory, Material Science and Technology Division
P.O. Box 2008, MS-6151, Oak Ridge, TN 37831, United States

*Corresponding author. E-mail : jwkim@chosun.ac.kr

Received February 15, 2012

Accepted for Publication March 23, 2012

This paper reports the irradiation effect on the deformation behavior and tensile fracture properties of A533B RPV steel. An inverse identification technique using iterative finite element (FE) simulation was used to determine those properties from tensile data for the A533B RPV steel irradiated at 65 to 100°C and deformed at room temperature. FE simulation revealed that the plastic instability at yield followed by softening for higher doses was related to the occurrence of localized necking immediately after yielding. The strain-hardening rate in the equivalent true stress–true strain relationship was still positive during the necking deformation. The tensile fracture stress was less dependent on the irradiation dose, whereas the tensile fracture strain and fracture energy decreased with increasing dose level up to 0.1 dpa and then became saturated. However, the tensile fracture strain and fracture energy still remained high after high-dose irradiation, which is associated with a large amount of ductility during the necking deformation for irradiated A533B RPV steel.

KEYWORDS : Irradiation Effect, A533B RPV Steel, Deformation Behavior, Tensile Fracture Property, Inverse Identification Technique, Iterative Finite Element Simulation

1. INTRODUCTION

Since the irradiation-induced changes in mechanical properties are the major degradation mechanisms in nuclear reactor components, it is important to understand the mechanical characteristics of irradiated materials to evaluate their structural designs and integrities. A number of studies have investigated the irradiation-induced changes in the mechanical properties of nuclear materials, including dose dependences of strength, ductility, and strain-hardening capacity [1–10]. However, most of these were observed for the uniform deformation regime only based on the engineering stress (σ_E) – engineering strain (ϵ_E) relationship. The effect of irradiation on the unstable deformation beyond the onset of necking has not been explored properly, even though in most cases its regime is larger than that for the uniform deformation. In addition, the effect of

irradiation on the fracture properties of materials important for design and integrity evaluations of nuclear facilities cannot be estimated from an analysis of $\sigma_E - \epsilon_E$ data. In order to investigate the effect of irradiation on the deformation and fracture properties for irradiated materials from their tensile data, it is necessary to analyze full true stress (σ_T) – true strain (ϵ_T) data covering uniform deformation, necking deformation, and final failure. The analysis of necking deformation from tensile data is particularly helpful in investigating the failure characteristics of irradiated materials because the fracture toughness of materials might be related to the tensile fracture strain and tensile fracture energy that are mainly characterized by unstable necking deformation [11].

Several studies have indicated that the analysis of $\sigma_T - \epsilon_T$ data provides more insights into the effect of irradiation on the deformation behavior and fracture properties of materials [11–15]. Byun and Farrel [12–14] investigated the tensile fracture stress (σ_F), tensile fracture strain (ϵ_F), and strain-hardening rate for various irradiated materials and proposed macroscopic deformation mode maps. Van Osch and de Vries [15] also investigated the strain-hardening behavior and tensile fracture stress for a vanadium alloy based on the full $\sigma_T - \epsilon_T$ curves obtained from inter-

[†]Corresponding Author:
Associate Prof. Jin Weon Kim
Department of Nuclear Engineering, Chosun University
375 Seosuk-dong, Dong-gu, Gwangju 501-759, Republic of Korea
TEL: +82-62-230-7109, FAX: +82-62-232-9218
E-mail: jwkim@chosun.ac.kr

rupted tensile tests. However, their results were based on a nominal $\sigma_T - \varepsilon_T$ relationship instead of the equivalent $\sigma_T - \varepsilon_T$ relationship that represents the more general stress and strain response of a material. Our previous studies [16,17] proposed using an inverse identification technique which employs iterative finite element (FE) simulation to determine the full equivalent $\sigma_T - \varepsilon_T$ curve, including unstable necking deformation from the tensile data. The study demonstrated that the inverse identification technique using iterative FE simulation is useful to determine the full equivalent $\sigma_T - \varepsilon_T$ curve from tensile data for flat specimens. The technique can reliably evaluate unstable necking deformation and tensile fracture properties of irradiated materials.

The present study evaluated the deformation behavior and tensile fracture properties of irradiated A533B reactor pressure vessel (RPV) steel from tensile data. The inverse identification technique using iterative FE simulation was used to study the effect of irradiation on these mechanical properties. The present study determined the full equivalent $\sigma_T - \varepsilon_T$ curves including unstable necking deformation from the tensile data. The strain-hardening rate and tensile fracture properties, i.e., equivalent tensile fracture stress, tensile fracture strain, and tensile fracture energy (E_f), were analyzed using the full equivalent $\sigma_T - \varepsilon_T$ curves. The analysis results were discussed with emphasis on the dose dependences of those properties for the A533B RPV steel.

2. TENSILE DATA

Using the inverse identification technique, the present study analyzed the tensile data for irradiated A533B RPV steel, which was obtained from an earlier study [4]. The A533B steel is a low-alloy steel with a quenched-and-tempered microstructure, commonly used for reactor pressure vessels in commercial light water reactors (LWRs). The material was irradiated to four levels of neutron dose (0.0001, 0.01, 0.1, and 0.89 dpa) at the hydraulic tube facility of the high flux isotope reactor (HFIR) at Oak

Ridge National Laboratory. The irradiation temperature was estimated to be about 65 to 100°C. Tables 1 and 2 give the chemical composition and heat treatment of the test material, and the irradiation and test conditions, respectively [4]. Small-size flat specimens nominally 8 mm × 1.5 mm × 0.25 mm (called the BES/NERI type) were used for tensile testing. All tests were conducted at ambient temperature on a screw-driven machine at a quasi-static strain rate of about 10⁻³ s⁻¹ [4].

Figure 1 presents the $\sigma_E - \varepsilon_E$ curves for the irradiated A533B RPV steel used in the present study. The $\sigma_E - \varepsilon_E$ curves were considerably changed by irradiation at low temperature (about 100°C). Both the uniform plastic deformation and the necking regimes existed in the $\sigma_E - \varepsilon_E$ curves before irradiation and at a low dose of 0.0001 dpa. At the intermediate dose of 0.01 dpa, the increase in yield stress (σ_{YS}) and decrease in elongation were more pronounced, and the strain-hardening region was eliminated. For the two higher doses of 0.1 and 0.89 dpa, a completely different behavior was observed [4]. The yield stress was

Fig. 1. Engineering Stress – Strain Curves for Irradiated A533B RPV Steel [4]

Table 1. Materials and Heat Treatment [4]

Material	Chemical composition	Heat treatment
A533B	Fe – 0.22 C – 0.25 Si – 1.48 Mn – 0.52 Mo – 0.68 Ni – 0.018 S – 0.012 P	Annealed at 880°C for 4 h and air-cooled, tempered at 660°C for 4 h, and then reheated at 610°C for 20 h.

Table 2. Irradiation and Test Conditions [4]

Material	Irradiation facility	Dose range (dpa)	Irradiation temperature (°C)	Test temperature (°C)	Specimen type
A533B	HFIR at ORNL	0-0.89	60-100	20	BES/NERI [4]

considerably higher than for the lower doses and coincided with the tensile stress (σ_U); there was no uniform plastic deformation, and necking began promptly at yield followed by continuous softening to final failure.

3. FINITE ELEMENT SIMULATION

3.1 Simulation Procedure

The present study applied an inverse identification technique using iterative FE simulation, which has been established to determine the full equivalent $\sigma_T - \varepsilon_T$ curves for metallic materials including unstable necking deformation [16]. The equivalent $\sigma_T - \varepsilon_T$ relationship to maximum load, up to the onset of necking, was directly calculated from experimental load–displacement ($F-\delta$) data using Equations (1) and (2):

$$\sigma_T = \frac{F}{A_o} \left(\frac{\delta}{L_o} + 1 \right) \quad (1)$$

$$\varepsilon_T = \ln \left(\frac{\delta}{L_o} + 1 \right) \quad (2)$$

where A_o is the initial cross-sectional area of the specimen and L_o is the initial gage length. The equivalent $\sigma_T - \varepsilon_T$ curve after the onset of necking was determined by the inverse identification method using iterative FE simulation, where the calculation was repeated with updated input until the numerical calculation of the load and unstable deformation fitted well the experimental data. This approach has been commonly used to determine the equivalent $\sigma_T - \varepsilon_T$ relationship for tensile data beyond the onset of necking and the fracture strain of materials [17-20]. The identification procedure using iterative FE simulation based on the existing studies [18,21] is summarized as following steps [16]:

- (i) Calculate the true stress – true strain curve up to necking from the load – displacement data using Eqs. (1) and (2), and extrapolate the curve after necking, using a power law fit.
- (ii) Perform a finite element simulation considering actual dimensions of each specimen with the true stress – true strain obtained by step (i) and compare load – displacement response with the experiments. Calculate the relative error of the load (ΔF_i) at a given displacement (δ_i), where ΔF_i is the difference between measured load (F_m) and predicted load (F_i).
- (iii) Adjust the true stress – true strain curve beyond the onset of necking based on ΔF_i obtained in step (ii) using Eq. (3) and replace the true stress – true strain curve with the updated one ($\sigma_i - \varepsilon_i$).

$$\sigma_i = \sigma_{i,o} + \sigma_{i,o} \left(\frac{\Delta F_i}{F_i} \right) \quad (3)$$

where σ_i and $\sigma_{i,o}$ are the updated and current true stresses at ε_i corresponding to a displacement of δ_i . Here, the true strain during unstable deformation, ε_i , is defined as the average axial strain in the smallest cross-section, expressed as

$$\varepsilon_i = \ln \left(\frac{A_o}{A_i} \right) \quad (4)$$

where A_o is the initial cross-section of specimen and A_i is the predicted cross-section of necking at the displacement (δ_i).

- (iv) Repeat the steps (ii) and (iii) until the relative error reaches a specified tolerance and take the finally updated $\sigma_i - \varepsilon_i$ as the true stress – true strain curve of the material. Thus, the curve obtained by this procedure is equivalent true stress – true strain curve that is considered an effect of multi-axial stress state during necking.

All analyzed specimens showed the onset of localized necking prior to final failure. The strain concentrated in the necking band, once the localized necking started. The tensile fracture strain was determined from the average of maximum logarithmic strain over the localized necking band at a displacement corresponding to the final failure in the load – displacement curve (Figure 2). The tensile fracture stress was determined as an equivalent true stress corresponding to the tensile fracture strain on an equivalent $\sigma_T - \varepsilon_T$ curve. The tensile fracture energy is a measure of the toughness of a material at a low constraint stress state and is defined by the area under the full equivalent $\sigma_T - \varepsilon_T$ curve, as given by Equation (3) [17]:

$$E_F = \int_0^{\varepsilon_F} \sigma_T d\varepsilon_T \quad (3)$$

Fig. 2. Procedure for Determining the Tensile Fracture Strain from the Simulation Results

Fig. 3. Finite Element Model used to Simulate the Tensile Test

3.2 Finite Element Model

The FE simulation was performed using ABAQUS, a general-purpose finite element program [22]. As shown in Figure 3, the FE model used in the analysis was a three-dimensional one-eighth model that consisted of a 20-node solid element with reduced integration (C3D20R in ABAQUS). This FE model is the same as that used in our previous studies [16,17]. Finer meshes were modeled near the center of the specimen; at the center of the specimen, twenty and four elements were layered in the width and thickness directions, respectively. The analysis included material and geometrical nonlinearities to properly simulate the necking of specimens. A geometrical imperfection is a form of localized reduction in width and thickness. An imperfection of 0.25% of the dimensions was embedded in the model to allow for necking initiation. The 0.25% imperfection was determined based on the sensitivity analysis, and it was enough to induce a necking but was less than the usual manufacturing tolerance for such tensile specimens. The embedded imperfection in the central cross-section resulted in easier computations [16–19,23]. For simplicity, micro-damage of the material and bifurcation of the specimens were not incorporated into the present model.

To verify the FE model, the simulated and experimental load – displacement curves were compared (Figure 4). In all cases, the predicted and measured loads and displacements at the onset of necking were almost identical. The load – displacement curve matched the experimental one for necking deformation almost perfectly up to final failure. In particular, the simulated load – displacement curve agreed well with the experimental one even if the $\sigma_E - \epsilon_E$ curves showed distinct necking at yield followed by continuous softening to final failure. Therefore, the FE model successfully simulated the load – displacement response of the tensile data including localized necking as well as diffuse necking. It was concluded therefore that the FE simulation

Fig. 4. Comparison of the Load – Displacement Curves Obtained from Experiments and FE Simulations for Irradiated A533B RPV Steel

can reliably describe the deformation behavior and fracture properties of irradiated A533B RPV steel.

4. RESULTS AND DISCUSSION

4.1 Patterns of Necking Deformation

The strain distribution obtained by simulation was used to examine the deformation pattern of tensile specimens during necking for irradiated A533B RPV steel. Figure 5 presents the contours of the maximum logarithmic strain at two different deformation steps for unirradiated and irradiated (0.89 dpa) specimens. The strain distribution during unstable necking deformation beyond the maximum load was distinctively characterized by the load – displacement curve shape, which was strongly dependent on the irradiation dose level. For unirradiated specimens that exhibited uniform plastic deformation in the load – displacement curve, the strain contours during unstable necking deformation spread along the plane perpendicular to the loading axis of the specimen (U-1). This pattern gradually changed with progressively more plastic deformation. Eventually, the equal-strain contours developed along the oblique plane with a slope of about 25 degrees to the cross-section of the specimen (U-2). However, for the specimen irradiated to 0.89 dpa that showed a plastic instability at yield in the load – displacement curve, the logarithmic maximum strain contours started to spread along an oblique plane with a slope of about 45 degrees to the cross-section of the specimen at the maximum load. This coincided with the yield point (I-1). The pattern continued to final failure (I-2). A considerable strain gradient also developed within a narrow band formed along the oblique plane.

Typically, development of equal-strain contours along

Fig. 5. Comparison of the Logarithmic Maximum Strain Contours for Unirradiated and Irradiated (0.89 dpa) Specimens

an oblique plane is evidence of localized necking in flat tensile specimens [17]. For specimens that showed uniform plastic deformation in the load – displacement curve, the simulation showed that diffuse necking occurs at the maximum load and gradually changes to localized necking after a certain amount of unstable deformation. This is the typical pattern of necking deformation observed for flat specimens under tensile load. However, for the irradiated specimens that showed a plastic instability at yield followed by continuous softening in the load – displacement curve, the localized necking began immediately after the onset of plastic deformation, without diffuse necking. In addition, the plastic strain propagated along the overall cross-section of the unirradiated specimens without a significant strain concentration, even if the localized necking had started, whereas the strain was concentrated within the localized necking band for the specimens irradiated to 0.89 dpa. These patterns of necking deformation revealed from the FE simulations correlated well with the microscopic deformation mode observed in the previous study [4]. Microstructures observed in the deformed tensile specimens for A533B RPV steel irradiated at higher doses (0.1 and 0.89 dpa) showed that the strain was strongly localized in narrow bands induced by dislocation channeling. However, dislocation tangles, typically observed for the plastically deformed material, were the predominant deformation mode for doses below 0.01 dpa.

Therefore, the plastic instability at yield and continuous load drop in the load – displacement curve for specimens irradiated to higher doses are associated with the onset of localized necking, rather than diffuse necking, at the yield and with significant strain concentration within the localized necking band, respectively. Also, for A533B RPV steel

Fig. 6. Equivalent True Stress – Strain Curves for Irradiated A533B RPV Steel Obtained from Tensile Data using FE Simulations

irradiated to higher doses, the onset of localized necking at yield might be related to the strain localization induced by dislocation channeling deformation, even though it is not known what triggers the dislocation channeling deformation.

4.2 Equivalent True Stress – True Strain Behavior

Figure 6 presents the full equivalent $\sigma_T - \epsilon_T$ curves including unstable necking deformation for A533B RPV steel irradiated at various doses. The curves were determined through the inverse identification technique using iterative FE simulation. The diffuse and localized necking points are indicated on the curves to distinguish the various tensile deformation regimes: uniform, diffuse necking, and localized necking deformation. The onset of diffuse necking was determined by applying Considère's criterion to the equivalent $\sigma_T - \epsilon_T$ curves. As noted in the previous section, the development of equal-strain contours along the oblique plane is an evidence of localized necking deformation. Thus, the onset of localized necking shown in Figure 6 was determined from the distribution of strain contours in the simulation results. These localized necking points coincided with those determined by stress-based criteria [17,24].

In Figure 6, the equivalent $\sigma_T - \epsilon_T$ curve at the lowest dose of 0.0001 dpa was almost identical over the whole strain range to that of the unirradiated material, which increased continuously with the true strain to final failure without apparent changes by onset of diffuse or localized necking. The curve for the intermediate dose of 0.01 dpa was also almost the same as that for the unirradiated material, except that the slope of the curve decreased in the higher strain region above 40% where localized necking began. At higher doses of 0.1 and 0.89 dpa, the equivalent $\sigma_T - \epsilon_T$ curves were shifted upwards from those at lower doses for a given true strain, and the curves initially dropped immediately after the onset of localized necking

and then increased with the true strain to final failure. These results indicate that the strain-hardening rate of irradiated A533B RPV steel is still positive during unstable necking deformation, including diffuse and localized necking deformation, regardless of the irradiation dose level, even though the $\sigma_E - \epsilon_E$ curves at 0.1 and 0.89 dpa exhibit a significant strain softening beyond the yield point. This strain-hardening behavior agrees with previous experimental and analytical investigations, which revealed that the strain-hardening rate in the $\sigma_T - \epsilon_T$ relationship was still positive after irradiation at higher doses, where the $\sigma_E - \epsilon_E$ curves showed a plastic instability at yield followed by continuous softening to the final failure [15,25,26].

Figure 6 also shows that the slope of the equivalent $\sigma_T - \epsilon_T$ curves, a measure of strain-hardening capacity, varied with the irradiation dose. These slopes were examined to investigate the effect of irradiation dose on the strain-hardening capacity of irradiated A533B RPV steel. For both the unirradiated and irradiated (0.0001 dpa) specimens, the slopes were slightly reduced soon after the onset of diffuse necking, and then stayed unchanged to the final failure despite the onset of localized necking that appeared after a certain amount of diffuse necking deformation. For specimens irradiated to 0.1 and 0.89 dpa, where the onset of localized necking at yield occurred, initially negative slopes appeared over a few percent of strain and then changed to positive slopes. However, the positive slope was much less than that of the unirradiated specimen. For specimen irradiated to the intermediate dose level of 0.01 dpa, the slope of the $\sigma_T - \epsilon_T$ curve during diffuse necking was almost the same as that for the unirradiated specimens, but it diminished beyond the onset of localized necking; the slope was similar to behavior observed for irradiation doses of 0.1 and 0.89 dpa. Consequently, the strain-hardening capacity of A533B RPV steel irradiated to lower doses, where the specimens showed uniform deformation and diffuse necking followed by localized necking deformation, was insensitive to the irradiation dose level and nearly the same as that of unirradiated material. However, it clearly decreased at higher doses when the necking deformation pattern changed.

Such dose dependence of the strain-hardening capacity is associated with the effect of irradiation on the necking deformation pattern. As shown in the previous section, the pattern of necking deformation was strongly dependent on the irradiation dose level. For the lower doses, the diffuse necking started at the maximum load and gradually changed to localized necking, and the strain concentration was insignificant even if the localized necking occurred. This means the material retained sufficient ductility when the localized necking began. In this case, the macroscopic strain-hardening capacity was less affected by the onset of localized necking and was insensitive to the irradiation dose level. This is because irradiation-induced defects and deformation-produced dislocations result in similar net effects on the strain-hardening behavior [11]. For the

higher doses, however, the onset of localized necking appeared immediately after the onset of plastic deformation, and the strain concentration was significant within a localized necking band. Such concentrated straining in a narrow band increases the thinning of the specimen thickness without further contraction of the width. Consequently, the macroscopic strain-hardening rate during localized necking is lowered from that at uniform deformation or diffuse necking, regardless of the hardening mechanism of the material. Therefore, the lower strain-hardening capacity at higher doses is related to the onset of localized necking at yield, and is followed by significant strain concentration rather than a change in the strain-hardening mechanism.

4.3 Tensile Fracture Properties

To investigate the irradiation dose dependence of the tensile fracture properties for A533B RPV steel, the equivalent tensile fracture stress, tensile fracture strain, and tensile fracture energy were obtained from the equivalent $\sigma_T - \epsilon_T$ curves. Figure 7 presents the equivalent tensile fracture stress for irradiated A533B RPV steel along with the yield stress and plastic instability stress (σ_{PIS}). The σ_{PIS} was defined as the true stress at maximum load. The equivalent fracture stress decreased by about 17% with increasing dose level up to 0.01 dpa, and then slightly increased above 0.1 dpa; the equivalent fracture stress at 0.89 dpa was almost equal to that for unirradiated material. On the other hand, the yield stress increased considerably with the dose level up to 0.1 dpa, and then more slowly increased at higher doses; the yield stress at 0.89 dpa was about double that of the unirradiated material. Thus, the tensile fracture stress was less sensitive to the irradiation dose compared to the yield stress and tensile fracture strain (Figure 8). This dose dependence is consistent with existing knowledge of the fracture properties of irradiated materials [11–15]. In addition, the equivalent tensile fracture stress was much higher than the yield stress at doses less than 0.01 dpa where the $\sigma_E - \epsilon_E$ curves exhibited a certain amount of uniform plastic deformation. However, for doses above 0.1 dpa, where the plastic instability at yield occurred, the fracture stress was almost equal to but slightly lower than the yield stress. This implies that A533B RPV steel is embrittled at doses above 0.1 dpa. The embrittlement is associated with an increase in yield stress rather than a decrease in fracture stress caused by neutron irradiation. This indicates that the radiation-induced embrittlement in the low temperature irradiation occurs from a reduction of the deformation capability from yield to fracture.

Figure 8 shows the equivalent tensile fracture strain as a function of the irradiation dose level, together with the uniform engineering strain (ϵ_U) and total engineering strain (ϵ_T). The tensile fracture strain decreased by about 77% with increasing irradiation dose to 0.1 dpa when plastic instability began at yield. It decreased at a lower rate in the higher dose range. At 0.89 dpa, however, the tensile fracture strain, $\epsilon_F = 16\%$, was much higher than

Fig. 7. Dose Dependence of the Equivalent Fracture Stress for Irradiated A533B RPV Steel

Fig. 9. Dose Dependence of the Tensile Fracture Energy for Irradiated A533B RPV Steel

Fig. 8. Dose Dependence of the Equivalent Fracture Strain for Irradiated A533B RPV Steel

the uniform and total engineering strains that were about $\epsilon_U = 0.6\%$ and $\epsilon_T = 1.3\%$, respectively. This indicates that the irradiated A533B RPV steel has a relatively large necking strain, or instability deformation capacity, even though it is embrittled by neutron irradiation. As shown in Figure 9, the variation of the tensile fracture energy with the irradiation dose was nearly the same as that of the tensile fracture strain; i.e., the tensile fracture energy was reduced exponentially by irradiation up to 0.1 dpa and then became saturated above 0.1 dpa. The saturated tensile fracture energy was about 20% of the value for unirradiated A533B RPV steel. The results indicate that the toughness of A533B RPV steel was still high even after being considerably reduced by irradiation, and the uniform ductility in the $\sigma_E - \epsilon_E$ relationship became negligible at high doses. This behavior agrees with the finding that

quenched-and-tempered steels can retain significant fracture toughness up to about 1 dpa, and is induced by the large instable deformation capability [5,25].

Figures 8 and 9 show that the tensile fracture properties were affected at doses below 0.1 dpa, and they became saturated and insensitive to the irradiation dose above 0.1 dpa. Such a unique dose dependence of the tensile fracture properties is associated with the density saturation of irradiation-induced defect clusters. Previous studies have shown that the saturation of point-defect clusters is observed at a dose range of 0.01 to 0.1 dpa for various materials, including A533B RPV steel, irradiated at about 100°C, and this results in a change in the irradiation-hardening behavior at a dose range of 0.01 to 0.1 dpa [4,10]. Therefore, the dose dependence of the tensile fracture properties can be related to the fact that the density of irradiation-induced defects increases with the dose and becomes saturated at dosages of 0.01 to 0.1 dpa.

5. CONCLUSIONS

This study involves the detailed evaluation of the equivalent true stress – true strain relationship for A533B RPV steel irradiated from 0 to 0.89 dpa at 65 to 100°C applying an inverse identification technique using iterative FE simulation. The irradiation effects on the deformation behavior and tensile fracture properties were discussed based on the equivalent true stress – true strain relationship. The following conclusions were drawn:

- 1) In the specimens irradiated to higher doses that showed a plastic instability at yield followed by continuous softening in the engineering stress – strain curves, localized necking, rather than diffuse necking, occurred at the maximum load. A significant strain concentration appeared in a narrow

localized necking band.

- 2) The strain-hardening rate of irradiated A533B RPV steel was still positive during unstable necking deformation, including both diffuse and localized necking deformation, regardless of the irradiation dose level. The rate was insensitive to the irradiation dose unless the irradiation considerably changed the necking deformation pattern.
- 3) The equivalent fracture stress decreased with increasing irradiation dose level up to 0.01 dpa and slightly increased above this level. However, it was less sensitive to the irradiation dose compared to the yield stress and tensile fracture strain.
- 4) The equivalent fracture strain and tensile fracture energy significantly decreased with increasing dose up to 0.1 dpa; then it decreased at a lower rate. However, they remained high after high-dose neutron irradiation, even if the uniform ductility was almost zero.
- 5) The most important finding of this study is the fact that the A533B steel retains a large amount of ductility during the necking deformation, which is a failure process. This might be the reason for the high toughness of the steel.

ACKNOWLEDGEMENTS

The experimental data used in this study was from earlier studies at Oak Ridge National Laboratory sponsored by US Department of Energy.

REFERENCES

- [1] Y. Dai, G. W. Egeland, and B. Long, "Tensile Properties of Ferritic/Martensitic Steels Irradiated in STIP-I," *J. Nucl. Mater.*, Vol. 377, pp. 115-121 (2008).
- [2] J. E. Pawel, A. F. Rowcliffe, G. E. Lucas, and S. J. Zinkle, "Irradiation Performance of Stainless Steels for ITER Application," *J. Nucl. Mater.*, Vol. 239, pp. 126-131 (1996).
- [3] K. Farrell and T. S. Byun, "Tensile Properties of Candidate SNS Target Container Materials after Proton and Neutron Irradiation in the LANCE Accelerator," *J. Nucl. Mater.*, Vol. 296, pp. 129-138 (2001).
- [4] K. Farrell, T. S. Byun, and N. Hashimoto, "Deformation Mode Maps for Tensile Deformation of Neutron-Irradiated Structural Alloys," *J. Nucl. Mater.*, Vol. 335, pp. 471-486 (2004).
- [5] K. Farrell and T.S. Byun, "Tensile Properties of Ferritic/Martensitic Steels Irradiated in HFIR, and Comparison with Spallation Irradiation Data," *J. Nucl. Mater.*, Vol. 318, pp. 274-282 (2003).
- [6] M. Matijasevic, E. Lucon, and A. Almazouzi, "Behavior of Ferritic/Martensitic Steels after n-irradiation at 200 and 300 °C," *J. Nucl. Mater.*, Vol. 377, pp. 101-108 (2008).
- [7] T. S. Byun, K. Farrell, E. H. Lee, J. D. Hunn, and L. K. Mansur, "Strain Hardening and Plastic Instability Properties of Austenitic Stainless Steels after Proton and Neutron Irradiation," *J. Nucl. Mater.*, Vol. 298, pp. 269-279 (2001).
- [8] Y. Dai, G. W. Egeland, and B. Long, "Tensile Properties of EC316LN Irradiated in SINQ to 20 dpa," *J. Nucl. Mater.*, Vol. 377, pp. 109-114 (2008).
- [9] B. V. Cockeram, R. W. Smith, and L. L. Snead, "The Influence of Fast Neutron Irradiation and Irradiation Temperature on the Tensile Properties of Wrought LCAC and TZM Molybdenum," *J. Nucl. Mater.*, Vol. 346, pp. 145-164 (2005).
- [10] T. S. Byun and K. Farrell, "Irradiation Hardening Behavior of Polycrystalline Metals after Low Temperature Irradiation," *J. Nucl. Mater.*, Vol. 326, pp. 86-96 (2004).
- [11] T. S. Byun, "Dose Dependence of True Stress Parameters in Irradiated BCC, FCC, and HCP Metals," *J. Nucl. Mater.*, Vol. 361, pp. 239-247 (2007).
- [12] T. S. Byun and K. Farrell, "Plastic Instability in Polycrystalline Metals after Low Temperature Irradiation," *Acta Mater.*, Vol. 52, pp. 1597-1608 (2004).
- [13] T. S. Byun, K. Farrell, and M. Li, "Deformation in Metals after Low-temperature Irradiation: Part I – Mapping Macroscopic Deformation Modes on True Stress–Dose Plane," *Acta Mater.*, Vol. 56, pp. 1044-1055 (2008).
- [14] T. S. Byun, K. Farrell, and M. Li, "Deformation in Metals after Low-temperature Irradiation: Part II – Irradiation Hardening, Strain Hardening, and Stress Ratios," *Acta Mater.*, Vol. 56, pp. 1056-1064 (2008).
- [15] I. V. van Osch and M. I. de Vries, "Irradiation Hardening of V-4Cr-4Ti," *J. Nucl. Mater.*, Vol. 271 & 272, pp. 162-166 (1999).
- [16] J. W. Kim and T. S. Byun, "Analysis of Tensile Deformation and Failure in Austenitic Stainless Steels: Part I – Temperature Dependence," *J. Nucl. Mater.*, Vol. 396, pp. 1-9 (2010).
- [17] J. W. Kim and T. S. Byun, "Analysis of Tensile Deformation and Failure in Austenitic Stainless Steels: Part II – Irradiation Dose Dependence," *J. Nucl. Mater.*, Vol. 396, pp. 10-19 (2010).
- [18] Y. Bao, "Dependence of Ductile Crack Formation in Tensile Tests on Stress Triaxiality, Stress and Strain Ratios," *Eng. Fract. Mech.*, Vol. 72, pp. 502-522 (2005).
- [19] Y. Ling, "Uniaxial True Stress-Strain after Necking," *AMP J. Tech.*, Vol. 51, pp. 37-48 (1996).
- [20] C. K. Oh, Y. J. Kim, J.H. Baek, and W. S. Kim, "Development of Stress-modified Fracture Strain for Ductile Failure of API X65 Steel," *Int. J. Fract.*, Vol. 143, pp. 119-133 (2007).
- [21] M. Joun, J. G. Eom, and M. C. Lee, "A New Method for Acquiring True Stress – Strain Curves over a Large Range of Strains using a Tensile Test and Finite Element Method," *Mech. Mater.*, Vol. 40, pp. 586-593 (2008).
- [22] Hibbit, Karlson, and Sorensen Inc., 2010, ABAQUS Ver. 6.9 User's Manual.
- [23] P. Koc and B. Stok, "Computer-aided Identification of the Yield Curve of a Sheet Metal after Onset of Necking," *Comp. Mater. Sci.*, Vol. 31, pp. 155-168 (2004).
- [24] Dieter, G.E., *Mechanical Metallurgy*, SI Metric Ed., McGraw-Hill, Inc. (1988)
- [25] G. R. Odette, M. Y. He, E. G. Donahue, and G. E. Lucas, "On the Relation between Engineering Load-displacement Curves and True Stress Strain Behavior in Tests on Flat Tensile Specimens," Small Specimen Test technique: Fourth Volume, ASTM STP 1418, Sokolov M, Landes J, Lucas G, ASTM International, West Conshohocken, PA, pp. 221-231 (2002).
- [26] K. Shiba and T. Hirose, "Deformation Behavior of Reduced Activation Ferritic Steel during Tensile Test," *Fus. Eng. Des.*, Vol. 81, pp. 1051-1055 (2006).