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Fracture Toughness of Irradiated Ferritic/Martensitic Steel for Sodium-cooled Fast Reactor(SFR) Fuel

Jong-Hyuk Baek[a], Thak-Sang Byun[b], Jun-Hwan Kim[a], Sung-Ho Kim[a], and Chan-Bock Lee[a]
[a] *SFR Fuel Development, Korea Atomic Energy Research Institute, Daejeon, 305-353, Republic of Korea*
[b] *Nuclear Materials Science and Technology, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
jhbaek@kaeri.re.kr

1. Introduction

A ferritic/martensitic steel was been used and/or considered as a primary candidate material in the sodium-cooled fast reactor (SFR) fuel because its low radiation-induced swelling and high resistance to irradiation hardening and embrittlement [1,2]. The mechanical capability, including tensile, creep and hardness, of HT9 steel has been verified up to very high dose (≥ 100 dpa) in a fast fission reactor facility [3-5]. But any practice to evaluate the degradation of radiation-induced fracture toughness has not been explored systematically for the steel. This study provides the fracture toughness data of high-dose irradiated and post-irradiation recovery annealed states of the steel.

2. Experimental

2.1. Specimens

The irradiated materials were taken from the fuel duct wall of a fast fission facility and their composition was represented in Table 1. Specimens were taken from various locations of the duct wall to include large ranges of dose and temperature: 3.2~144.8 dpa and 380.4~ 502.6°C. This study has been focused on fracture toughness measurement using small bend bars (13 × 3 × 4 mm) in as-irradiated and thermally-annealed conditions. For the full recovery of irradiation defects, the annealing was performed at 650°C for 2h according to micro-hardness measurements for the annealed samples.

Table 1 Chemical composition of the test materials (wt.%)

Fe	Cr	Ni	Mo	Mn	C	Ti
Bal.	11.8	0.51	1.03	0.50	0.21	<0.01
V	W	Si	Al	S	P	N
0.33	0.24	0.21	0.03	0.003	0.008	0.006

2.2. Testing and Analysis

Static fracture toughness or fracture resistance (J-R) tests have been performed for the irradiated and annealed bars in a MTS servo-hydraulic testing machine with a high vacuum, high temperature furnace in a radiation lab at ORNL. All J-R fracture tests were run in a displacement-controlled three-point bending mode using the fracture testing program of the MTS testing system, which was based on the standard procedure described by the ASTM Standard E 1820-09, Standard Test Method for Measurement of Fracture Toughness. Prior to the J-R fracture tests, the 13 mm long bars were notched and pre-cracked at room temperature in air. The pre-cracking condition varied with initial notch depth and hardness of the specimens. A typical condition for starting crack growth was a cyclic load of 600 ±500 N at 30 Hz.

The load versus load-line displacement data were recorded and used for analysis to obtain interim fracture toughness (J_Q). In the analyses to construct J-Resistance curve (or J-Δa curve), the crack growth values were obtained by the normalization curve method using the optically measured initial and final crack lengths. The final fracture toughness data are also given in the form of stress intensity factor, K_{JQ}, which can be converted from the J_Q data using the relationship:

$$K_{JQ} = \sqrt{(J_Q \cdot E)/(1-\nu^2)}$$

where E is the Young's modulus at a given temperature and ν the Poisson ratio (=0.28).

3. Results and Discussion

3.1. As-irradiated state

The fracture toughness of as-received state was revealed almost constant value of 250 MPa•m$^{1/2}$ regardless of test temperatures, as shown in Fig. 1. In the case of the specimens irradiated at 380.4 and 401.3°C, the fracture at lower test temperatures less than 250°C showed the brittle mode and fracture toughness values were as low as less than 100 MPa•m$^{1/2}$ and increased as an increase of test temperatures. In the case of the specimens irradiated above 443.5°C, however, the fracture mode was stable ductile and the fracture toughness was reduced with increasing the test temperatures. The fracture toughness values of the higher-temperature (≥443.5°C) irradiated specimens were ranged from 119 to 151 MPa•m$^{1/2}$ at 600°C. It was interpreted that the fracture integrity of the steel would be retained at temperature as high as 600°C even as high dose of 144.8 dpa. The fracture toughness of the irradiated state was not affected by the difference of irradiation dose.

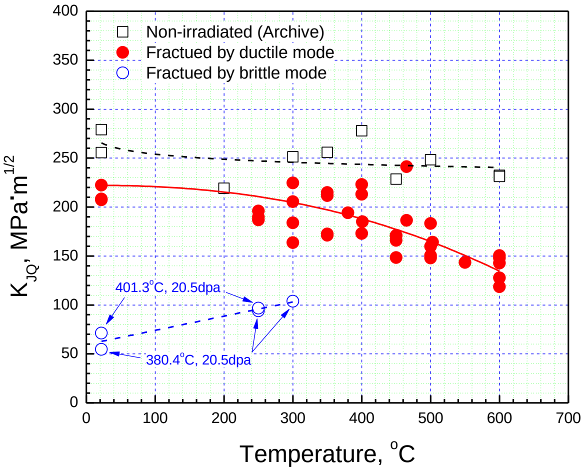

Fig. 1 Fracture toughness as a function of test temperature

3.2. As-annealed state

An annealing after neutron irradiation above 550°C would remove the piled defects from the irradiation and the fracture toughness would be recovered up to that of as-received state. Fig. 2 showed the fracture toughness after post-irradiation anneal at 650°C for 2h. For the irradiated specimens at both 379 and 464°C, the fracture toughness was similar to or higher than that of as-received state. The recovery anneal at that temperature was effective to remove the irradiation defects and would be recommended to extend the life of the high-dose steel.

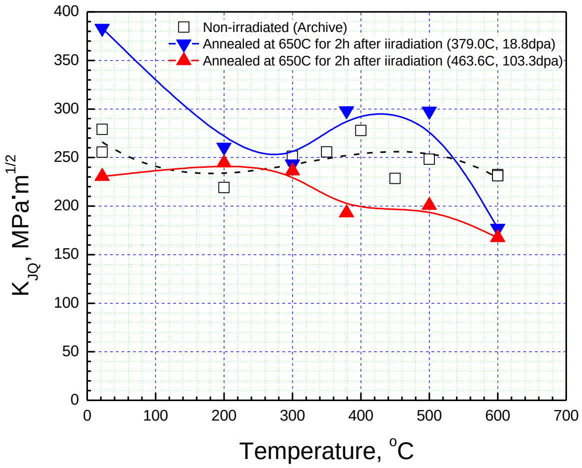

Fig. 2 Fracture toughness after post-irradiation anneal at 650°C for 2h

4. Conclusions

The fracture toughness of the steel was evaluated in the range of 22 to 600°C by using irradiated (max. 150 dpa) fuel duct in a fast fission facility. The fracture toughness of as-irradiated state was very dependent on irradiation temperatures and was as low as less than 100 $MPa\cdot m^{1/2}$ below 401°C. The fracture toughness decreased gradually as an increase of test temperatures. After a recovery anneal at 650°C for 2 h, however, the fracture toughness of as-annealed state was similar to or higher than that of as-received state.

Acknowledgement

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