ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 466–470

journal of nuclear materials

Deformation analysis of small size bend specimens by FEM calculation to estimate irradiation induced embrittlement of Mo and W

Kazukiyo Ueda [a,*], Manabu Satou [b], Akira Hasegawa [b], Katsunori Abe [b]

[a] *Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Aramaki-aza-Aoba 01, Sendai 980-8579, Japan*

[b] *Department of Quantum Science and Energy Engineering, Tohoku University, Aramaki-aza-Aoba 01, Sendai 980-8579, Japan*

Abstract

Irradiation-induced embrittlement of Mo, W and their alloys was studied using a three-point bending test. The specimens were in shape of a small disk, identical to a TEM sample. The shift of ductile–brittle transition was observed. In this paper, the finite element method (FEM) was adopted for the analysis of deformation behavior of specimens in the bend test. Spatial distributions of stress and strain of bend specimen were obtained. The plastic deformation that mainly contributes to deformation of specimen was found to be restricted in a small area. Discussion of the size effect in bending deformation is presented. The small three-point bend method was useful to obtain information on mechanical properties of irradiated materials from the load–deflection curves, but in order to extract precise information, i.e. local stress and strain, FEM calculation concerning irradiation hardening should also be conducted simultaneously.

1. Introduction

Mechanical property testing of neutron irradiated materials adds several difficulties to testing. For studying irradiation-induced embrittlement of a material for fusion reactors, exposure of several years in the highest flux test rectors is often required. These specimens will generally become highly radioactive and the cost of the irradiation will be high. In addition, space is costly and limited in the fission reactors for the simulation of fusion reactor. The study of irradiation damage of material using small specimen has become more important issue, because small specimens reduce the above difficulties.

Mechanical properties of materials after neutron irradiation are greatly dependent on material and irradiation conditions. It is important to evaluate the changes of mechanical properties of materials after irradiation for heavily irradiated materials, i.e. Molybdenum (Mo) and Tungsten (W) as the divertor structural material of fusion reactor [1–3] with respect to the safety operation. We have studied the effect of heavy neutron irradiation on these materials using the miniaturized three-point bend test [4–6]. Specimen was in shape of a disk, which is the same as a transmission electron microscopy (TEM) disk in size.

In the three-point bend test, the distribution of stress in the deforming specimen is not uniform. In initial stage of deformation of bend specimen, specimen deforms elastically in whole area. In subsequent deformation, both elastic and plastic regions coexist in the specimen, but the yielding area propagates radially as specimen deforms. In three-point bend test, there are geometrical and material nonlinearity, and they cause difficulties in evaluating mechanical properties of the material.

The finite element method (FEM) has been often used for analysis of complex structures deforming extensively, and proved to be effective for extracting useful engineering information.

In this paper, we conducted FEM analyses of the three-point bend tests using the stress–strain curves of the irradiated and nonirradiated Mo in the uni-axial

---

[*] Corresponding author. Tel.: +81 22 217 7924; fax: +81 22 217 7925; e-mail: kueda@jupiter.qse.tohoku.ac.jp.

0022-3115/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(98)00307-9

tensile tests in order to obtain distributions of stress and strain in deforming bend specimens. We attempted to show effect of irradiation hardening on the distributions of stress and strain in the three-point bend specimens.

2. Experimental method and analysis

2.1. Three-point bend test

In order to evaluate deformation behavior of irradiated Mo, W and its alloy, the three-point bend test was conducted. A specimen in the bend test was a disk with 3 mm of diameter and 0.25 mm of thickness, which has the same shape to transmission electron microscopy (TEM) disk. The test fixture is shown schematically in Fig. 1. The upper and lower supports of the fixture were prepared from tungsten wire. The radius of curvature of the supports was 0.25 mm. The testing apparatus was mounted on an Instron type universal test machine. The bending tests were carried out at a cross-head speed of 0.2 mm/min. During the tests, load on the specimen was measured using a load-cell, and deflection was measured from the displacement of cross-head simultaneously. More details were described elsewhere [4].

Fig. 2 shows typical load–deflection curves from the three-point bend tests. The specimens were stress-relieved TZM alloy (Mo–5wt.%Ti–0.1%Zr) irradiated at 1023 K to 11 dpa. The bend tests were conducted at test temperature of 173, 243 K, and room temperature. The specimen fractured in the initial linear region in the load–deflection curve at test temperature of 173 K. In this region, it was considered that almost whole of specimen deformed elastically. For specimens at test temperature of 243 K and room temperature, load–deflection curves showed the deviation from the linear portion as the specimen deformed, like yielding in uniaxial tensile tests. In this region, it the decrease of gradient of the curves as the specimen deforms shows the radial propagation of the plastic deformation area which originated from the point with maximum stress (tensile and compressive stresses on the center of surfaces). The deflection to failure increases with test temperature increases. This shows that the ductile–brittle transition is in the range of these temperatures.

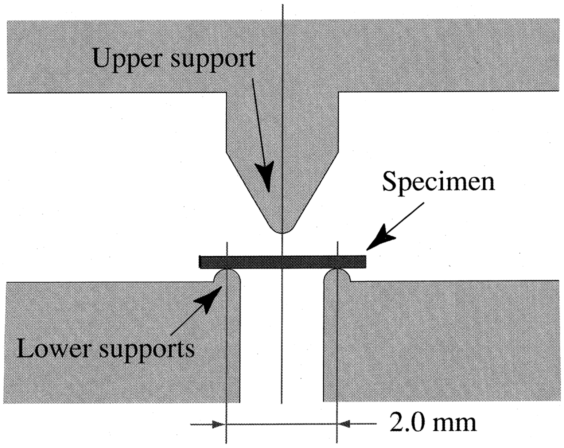

Fig. 1. Schematic cross-section of the three-point bending test.

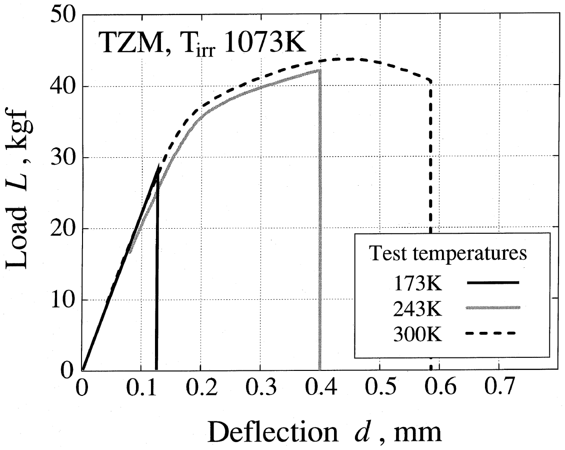

Fig. 2. Typical load–deflection curves of the three-point bend test at various test temperatures for TZM irradiated to 11 dpa.

For irradiated W, all specimens fractured in the initial linear region in the load–displacement curves at room temperature, similar to the behavior of TZM at a test temperature of 173 K in Fig. 2. In the linear portion of load–deflection curve, a large fraction of the specimen volume deforms elastically.

2.2. Analysis method

FEM calculations were carried out for the distribution of stress and strain of a specimen during the three-point bend test. These were conducted using the elasto-plastic analysis FEM program, MARC [7]. This FEM code was executed using the supercomputer NEC SX-3R of the Computer Center at Tohoku University.

We assumed that a deforming body in FEM calculations was a rectangle which deformed in plane strain condition. There was difference between the three-point bend specimen and the deforming body in FEM calculation, i.e. the deforming body had infinite length in the direction of the support. Since the length was ten times larger than the thickness of specimen, the difference could be ignored to obtain the tendency of the distribution of stress and strain in the three-point bend specimen. The mesh of the FEM model is shown in Fig. 3. The relative dimensions of the FEM model are

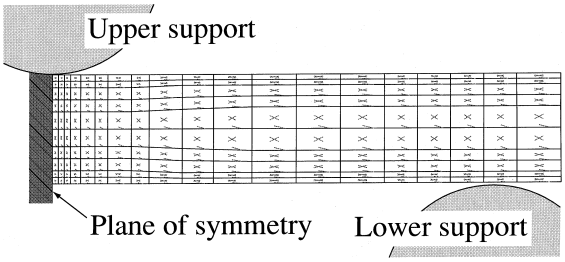

Fig. 3. FEM mesh model used in this study. Because of the symmetric configuration, the analysis were conducted for the half part of specimen.

width of 3 and height of 0.25, which is the same proportion of the width to the thickness of the specimens in the experimental bend test. Because of geometrical symmetry, the analyses were done for half of the specimen. The FEM model comprises eight-noded isoparametric elements. We assumed that the elements deformed in plane strain condition during deformation. It also assumed that the upper and lower supports were rigid bodies, and there was no friction between the deforming specimen and the supports.

The deformation behaviors of the FEM elements are ruled by parameters given as uni-axial tensile true stress–true strain curve in MARC. The stress–strain curves used for the FEM elements are shown in Fig. 4. These data were based on the experimental results obtained from uni-axial tensile test of irradiated and nonirradiated Mo. The two cases in the FEM calculations were called SS-1 and SS-2, and simulated which were based on nonirradiated and irradiated Mo, respectively. The yield stress of the material was 740 MPa for SS-1 and 1540 MPa for SS-2, and the work-hardening rate of SS-2 was slightly larger than SS-1 [8].

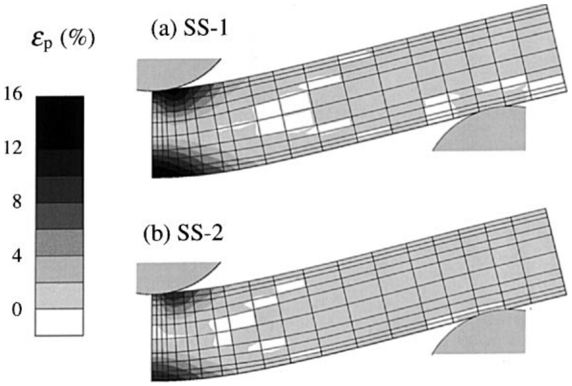

Fig. 5. Distribution of equivalent plastic strain in the bending specimen, (a) SS-1 and (b) SS-2. Deflection corresponds to 0.2 mm in the experimental bend test.

3. Results and discussion

FEM analyses were conducted for deformed specimens in the three-point bend test. In the experimental bend test, some specimens of irradiated Mo failed at deflection of 0.2 mm or higher, so that we show the result of FEM analysis of specimen bent at this deflection [4].

Fig. 5 shows the distributions of equivalent plastic strain ε_p in each specimen. The deflections in FEM calculation correspond geometrically to 0.2 mm in the experimental three-point bend test specimen. In the vertical direction, ε_p decreases and reaches zero on the neutral axes from the lower surface (the tensile-side surface) to the inside of the specimen, and then increases to the upper surface (the compressive-side surface). In the horizontal direction, the yielding regions, which contribute mainly to the deflection of bending, is

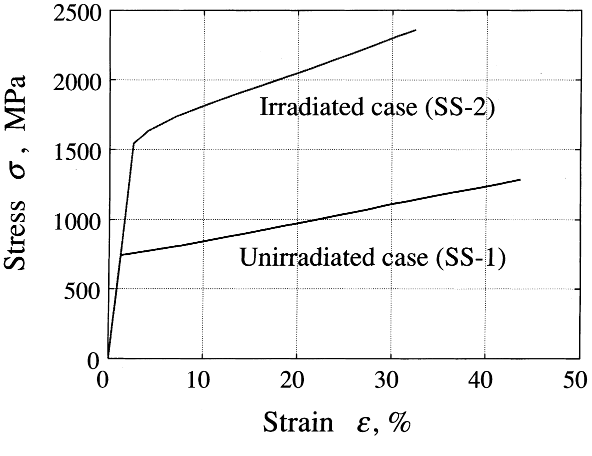

Fig. 4. Stress-strain curves in uni-axial tensile tests for unirradiated and irradiated molybdenum [8].

localized near the plane of symmetry, where the bending moment reaches a maximum value. The yielding region in SS-1 is larger than that in SS-2. The regions where ε_p >2% are 14% of whole area of the model for SS-1, and 9% for SS-2. The plastically deformed regions are concentrated near the surfaces of the specimen at this deflection.

Fig. 6 shows the equivalent plastic strain ε_p and von Mises stress σ_v as the function of the distance (l) from the plane of symmetry on the tensile-side surface obtained by FEM analysis. This deformation corresponds to the experimental bend specimen with deflection of 0.20 mm. The horizontal axis is the distance l from the plane of symmetry so that l for the point of the lower support touching on the specimen is 1.0. In both models, the equivalent plastic strain ε_p is maximum value at $l = 0$ and decreases rapidly as l increases. The von Mises stress σ_v decreases slowly with l comparing with the case of ε_p. Maximum ε_p is 15% for SS-1 and 11% for SS-2. But these values are of deformation of very small area obtained by FEM analysis, and the difference of miniature and standard specimen in size must be addressed. The stress in SS-2 is more than twice of the stress in SS-1 at the same distance throughout l. But the difference of ε_p of SS-1 and SS-2 is not so much comparing to the stress because of the higher yielding stress of SS-2.

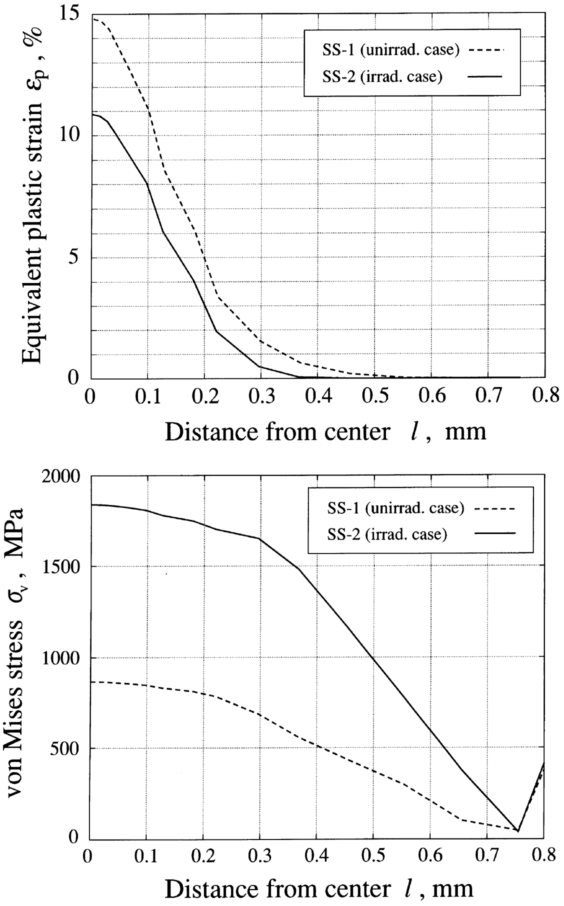

Fig. 6. The distance from the center along the tensile surface versus equivalent plastic strain and von Mises stress at deflection of 0.20 mm.

Fig. 7 shows FEM analysis for the change of maximum equivalent plastic strain ε_p during bend deformation of specimen of SS-1 and SS-2 cases. The maximum ε_p is always on the tensile-side surface near the plane of symmetry throughout the deformation of the specimen. The horizontal axis is the displacement d of the upper support. The vertical axis is the maximum ε_p in the specimen deformed at displacement d. The displacements where ε_p begins to increase are different for case of SS-1 and SS-2. The maximum ε_p starts to increase at displacement 0.027 mm of the upper support for SS-1 and 0.070 mm for SS-2. It is considered that the deflections d at which local plastic deformation begins to increase are directly dependent on the yield stresses given as material parameters for each models. For evaluation of mechanical properties using bending test, load and deflection were used in former works by other researchers. But these results showed FEM analysis should be conducted simultaneously for materials to extract local plastic strain from deflection and to evaluate deformation behavior of the materials. For irradiated materials, irradiation hardening also should be concerned to estimate maximum plastic strain in specimen deformed at a displacement.

Many factors should be considered to understand size effects in miniature specimens. One of the factors is the relation between grain size of specimen and minimum length of specimen., It was considered that the minimum length, i.e. the thickness of typical miniature tensile specimen, should be at least about five times

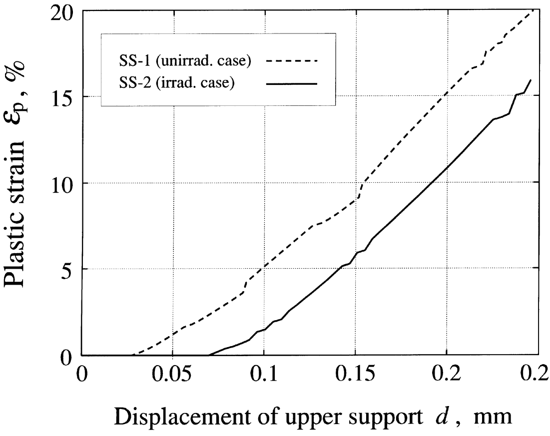

Fig. 7. Equivalent plastic strain at the center of tensile stress loaded side versus displacement of the upper support in the vertical direction.

larger than the grain size of specimen to obtain polycrystalline deformation behavior from tensile test [9]. This point should be considered also in the three-point bend specimen. As described below, the distributions of stress and strain of bend specimen calculated in this paper is important to consider effects of minimum length of specimen and grain size.

In analogy with the case of tensile specimen, we assume that the region must contain at least five grains where the stress and strain is regarded as average properties. (a) For a material with fine grain structure such as stress-relieved molybdenum, of which the grain size was 2 μm [4], the average value of calculated stress and strain in the region of ~5 × 2 μm is of significance, since we could obtain maximum local strain in the bend specimen from the average calculated strain in region ranging 10 μm in both directions of thickness and of beam from the center of the tension-side surface. Therefore, the maximum local strain in the bend specimen could be estimated from the deflection of a specimen of thickness of 250 μm ($\gg$10 μm). (b) For a material such as recrystallized molybdenum, of which the grain size was about 20 μm [4], five grains range wide over 100 μm. In that case, the deflection of the three-point bend test for a specimen with the thickness of 250 μm (>100 μm) mainly reflects properties of grains on the surface area, rather than average properties of many grains. Thus, to evaluate maximum local stress and strain from the deflection of a miniature bend specimen, the number of grains which contribute to the local deformation should be considered. Since the result of Fig. 6 showed that strain varied more rapidly around the maximal point, than stress. The above point should be noted in estimation of local strain than in that of local stress.

4. Summary

Deformation analysis of small specimens during the three-point bend test was conducted by FEM calculation. The distributions of stress and strain in the bend specimen and their change during deformation were obtained. The analysis showed that the region of plastic deformation is confined to the center of the specimen near the surfaces. The beginning of local plastic deformation was significantly dependent on the yield stress of the material. The relation between the macroscopic deflection and the microscopic stress and strain distributions in the specimen was obtained, which is useful to consider the influence of grain size on the average properties of materials in the miniature bend test.

Acknowledgements

This work was supported by JUPITER (Japan–USA Program of Irradiation Test for Fusion Research) program, Collaboration Project for Fusion Materials between Monbusho of Japan (the Ministry of Education, Science, Culture and Sports) and Department of Energy of the United States.

Part of the financial support was provided through the Grant-in-Aid for Scientific Research from the Monbusho.

References

[1] S. Nishio, T. Ando, Y. Ohara, S. Mori, T. Mizoguchi, M. Kikuchi, A. Oikawa, Y. Seki, Fusion Eng. Des. 15 (1991) 121.
[2] V.V. Rybin, D.L. Smith, J. Nucl. Mater. 191–194 (1992) 30.
[3] T. Tanabe, N. Noda, H. Nakamura, J. Nucl. Mater. 196–198 (1992) 11.
[4] K. Ueda, M. Satou, A. Hasegawa, K. Abe, Sci. Rep. RITU A 45, 1997, pp. 163.
[5] K. Abe, M. Satou, A. Hasegawa, K. Ueda, Effects of neutron irradiation on mechanical properties of Mo–Re alloys, to be published.
[6] A. Hasegawa, K. Ueda, M. Satou, K. Abe, these Proceedings.
[7] MARC GENERAL PURPOSE FINITE ELEMENT PROGRAM, MARC Analysis Research Corporation (1995).
[8] A. Hasegawa, K. Abe, M. Satou, K. Ueda, C. Namba, J. Nucl. Mater. 233–237 (1996) 565.
[9] N. Igata, K. Miyahara, T. Uda, S. Asada, ASTM STP 888 (1986) 161.