Effect of irradiation hardening on brittle fracture performance of box-shaped blanket fabricated by F-82H

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Fusion reactor blankets designed for DEMO are based on a water cooled ceramic breeder. The unstable fracture of the box-shaped blanket would occur by the superimposition of three factors as follows: (1) it is the reduction of fracture toughness for structural materials, such as F-82, caused by the significant irradiation hardening, (2) it is the formation of cracks which act as the initiation point of the fracture, and (3) it is the excessive tensile load caused by the inner pressure to In-Box loss of coolant accident (LOCA). In the present study, application of Weibull stress criterion to fracture assessment is to investigate the effect of irradiation hardening on the brittle fracture performance of box-shaped blanket fabricated by F-82H. Both structural analysis of the box-shaped blanket simulating In-Box LOCA and deformation behavior analysis of irradiated toughness specimens were conducted by elastic-plastic finite element analysis (FEA). Weibull stress values calculated from FEA of irradiated toughness specimens were higher than those from FEA of irradiated structural components. It, therefore, is considered that the irradiation hardening of structural materials would not promote the brittle fracture at the corner of rectangular coolant tubes of the blankets caused by the load of In-Box LOCA.

Keywords: Reduced activation ferritic/martensitic steel, Water cooled ceramic breeder blanket, In-Box LOCA, Irradiation hardening, Brittle fracture and Weibull stress criterion

1. Introduction

Fusion reactor blankets designed for DEMO are based on a water cooled ceramic breeder. The pressurized water with 15.5 MPa between 290 and 325 $^{\circ}$C is used as the coolant [1]. During the steady state operation, the inner wall surface of the rectangular coolant tubes which are built in the first wall (FW) is maintained at temperatures of about 300 $^{\circ}$C. Therefore, structural materials around the inner wall surface of the tubes would be exposed to fusion neutron irradiation at about 300 $^{\circ}$C. Reduced activation ferritic/martensitic (RAFM) steels, such as F-82H [2], are recognized as the primary structural material candidates for fusion blanket systems. It is clarified that the high fluence neutron irradiation under 300 $^{\circ}$C causes significant hardening and reduction of fracture toughness for F-82H [3, 4]. Cracks or winkles at the corner of the inner wall surface are possibly formed through the drawing of the fabrication process of the rectangular tubes [5]. These cracks will act as the initiation point of the fracture. The cooling pipes are installed between the mixed pebble beds [1]. If the pipe rupture occurs, the pressure inside the box-shaped blanket will increase and finally become equal to the pressure of the pressurized water, 15.5 MPa. Such event is called as loss of coolant accident (In-Box LOCA). The inner pressure by In-Box LOCA causes the large deformation of structural materials. As pointed out above, the unstable fracture of the box-shaped blanket would occur by the superimposition of three factors: (1) it is the reduction of fracture toughness for structural materials caused by the significant irradiation hardening, (2) it is the formation of cracks which act as the initiation point of the fracture, and (3) it is the excessive tensile load caused by the inner pressure to In-Box LOCA.

Weibull stress model originally proposed by the Beremin group [6] based on weakest link statistics provides a framework to quantify the relationship between macro and microscale driving forces for cleavage fracture (brittle fracture) in ferritic steels. They introduced Weibull stress σ_w as a probabilistic fracture parameter, computed by integrating a weighted value of maximum principal stress (MPS) over the process zone of cleavage fracture (i.e., the crack front plastic zone). One of the advantages is that critical Weibull stress $\sigma_{w,cr}$ is dependent on not crack configurations/loading modes but material properties. Prediction method based on Weibull stress criterion is available to estimate the brittle fracture performance for structural components from toughness specimens. In the present study, application of Weibull stress criterion to fracture assessment is to investigate the effect of irradiation hardening on the brittle fracture performance of box-shaped blanket fabricated by F-82H.

2. Numerical analysis methods
2.1 Model of structural components

Structural analysis of the box-shaped blanket simulating In-Box LOCA was conducted by elastic-plastic finite element analysis (FEA). Figure 1 shows a two-dimensional FE model of structural components. The internal pressure of 15.5 MPa was applied to the inner wall surface of the box-shaped blanket as well as the cooling channels. Two-dimensional generalized plane strain was employed to the analysis. The minimum element dimension near the crack tip was 0.03 x 0.03 mm^2 in accordance with ISO 27306 [7]. A crack was introduced at the corner of the 4th tubes from the edge. Crack depths a were 0.25, 0.5 and 1.0 mm. Initial crack mouth opening displacement (CMOD) was 0.014 mm.

2.2 Model of toughness specimens

Figure 2 shows a FE-model constructed for analysis of miniaturized toughness specimens (Hf-1/3PCCVN). The specimens had a ratio of crack depth to specimen width (a_0/W) of 0.4 [4]. Symmetry conditions enable analysis using one-quarter of 3D models with appropriate constraints imposed on the symmetry planes. The minimum element dimension near the pre-crack tip was also 0.03 x 0.03 mm^2 in 2D plane in accordance with ISO 27306 [7]. The FE model was loaded by jig of rigid bodies imposed on the specimen surface.

2.3 Constitutive equation for elastic-plastic FEA

A nonlinear FE-code, ANSYS 17.0, was used, where yielding condition following von Mises yield criterion. It is reported that the reference temperature of F82H-IEA increased up to over 100 ºC after 18 dpa irradiation at 300 ºC [4]. F-82H after the irradiation embrittles at room temperature (RT). In the FEA of structural components, it is assumed that structural materials (F-82H) were uniformly irradiated at 300 ºC up to 20 dpa and then were loaded by the internal pressure of 15.5 MPa at RT as the safe-side evaluation. Therefore, Constitutive equations at RT of both unirradiated and irradiated F-82H were utilized. Constitutive equation of unirradiated F82H-IEA was already established by Dr. Shiba [8]. Calibrated true stress-true strain curve with Bridgman's equation [9] was used for elastic-plastic FEA as shown in Fig. 3. Approximation true stress-true strain curves for irradiated F82H-IEA have been reported [10]. Assuming Young's modulus of $E = 218$ GPa is unchanged after irradiation, the constitutive equation of irradiated F82H-IEA was derived as shown in Fig. 4.

3. Results

3.1 FEA of structural components

Figure 5 shows a contour map of maximum principal stress (MPS) for the FW without a crack. The positive and negative values represent tensile and compression loads, respectively. The tensile load can induce the crack initiation and propagation. It, therefore, is assumed that there is a crack at the corner of the 4th tubes from the edge as show in Fig. 1. Figure 6 shows contour maps of stress triaxiality factor (STF), equivalent plastic strain (EPS) and MPS near the crack-tip. The field where STF was higher than 1.5 was widely extended around the crack-tip in both unirradiated and irradiated materials.
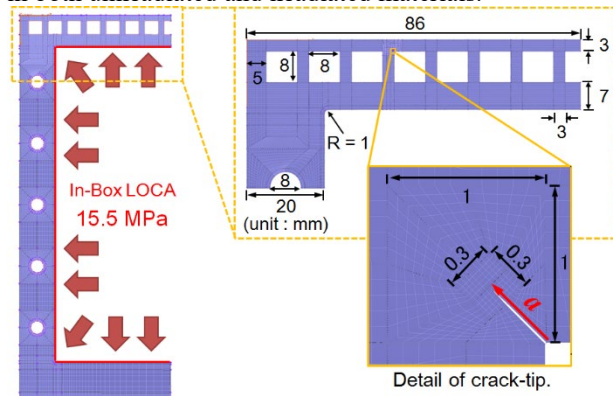
Plastic deformation was suppressed by the irradiation hardening and then CMOD was decreased.

Figure 7 shows distribution of MPS ahead of the crack-tip. MPS near the crack-tip was almost independent on crack depth and was increased by the irradiation hardening.
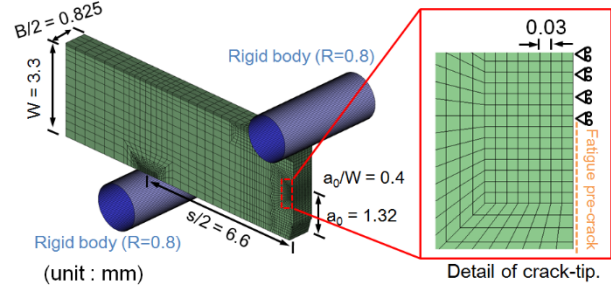

Fig. 2. One-quarter 3D FE model of miniaturized toughness specimens.
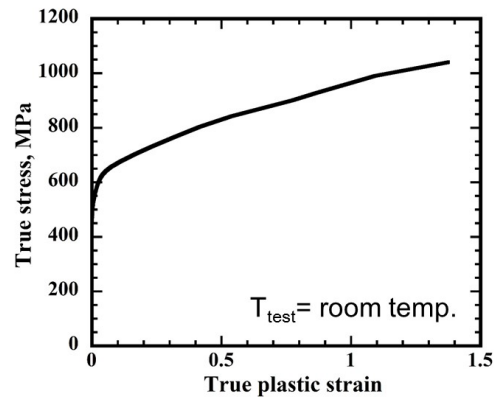

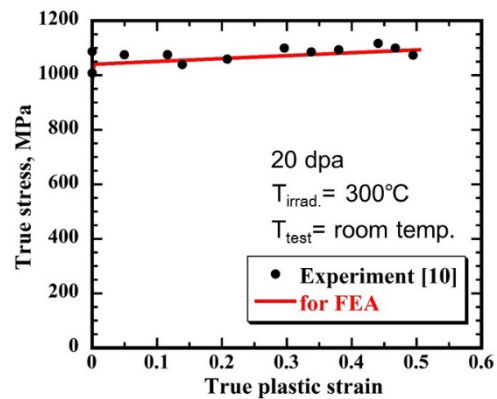Fig. 3. True stress-true plastic strain curve of unirradiated F82H-IEA for FEA [8].

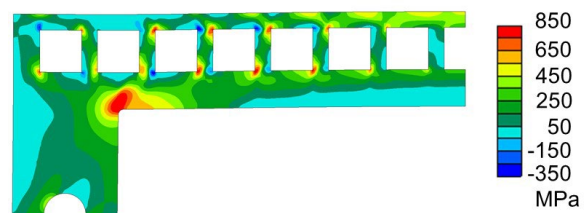Fig. 4. True stress-true plastic strain curve of irradiated F82H-IEA for FEA [10].

Fig. 5. Contour map of MPS for the FW without a crack.

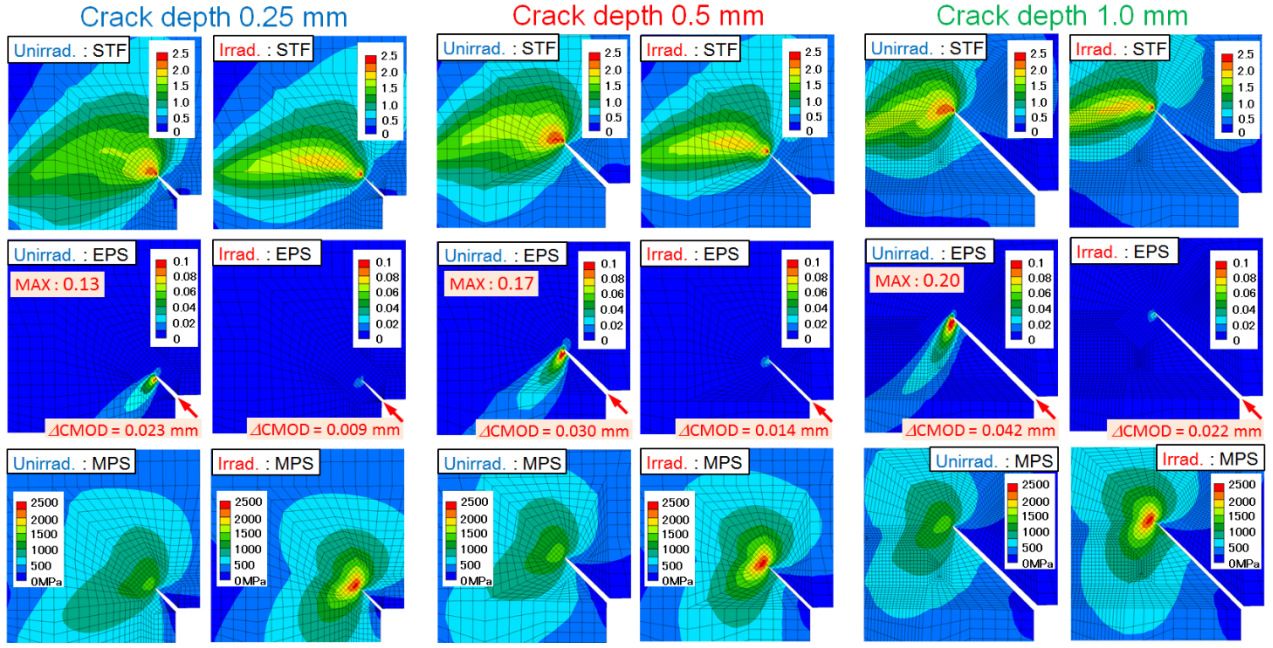Fig. 1. 2D FE model of structural components.

Fig. 6. Contour maps of STF, EPS and MPS near the crack-tip of structural components.
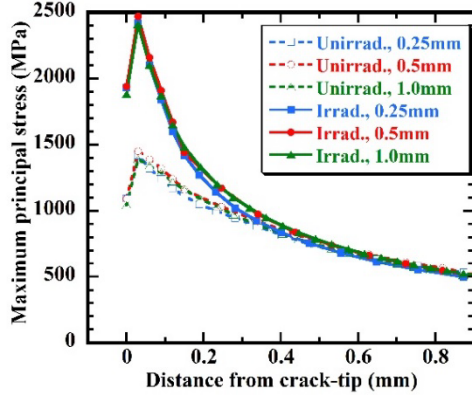

Fig. 7. Distribution of MPS ahead of the crack-tip.

3.2 FEA of toughness specimens

Figure 8 shows load and load line displacement curves of numerical data and typical experimental data. Numerical data from FEA were generally consistent with experimental data. J-value was calculated with a load and a load line displacement in accordance with ASTM E 1820 [11]. Values of J-integral were converted to their equivalent values in terms of stress intensity factor K_J by the following equation:

$$K_J = \sqrt{\frac{J \cdot E}{1 - \nu^2}} \qquad (1)$$

where ν is Poisson's ratio. Poisson's ratio is an inherent physical property of material. The unirradiated value of 0.29 at RT shall be used in the irradiated conditions.

4. Discussions

The brittle fracture performance of irradiated structural components is discussed based on Weibull stress criterion. The Weibull stress σ_w is defined as

$$\sigma_w = \left[\frac{1}{V_0} \int_{V_f} \left(\sigma_{eff} \right)^m dV_f \right]^{1/m} \qquad (2)$$

where V_0 and m is the reference volume and Weibull shape parameter, respectively, V_f is the fracture process zone almost corresponding to the plastic zone near the crack-tip, and σ_{eff} is an effective stress for cleavage fracture which is normally represented by the MPS. Equation (2) is converted by a first-order approximation as follows.

$$\sigma_w = \left[\sum \frac{V_i}{V_0} \sigma_{pi}^m \right]^{1/m} \qquad (3)$$

where V_i and σ_{pi} are the volume and the average value of MPS of ith element, respectively. Hence, a unit of 1 mm^3 was adopted as V_0 for convenience [12]. Crack length for structural components was assumed to be 1 mm.

Reported values of m for structural steels range from 10 to 50 [6, 12, 13]. The lower toughness material generally has a lower value of m. Therefore, m of the irradiated materials would be a lower value compared to that of the unirradiated materials. Values of m in the parametric analysis were in the range from 5 to 25. Table 1 summarizes Weibull stress obtained from FEA of irradiated structural components. Figure 9 shows a relationship between Weibull stress and K_J obtained from FEA of irradiated toughness specimens. It is reported that the reference temperature of unirradiated F82H-IEA was about -110 ºC but the temperature increased up to over 100 ºC after 18 dpa irradiation at 300 ºC [4]. In the FEA of structural components, it is assumed that irradiated F-82H embrittled at RT and then was loaded by the internal pressure of 15.5 MPa at RT as the safe-side evaluation. Therefore, the brittle fracture performance of irradiated structural components is discussed at RT. K_{Jc} was determined for experimental data from J at the onset of cleavage fracture. A median value of K_{Jc} at RT was determined as 71 MPa m$^{1/2}$ by using master curve
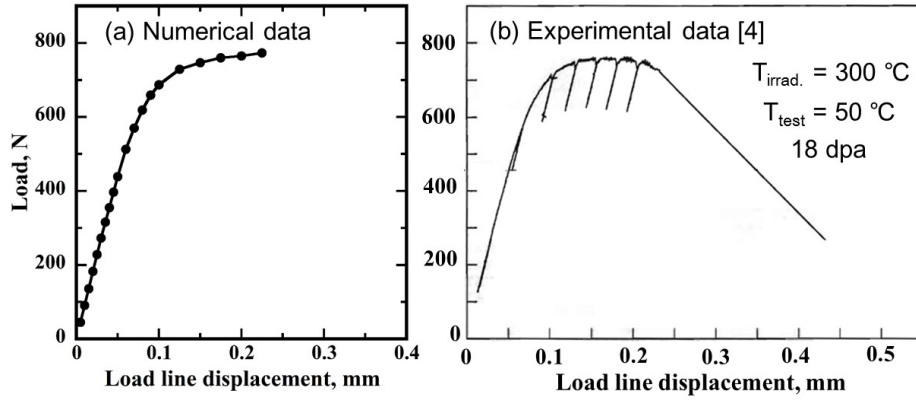
Fig. 8. Load and load line displacement curves of (a) numerical data and (b) typical experimental data by using the unloading compliance method [4].

Table 1. Weibull stress obtained from FEA of irradiated structural components.

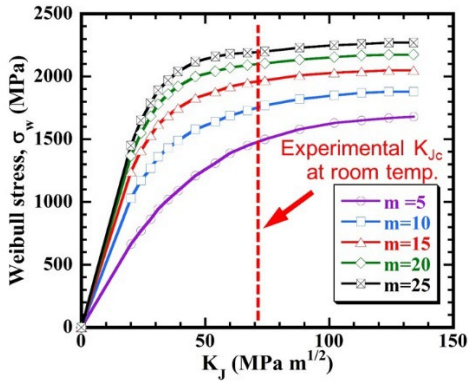| Crack depth	$m = 5$	$m = 10$	$m = 15$	$m = 20$	$m = 25$
0.25 mm	1050 MPa	1499 MPa	1768 MPa	1947 MPa	2073 MPa
0.5 mm	1085 MPa	1540 MPa	1818 MPa	2005 MPa	2136 MPa
1.0 mm	1055 MPa	1530 MPa	1816 MPa	2008 MPa	2144 MPa

Fig. 9. Weibull stress vs. K_J obtained from FEA of irradiated toughness specimens.

methodology [4, 14]. Weibull stress at $K_{Jc} = 71$ MPa m$^{1/2}$ were 1478, 1753, 1961, 2099 and 2196 MPa for $m = 5$, 10, 15, 20, 25, respectively. These values were higher than those from FEA of irradiated structural components as summarized in Table 1. It, therefore, is considered that the irradiation hardening of structural materials would not promote the brittle fracture at the corner of rectangular coolant tubes of the blankets caused by the load of In-Box LOCA. In this estimation, the assumed m-value was used. For the more accurate estimation, the m-value of the unirradiated and irradiated F-82H needs to be identified in the future work.

5. Conclusion

The effect of irradiation hardening on the brittle fracture performance on the box-shaped blanket fabricated by F-82H was investigated based on Weibull stress criterion. Weibull stress calculated from FEA of irradiated toughness specimens were higher than those from FEA of irradiated structural components. The irradiation hardening of structural materials would not promote the brittle fracture at the corner of rectangular coolant tubes of the blankets caused by the load of In-Box LOCA.

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