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# Fracture toughness characterization of JLF-1 steel after irradiation in HFIR to 5 dpa

M.A. Sokolov [a,*], A. Kimura [b], H. Tanigawa [c], S. Jitsukawa [c]

[a] *Oak Ridge National Laboratory, Metals and Ceramics Division, Oak Ridge, TN 37831-6151, USA*
[b] *Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan*
[c] *Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

**Abstract**

Fracture toughness specimens of the ferritic–martensitic steel JLF-1 were investigated before and after irradiation at two different temperatures in the High Flux Isotope Reactor. Small (12.5 mm in diameter with thickness of 4.6 mm) disk-shaped compact tension specimens were irradiated at average temperatures of ~250 °C and 377 °C to ~4 dpa. Small, 3.33 × 3.33 × 25 mm, pre-cracked Charpy specimens were irradiated at ~300 °C and 500 °C to 5 dpa. Transition fracture toughness was evaluated in terms of the reference temperature $T_0$ for each irradiation temperature and dose and compared to unirradiated $T_0$. Current fracture toughness shifts compared with $T_0$ shifts of F82H and 9Cr2WVTa steels irradiated at similar conditions. The present results show that JLF-1, F82H, and 9Cr–2WVTa steels have very similar resistance to radiation embrittlement after doses of 4–5 dpa in the temperature range from 250 °C to 500 °C.


## 1. Introduction

The reduced-activation ferritic–martensitic (RAFM) steel JLF-1 is one of several candidate low-activation materials for fusion applications. This material has slightly higher Cr content (~9%) than F82H (~7.5%) steel but similar to 9Cr–2WVTa steel developed at ORNL. The potential for application of RAFM steels as the structural materials for fusion power plants depends on their ability to maintain adequate level of fracture toughness at the operating temperatures and neutron doses. However, only a limited amount of data on the effects of radiation on fracture toughness of RAFM steels is available. In this study, the effects of irradiation to 5 dpa in the temperature range from 250 °C to 500 °C on fracture toughness and Charpy impact properties of JLF-1 steel were investigated.

## 2. Experimental

### 2.1. Material and irradiations

Specimens of JLF-1 steel were irradiated in the ORNL High Flux Isotope Reactor. Two capsules with europium oxide ($Eu_2O_3$) thermal neutron shields were irradiated in the removable beryllium positions. Details of the irradiation conditions and the capsules design and loading can be found

* Corresponding author. Tel.: +1 865 574 4842; fax: +1 865 574 0641.
*E-mail address:* sokolovm@ornl.gov (M.A. Sokolov).

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elsewhere [1]. The bottom and top parts of these capsules were loaded with disk-shaped compact tension [DC(T)] specimens that were used for fracture toughness characterization. The small (12.5 mm diameter with thickness of 4.6 mm) DC(T) specimen was developed at ORNL for testing irradiated materials [2]. Six DC(T) specimens were irradiated in each 'low-' and 'high-'irradiation temperature capsule to ~4 dpa. Irradiation temperatures were measured by thermocouples. In the low-temperature capsule, six DC(T) specimens were irradiated at an average temperature of 250 °C; temperature variation during irradiation was within ±19 °C for a given specimen. In the high-temperature capsule, six DC(T) specimens were irradiated at an average temperature of 377 °C; temperature variation during irradiation was within ±30 °C for a given specimen. In addition to DC(T) specimens, miniature SS-3 type sheet-tensile specimens (7.62 mm gage length, 1.52 mm gage width and 0.76 mm gage thickness), and 1/3-size ($3.3 \times 3.3 \times 25.4\ mm^3$) Charpy specimens, both V-notch (CVN) and precracked (PCVN), were irradiated in both capsules. However, tensile and Charpy specimens were irradiated in the middle sections of the capsules. In the 'low-temperature' capsule, specimens were irradiated at an average temperature of 300 °C to ~5 dpa. In the 'high-temperature' capsule, specimens were irradiated at an average temperature of 500 °C to ~5 dpa.

### 2.2. Fracture toughness testing procedure

The fracture toughness tests were conducted in accordance with ASTM Standard E1921-05. The unloading compliance method used for measuring the *J*-integral with these specimens is outlined in Refs. [2,3].

Unirradiated specimens were tested in the laboratory on a 98-kN (22-kip) capacity servohydraulic machine, and irradiated specimens were tested in a hot cell with a 490-kN (110-kip) capacity servohydraulic machine. Both machines were fitted with a 22-kN (5-kip) load cell. The broken unirradiated specimens were examined with a calibrated measuring optical microscope to determine the initial and final crack lengths. The irradiated specimens were photographed, and the crack lengths were measured on enlarged prints of the fracture surfaces.

It was assumed that the transition fracture toughness of JLF-1 steel complies with the master curve methodology. This methodology of Wallin [4,5] uses a concept of universal temperature dependence of fracture toughness in the transition region. The master curve methodology has been widely applied for low-alloy reactor pressure vessel steels. The current physical background for this methodology suggests that it is applicable to a wide variety of ferritic bcc steels, including tempered ferritic–martensitic steels like JLF-1, yet the transition fracture toughness data for this class of steels are rather sparse. The biggest advantage of this methodology is the ability to describe temperature dependence of fracture toughness in the transition region by means of testing a relatively low number of small size specimens. This provides an efficient means for post-irradiation characterization of RAFM steels for fusion application, including this study. However, ASTM standard E1921 prescribes several validity requirements. For example, the specimen remaining ligament, $b_0$, must have sufficient size to maintain a condition of high crack-front constraint at fracture. A $K_{Jc}$ datum is considered invalid if it exceeds the $K_{Jc\ (limit)}$ requirement of the ASTM Standard E 1921:

$$K_{Jc(limit)} = \sqrt{\frac{b_0 \sigma_{YS}}{30} \cdot \frac{E}{1 - v^2}}, \quad (1)$$

where $\sigma_{YS}$ is the yield strength, $E$ is Young's modulus, and $v$ is Poisson's ratio of the material at the test temperature. Some small specimen data may need constraint correction prior to application of E1921 analysis like the one suggested by Odette et al. [6,7]. All irradiated $K_{Jc}$ data in this study satisfied the $K_{Jc(limit)}$ requirement of the ASTM Standard E 1921, Eq. (1). Thus, no constraint correction was made to the data.

The ASTM standard E1921 also requires a certain number of specimens to be tested within $T_0 \pm 50$ °C range, where $T_0$ is the transition fracture toughness reference temperature. Unfortunately, this requirement of the E1921 standard was not satisfied in this study because too few specimens were irradiated in the capsules and some of them were tested at temperatures below $T_0 - 50$ °C in order to satisfy the requirement in Eq. (1). Thus, the current $T_0$ values should be considered as estimate values only.

## 3. Results and discussion

Tensile properties determined with SS-3 sheet-tensile specimens showed that irradiation at ~300 °C to 5 dpa resulted in significant hardening of JLF-1 steel. Room temperature yield strength increased by 314 MPa (from 525 MPa in the unirradiated condition to 839 MPa after irradiation). This result is in agreement with available hardening measurements on JLF-1 steel [8,9], but somewhat less than observed for such irradiation conditions on Eurofer97 [10,11] and F82H [3,12,13] steels. The observed hardening suggested a transition temperature shift after the same irradiation level of at least 100 °C. However, Charpy impact data showed a relatively low DBTT shift of 48 °C after irradiation at 300 °C to 5 dpa, while irradiation at 500 °C exhibited a DBTT shift of only 19 °C. In both cases, irradiation resulted in some increase of the upper-shelf energy. Fig. 1 provides Charpy curves of JLF-1 steel in the unirradiated condition and after irradiation at 300 °C and 500 °C to 5 dpa conditions.

The fracture toughness tests of JLF-1 steel DC(T) specimens showed a 144 °C shift of $T_0$ after irradiation at 250 °C to 4 dpa, and only a 37 °C shift after irradiation at 377 °C to 4 dpa, see Fig. 2. Test temperatures for PCVN specimens were selected based on Charpy impact data since the specimens were irradiated together. Test results revealed very low toughness values, indicating that the resulted test temperature were too low. These low toughness values did not allow for evaluation of $T_0$ values. This experience demonstrates that for such small specimens, there is a very narrow test temperature range where useful fracture toughness data can be generated. Thus, careful planning by increasing the number of specimens available for tests, and utilization of all information from tensile, hardness, and Charpy data, become a critical preparation for post-irradiation examination with fracture toughness specimens. These data continue the controversy of a low Charpy DBTT shift after 300 °C irradiation compared with a relatively high level of hardening. The reasons for such a suspiciously low Charpy DBTT shift are not clear at this point. The irradiation temperature, that is a typical suspect for such deviations, was ruled out as a potential cause of discrepancies in the data since the irradiation temperature was monitored by thermocouples. The small number of tested specimens could be one of the potential reasons. Additional work needs to be performed to resolve this issue.

The current data allow comparison of the radiation embrittlement of JLF-1 steel with F82H and 9Cr–2WVTa data since those steels were irradiated in the same temperature range and to similar doses [13], see Fig. 3. These data show that JLF-1, F82H, and 9Cr–2WVTa steels have very similar resistance to radiation embrittlement after doses of 4–5 dpa in the temperature range from 250 °C to 500 °C.

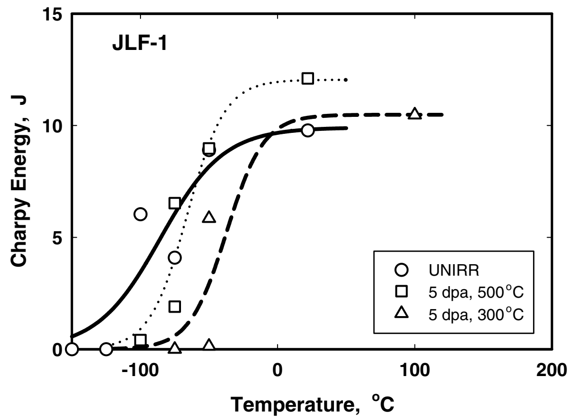


Fig. 1. Charpy impact data of JLF-1 steel in the unirradiated and irradiated conditions.

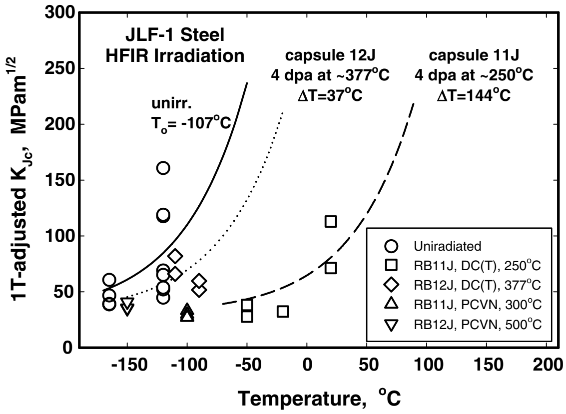


Fig. 2. 1T size-adjusted fracture toughness data of JLF-1 steel in the unirradiated and irradiated conditions.

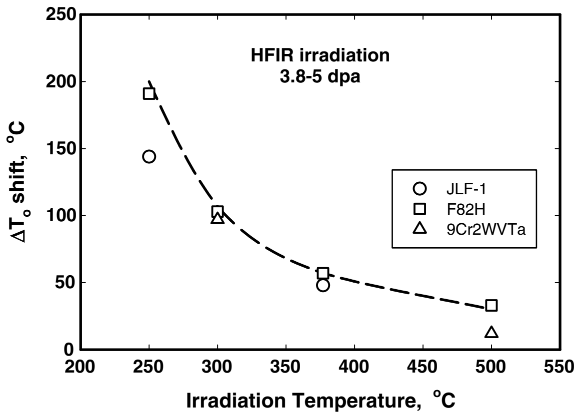


Fig. 3. The effect of irradiation temperature and dose on transition temperature shift of different RAFM steels.

## 4. Summary

The master curve methodology was applied to characterize the transition fracture toughness of JLF-1 steel before and after irradiation. Application of the master curve methodology showed that there is a very narrow test temperature range where useful fracture toughness data can be generated for such small specimens.

Specimens irradiated at ~377 °C exhibited a modest shift of 37 °C in the reference fracture toughness temperature, $T_0$. However, the $T_0$ shift of specimens irradiated at ~250 °C was much larger (144 °C). These results show that JLF-1, F82H, and 9Cr–2WVTa steels have very similar resistance to radiation embrittlement after doses of 4–5 dpa in the temperature range from 250 °C to 500 °C.

Present data indicate that Charpy DBTT shifts were less than $T_0$ shifts. However, the small number of PCVN and CVN specimens did not allow a quantitative assessment of this difference.

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