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# Creep behavior of reduced activation ferritic/martensitic steels irradiated at 573 and 773 K up to 5 dpa

M. Ando [a,*], M. Li [b], H. Tanigawa [a], M.L. Grossbeck [b,c], S. Kim [d], T. Sawai [a], K. Shiba [a], Y. Kohno [e], A. Kohyama [d]

[a] *Fusion Structural Materials Development Group, Directorates of Fusion Energy Technology, Fusion Research and Development Directorate, Japan Atomic Energy Agency (JAEA), Japan*

[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

[c] *University of Tennessee, Knoxville, TN 37996-2300, USA*

[d] *Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

[e] *Muroran Institute of Technology, Muroran, Hokkaido 050-8585, Japan*

**Abstract**

The irradiation creep behavior of F82H and several variants of JLF-1 steel has been measured at 573 and 773 K up to 5 dpa using helium-pressurized creep tubes irradiated in HFIR. These tubes were pressurized with helium to hoop stress levels of 0–400 MPa at the irradiation temperature. The results for F82H and JLF-1 with a 400 MPa hoop stress showed small creep strains (<0.25%) after irradiation at 573 K. The irradiation creep strain at 573 K in these steels is linearly dependent on the applied stress at stress levels below 250 MPa. However, at higher hoop stress levels, the creep strain becomes nonlinear. At 773 K, the irradiation creep strain of F82H is linearly dependent on the applied stress level below 100 MPa. At higher stress levels, the creep strain increased strongly. The creep compliance coefficients for F82H and JLF-1 are consistent with the values obtained for other steels. These data contribute to the materials database for ITER test blanket design work.



## 1. Introduction

Reduced activation ferritic/martensitic steels (RAFs) are the most promising candidates for blanket structural materials for fusion reactors. Irradiation creep has been recognized as one of the most important properties for engineering data due to the blanket structural design. Several researchers have reported on irradiation creep and void swelling behavior of austenitic stainless steels (Type 316 and PCA) and ferritic steels (HT9 and 9Cr–1Mo) irradiated above 673 K in the Fast Flux Test Facility (FFTF), the High Flux Isotope Reactor (HFIR), and other reactors [1–6]. In addition, some results of irradiation creep experiments on RAFs above 663 K have been reported by the Japan/US collaboration program for fusion materials [7]. For fusion reactors, it is anticipated that irradiation creep of RAFs at lower temperatures could be also significant, and this would have a large impact on the life

* Corresponding author. Tel.: +81 29 282 6146; fax: +81 29 282 5551.

*E-mail address:* ando.masami@jaea.go.jp (M. Ando).

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expectancy of a water-cooled blanket system. However, irradiation creep behavior of RAFs at temperatures below 673 K has not yet been reported. In a fusion reactor, some transmutations are produced by high-energy neutrons in the first wall. These are mainly gas atoms (helium and hydrogen) and some solid transmutation products. It is possible that this production of interstitial impurities will affect the irradiation creep and swelling rates during irradiation. The effect of transmutation products on irradiation creep behavior also has not been reported in ferritic steels.

The objectives of this investigation are to provide creep data for a materials database for blanket structural design in fusion reactors and to understand the irradiation creep behavior of RAFs at low temperatures. The effects of helium and manganese on irradiation creep behavior were also investigated.

## 2. Experimental procedure

The materials were the F82H IEA heat (8Cr-2WVTa) provided by Japan Atomic Energy Research Institute (Present name: Japan Atomic Energy Agency), JLF-1 (9Cr-2WVTa), manganese-doped JLF-1, and boron-doped JLF-1 provided by Japanese Monbusho (Present name: MEXT). The chemical compositions and heat treatments of these materials are given in Table 1. Boron-doped JLF-1 was provided to investigate the effect of helium on irradiation creep. Helium is produced from the reaction $^{10}B(n,\alpha)\ ^{7}\mathrm{Li}$ during irradiation. To study the effect of manganese, two variants of Mn-doped JLF-1 were prepared. Manganese is produced by nuclear transmutation of Fe in a fusion reactor.

The tube specimens had dimensions of 4.57 mm outside diameter and 22.4 mm length with a 0.2 mm wall thickness as shown in Fig. 1. End caps were electron beam welded to the tube segments, and the specimens were pressurized with high purity helium (99.999% He) to obtain the desired hoop stresses at the irradiation temperatures. The hoop stresses ranged from 0 to 400 MPa at the irradiation temperature. These tubes, including control tubes for thermal creep testing, were fabricated by Westinghouse Hanford Company in 1996, and the tube diameters were measured by a laser micrometer system at Pacific Northwest National Laboratory prior to irradiation.

Irradiation was performed in the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR) to atomic displacement levels up to 5 dpa in the removable beryllium (RB) position. Nominal irradiation temperatures were 573 and 773 K. These tubes were irradiated in the HFIR

Table 1
Chemical composition of F82H and JLF-1 steels (wt%)

| | C | Si | Mn | S | Cr | W | V | Ta | Ti | N | B |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F82H IEA heat | 0.09 | 0.07 | 0.10 | 0.0010 | 7.87 | 1.98 | 0.19 | 0.030 | 0.004 | 0.0070 | 0.0002 |
| JLF-1 | 0.10 | 0.05 | 0.45 | 0.0026 | 8.88 | 1.95 | 0.20 | 0.090 | 0.002 | 0.0215 | 0.0002 |
| B-doped JLF-1 | 0.10 | 0.04 | 0.46 | 0.0027 | 8.87 | 1.94 | 0.19 | 0.090 | 0.002 | 0.0218 | 0.0022 |
| Mn-doped JLF-1(A) | 0.10 | 0.05 | 0.98 | 0.0028 | 8.92 | 1.96 | 0.20 | 0.092 | 0.005 | 0.0242 | 0.0003 |
| Mn-doped JLF-1(B) | 0.10 | 0.05 | 1.98 | 0.0032 | 8.94 | 1.95 | 0.20 | 0.091 | 0.005 | 0.0240 | 0.0003 |

Heat tretment JLF-1: Normalizing: 1323 K 1 h AC, Tempering: 1053 K 1 h AC.
F82H IEA Normalizing: 1313 K 40 min AC, Tempering: 1023 K 1 h AC.

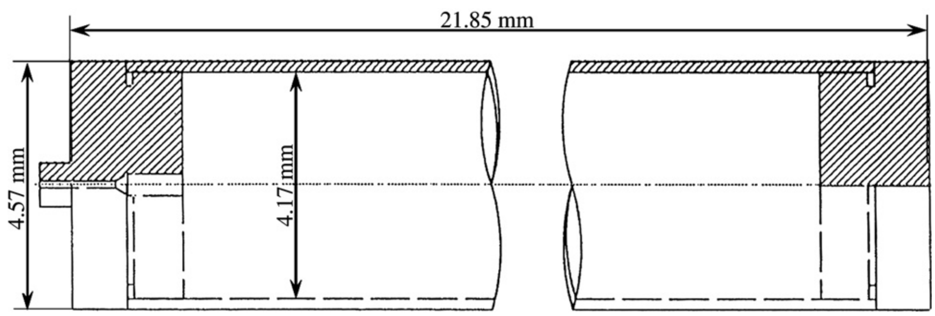


Fig. 1. Geometry of the pressurized tube specimen.

from cycle 352 to cycle 361 for an accumulated exposure time of 224 equivalent full power days [8]. The dose rate for specimens in this experiment ranged from $2.17 \times 10^{-7}$ to $3.08 \times 10^{-7}$ dpa/s.

The tubes were measured with a non-contacting laser micrometer system capable of a precision of ±250 nm. Each tube was measured three times. The average diameter of the central three-fifths of each tube was used in the analysis of the data. Creep strain was calculated from tube diameter measured before and after irradiation. The uncertainty in the diametral change or strain is 0.05%.

## 3. Results and discussion

Fig. 2 provides the results of irradiation creep measurements for pressurized tube specimens irradiated at 573 and 773 K. In this experiment, a total of 30 tubes was measured in the hot cell. The actual uncertainty in the magnitude of the stress is mainly a result of uncertainty in the irradiation temperature. This uncertainty in the stress is given approximately by

$$\Delta\sigma/\sigma \approx \frac{|T_{\text{test}} - T_{\text{target}}|}{T_{\text{target}}}, \tag{1}$$

where the temperature is in Kelvin. To compare the data of pressurized tube specimens with those of uniaxial specimens, the 'effective stress' is used. For a pressurized tube specimen with biaxial stress state, the effective stress is given by

$$\sigma_{\text{eff}} = \frac{\sqrt{3}}{2}\sigma_{\text{Hoop}}, \tag{2}$$

where $\sigma_{\text{eff}}$ is the effective uniaxial stress and $\sigma_{\text{Hoop}}$ is the hoop stress in the tube wall. Effective creep strain is calculated from the change in the outer diameter of tube following irradiation. Using the measured diameters, the effective creep strain is calculated by the following expression:

$$\varepsilon_{\text{eff}} = 1.15\left(\frac{2}{\sqrt{3}}\right)\frac{\Delta D}{D_{\text{o}}}, \tag{3}$$

where $\Delta D$ is the change in the tube's outer diameter before and after irradiation, $D_{\text{o}}$ is the outer diameter before irradiation. The outer diameter strain is converted to the mid-wall strain by a factor of 1.15, and the measured strain, that is biaxial strain, is converted to the effective uniaxial strain by the factor $\frac{2}{\sqrt{3}}$ [9].

Fig. 3 shows the relationship between the effective strain and the effective stress in each steel irradiated at 573 K. All of the steels exhibit similar irradiation creep behavior at 573 K up to 5 dpa. The irradiation creep strain in these steels is nearly linearly dependent on the effective stress level for stress levels below 200 MPa. However, the creep strain becomes nonlinear at higher stress levels. Above 320 MPa, creep strain tends to increase strongly with increasing stress. Fig. 4 shows the relationship between the effective strain and the effective stress in these steels irradiated at 773 K. The irradiation creep strain of F82H is linearly dependent on the effective stress level for stress levels below 100 MPa. At higher stress levels, the creep strain increased strongly in these steels because thermal creep had also occurred during irradiation.

For F82H and JLF-1 steels, a stress-free tube was included to monitor swelling. The data from each

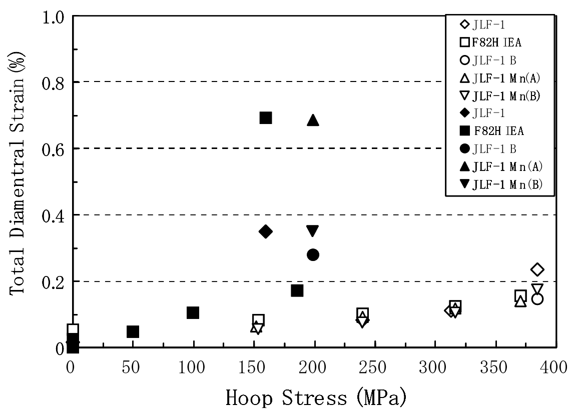


Fig. 2. Hoop stress dependence of irradiation creep at 573 and 773 K.

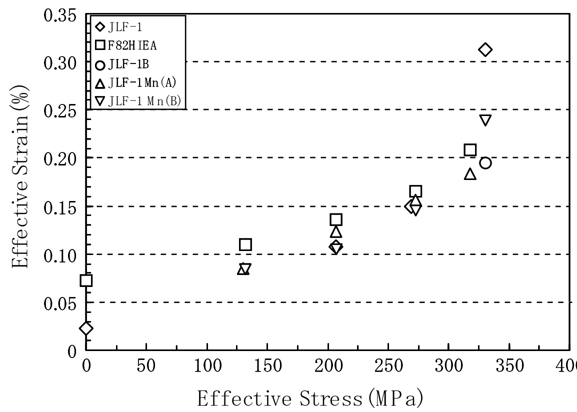


Fig. 3. Relationship between effective strain and effective stress at a temperature of 573 K and a displacement level of 5 dpa.

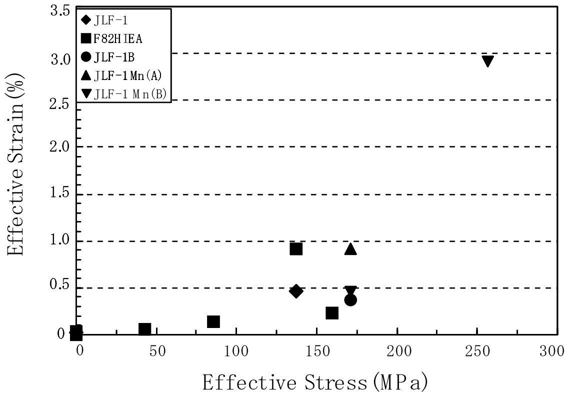


Fig. 4. Relationship between effective strain and effective stress at a temperature of 773 K and a displacement level of 5 dpa.

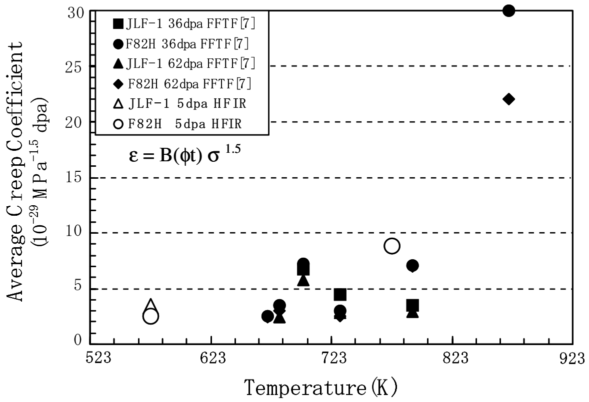


Fig. 5. Temperature dependence of average creep coefficient for JLF-1 and F82H irradiated in the High Flux Isotope Reactor (present research) and the Fast Flux Test Facility [7].

stress-free tube show that swelling is very small in this condition, below 0.06%. The creep strains were calculated from measured diametral strains. Thus, these values include stress-enhanced swelling and thermal creep. However, stress-free swelling was determined to be negligible, and total swelling and thermal creep were shown to be very small at 573 K up to 5 dpa.

Irradiation creep behavior can be explained by the stress induced preferential absorption (SIPA) mechanism [10]. Furthermore, at the highest stress level, irradiation creep behavior tends to change from the SIPA mechanism to a climb-glide mechanism [11]. The stress and fluence dependence of in-reactor creep behavior can be predicted for the SIPA irradiation creep model using the following expression:

$$\varepsilon = B\sigma^n \phi t, \tag{4}$$

where $\varepsilon$ is the effective creep strain, $B$ is the average creep coefficient, $\sigma$ is the effective stress, $n$ is the stress exponent, and $\phi t$ is the fast neutron fluence.

Fig. 5 shows the temperature dependence of the average creep coefficient from this investigation and irradiation creep data for JLF-1 and F82H irradiated in FFTF/MOTA. A creep stress exponent of $n = 1.5$ was determined from these data [7]. A stress exponent of 1.5 also provides a good fit for the data obtained in the present experiment. It is shown that the average creep coefficient of F82H and JLF-1 irradiated at 573 K is nearly equal to that of F82H and JLF-1 irradiated at 663–733 K in FFTF, and the average creep coefficient of F82H at 773 K is very similar to that of F82H at 793 K in FFTF, although the thermal creep and swelling-enhanced creep data are not distinguished. Thermal creep testing is now in progress with control tubes at JAEA, using the same thermal histories as experienced by the in-reactor creep specimens in the HFIR, to provide thermal creep data to support the estimate of negligible thermal creep.

The effect of helium on irradiation creep of ferritic/martensitic steels was also examined using boron-doped JLF-1. Only one specimen irradiated at 573 K with highest hoop stress level was measured. Helium production after irradiation was estimated to be about 20 appm and was controlled using a thermal neutron shielded capsule. The creep strain of B-doped JLF-1 was smaller than that of other steels at the highest stress level. It is suggested that helium production affects the diffusion and mobility of irradiation-induced point defects, although the mechanism of the helium effect cannot be adequately explained from these data. For Mn doped JLF-1 steels, the effect of Mn on irradiation creep in these steels irradiated at 573 K was very small; irradiation creep behavior was similar to JLF-1 steel.

Some tubes of F82H and JLF-1 with three stress levels (zero, the middle and the highest stress) were selected for microstructural examination. These tube specimens were cut in the central region with a low speed saw after measurement of the tube diameter. Small specimens were removed from a ring-like specimen obtained from the cut tube. These pieces were sent to the WASTEF Facility of JAEA. TEM specimens were made from some pieces using a focused ion beam polishing machine. For JLF-1 steel, the microstructural analysis was performed using similar pressurized tubes irradiated in the FFTF/MOTA [12]. It was reported that no major changes in microstructure were observed in JLF-1 with a hoop stress of 60 MPa up to 60 dpa at 703 K. However, a difference in the Burgers vector anisotropy by as much as a factor of 10 was observed from the analysis of dislocation density. In this experiment, the creep strain of JLF-1 from the HFIR irradiated specimen (hoop stress 400 MPa, 573 K, 5 dpa) and the FFTF irradiated specimen (hoop stress 60 MPa, 703 K, 60 dpa) were almost the same. The HFIR irradiated specimens may have a larger Burgers vector anisotropy because they were exposed at higher stress levels and lower irradiation temperatures than the FFTF irradiated specimens. Detailed investigation of these microstructures following irradiation will be performed in future studies.

## 4. Conclusion

(1) Irradiation creep of each reduced activation ferritic steel (JLF-1 series and F82H) exhibited similar behavior below 573 K up to 5 dpa. The irradiation creep strain in these steels is almost linearly dependent on the effective stress level for stresses below 200 MPa. At 773 K, the irradiation creep strain of F82H is linearly dependent on the effective stress level for stress levels below 100 MPa. At higher stress levels, the creep strain increased strongly in these steels because thermal creep had also occurred during irradiation.

(2) Temperature dependence of the irradiation creep behavior was estimated, and the average creep coefficient of F82H and JLF-1 irradiated at 573 K was found to be nearly equal to that of other steels irradiated at temperatures between 663 and 733 K in FFTF.

(3) The creep strain of the specimen with the highest helium level was smaller than that of other steels at the highest stress level. For Mn-doped JLF-1 steel, the effect of Mn on irradiation creep was very small, and irradiation creep behavior was similar to that of JLF-1 steel.

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