Evaluation of the Depth-dependent Yield Strength of Ion-irradiated F82H Steels Using a FE Analysis and Nanoindentation

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1. Introduction

Reduced-activation ferritic-martensitic steels have been developed as candidate materials for the blanket structure of fusion and fission reactors because F82H steels have a relatively low shift characteristic in the ductile-to-brittle transition temperature (DBTT) after neutron irradiation [1]. A study on the material properties change of F82H steels under radiation environment was performed by several researchers, in which an ion-irradiation test was carried out to simulate a neutron irradiation environment [2]. However, the irradiation damage level depends on the depth from the specimen surface in an ion-irradiation test, and a more detailed approach is needed to evaluate the material property changes in depth (dose level).

In this paper, changes in the depth-dependent yield strength and damage level of irradiated and unirradiated F82H steels were predicted using nanoindentation and FE modeling techniques by dividing the damaged region into several layers. Moreover, the applicability of the reverse algorithm, which is to obtain stress-strain curves of the target material, was evaluated.

2. Evaluation of Elastic Plastic Material Behavior

2.1 Nanoindnetation

The base material used in this study is F82H (Fe-0.1C-8Cr-2WVTa in wt%) reduced-activation ferritic/martensitic steel. F82H steel was irradiated by Fe3+ ions with an acceleration energy of 1.7 MeV. The irradiation was performed in a vacuum (2.10×10^{-5} Pa) at a temperature of 573 K. The displacement damage was calculated using the SRIM code, and the profile is shown in Fig. 1. Samples with two different peak damages, i.e., 3 and 10 dpa, were prepared. A total of nine indentation test cases were considered by changing the indentation load, 10mN, 30mN, and 50mN. The hardness and elastic modulus were decreased with an increase in the indentation load, while those were increased with an increasing dose level for the irradiated specimens. This means that material hardening occurred with an increasing dose level, and more plastic work is required at the same displacement from the surface. Moreover, in the case of the same dose level for irradiated specimens, hardness at a low indentation load (depth) was higher than that at a high indentation load (depth) since the hardening effect by ion-irradiation is decreased when increasing the indentation depth.

2.2 Prediction of material properties for F82H steels

The bulk elastic moduli of unirradiated and irradiated specimen were characterized through a reverse algorithm and FE analyses in this study. The elastic modulus of unirradiated and irradiated F82H steel was determined as 150 GPa owing to the result that unloading curves from the nanoindentation test were almost identical between the two cases. The radiation damage zone was divided into five different layers, each layer of which is set to have an average dose level as the relative height of each column, as depicted in Fig. 1, and those were used as input data for FE analyses [3]. In the case of unirradiated specimens, for the nonlinear material properties, a trial set was generated at 200-1000 MPa for σ_y and 0-1 for n. The parameter set of σ_y=800MPa and n=0.05 was found to show a good match to the experimental data with 0.166 of estimated error at a load of 50mN. In the case of the irradiated specimen, E and n were assumed as constant values identical to the unirradiated specimen. An increase of $\Delta\sigma_y$ in the radiation damage level of each layer is often expressed as follows [4]:

$$\Delta\sigma_y = A\Phi^p \tag{1}$$

where Φ represents the radiation fluence, which can be replaced by dpa, the exponent p is the slope of increment of $\Delta\sigma_y$ in a log plot.

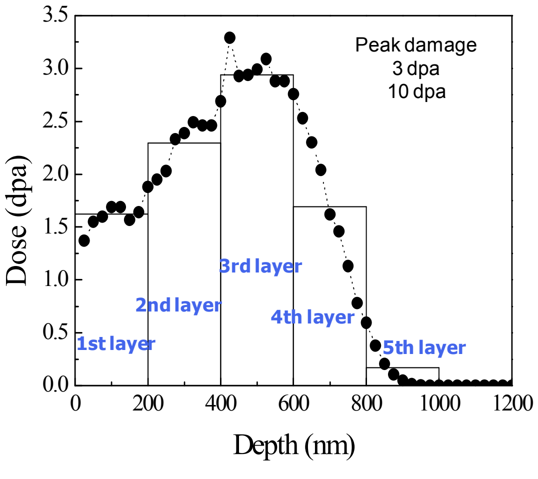

Fig. 1. Depth profile of dose calculated by using the SRIM code

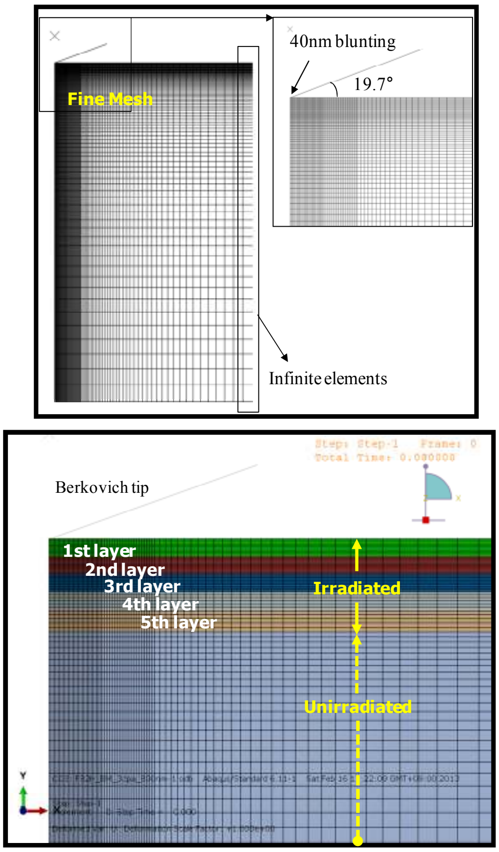

Fig. 2. Typical FE model for nanoindentation simulation

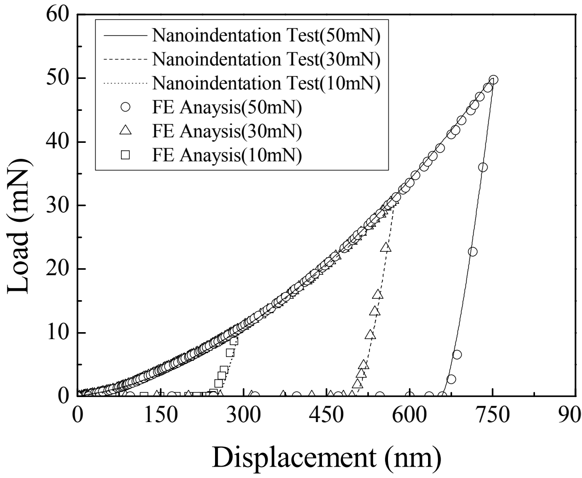

Fig. 3. Comparison of the experimentally measured and the computed *L-h* curve by determined material parameters for F82H steels irradiated at 10 dpa

A large number of FE simulations were carried out to find the optimum value of the coefficient in Eq. (1). The error was estimated by comparing the load-displacement curves from the nanoindentation test with the FE simulation results. An optimum value of A = 500MPa for both the maximum damage level of 3 dpa and 10 dpa, and p = 0.2 for 3 dpa with 0.047 of estimated error at a load of 50mN, and p=0.7 for 10 dpa with 0.1216 of estimated error at a load of 50mN were found, as shown in Fig. 3, respectively. The simulation results showed a good agreement with experimental observations. Note that all cases of *L-h* curve at 10mN, 30mN, and 50mN from an FE analysis using the optimum values of the material parameters agree well with experimental values, which mean that the material parameters of each layer adequately follow the intrinsic material properties. Furthermore, the plastic deformation was extended to about 1μm from the surface of specimen at 10mN of indentation load in the FE analysis, and its *L-h* curve shows a mixed material property of each layer well. After the 10mN indentation load, the *L-h* curve follows based on an unirradiated material property.

3. Conclusions

In this study, the elastic-plastic material properties for unirradiated and irradiated F82H steel were characterized. Ion-irradiation generated a depth-dependent damage zone from the surface at the nano-meter scale, and the material properties are changed owing to the relative irradiation level. Nanoindentation tests were conducted at various indentation loads and irradiation levels. To find the material property change of the damage zone, an FE analysis was applied. The damage zone was divided into five layers, and the elastic modulus and work hardening coefficient were fixed at 150GPa and 0.05 based on preliminary FE analyses. The unknown parameter for an irradiated specimen, i.e., yield strength, was evaluated in a few trial simulations using simple power law expressions, by comparing with the experimentally measured *L-h* curves. We found that the computed yield strength of the irradiated F82H steel is almost identical with the experimentally measured *L-h* curves. The obtained parameters in the power law expression are A = 500 and p = 0.2 for 3 dpa and A = 500 and p = 0.7 for 10 dpa, respectively.

In summary, this work showed that the yield strengths of an ion-irradiated region, which vary with depth, can be evaluated by combining nanoindentation tests with an FE modeling, as proposed in this study.

REFERENCES

[1] E. Wakai, S. Matsukawa, T. Yamamoto, Y. Kato, F. Takada, M. Sugimoto and S. Jitsukawa, Mechanical Property of F82H Steel Doped with Boron and Nitrogen, Material Transactions, The Japan Institute of Metals, Vol. 45, No. 8, p. 2641-2643, 2004.

[2] R. L. Klueh, M. A. Sokolov, K. Shiba, Y. Miwa, and J. P. Robertson, Embrittlement of Reduced-activation Ferritic/Martensitic Steels Irradiated in HFIR at 300°C and 400°C, Journal of Nuclear Materials, Vol. 283-287, p. 478-482, 2000.

[3] ABAQUS, INC., User's Manual, ABAQUS Version 6.9-1, 2010.

[4] T. S. Byun and K. Farrell, Irradiation Hardening of Polycrystalline Metals after Low Temperature Irradiation, Journal of Nuclear Materials, Vol. 326, p. 86-96, 2004.