Journal of Nuclear Materials 386–388 (2009) 264–267

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Creep behavior of the F82H steel under irradiation with 17 MeV protons at 300 °C

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ABSTRACT

Although fusion blankets are exposed to severe irradiation, its rear side would stay at rather a modest condition. In this research, the irradiation-induced deformation of F82H IEA-heat steel at 300 °C was examined. A torsion creep apparatus with a strain resolution of $\sim 10^{-7}$ was used with 17 MeV protons (2×10^{-7} dpa/s). At the lowest stress of 30 MPa, deformation in the direction against applied stress was observed. This 'negative creep' was attributed to the increase in elastic modulus due to irradiation. Such an effect was compensated for each measurement based on the modulus data measured during irradiation. Stress exponent n of irradiation creep rates was 1.5, very close to that of creep strain at 5 dpa of pressurized tubes. The predicted stress relaxation was slower than that for 5% cold-worked Type 316L steel, resulting mainly from the difference in n, smaller and closer to unity in the latter.

1. Introduction

Reduced activation ferritic/martensitic steels (RAFs), including F82H steel, are promising candidates for the in-core structure materials of fusion reactors. An irradiation creep has been recognized as one of the important engineering factors for the blanket design, and in-reactor creep behavior of RAFs above 400 °C was examined in the fast flux test facility (FFTF) [1]. In fusion reactors, however, many portions of the core components, e.g., a rear side of the blanket and the vacuum vessel, will be subject to irradiation damage at lower temperatures. Thus, the irradiation creep of RAFs at lower temperatures should also be examined, and this may present a significant importance particularly for the life expectancy of a water-cooled blanket. However, no irradiation creep behavior of RAFs at temperatures below 350 °C has been reported, except for the in-reactor strain measurement at 5 dpa in the high flux isotope reactor (HFIR) using pressurized tubes [2].

The objective of this report is to examine the irradiation creep behavior of F82H steel at 300 °C under irradiation with 17 MeV protons from a cyclotron accelerator. In-beam creep measurements provide a good control of temperature, stress and radiation damage rate. Moreover, it enables a direct measurement of irradiation creep rates which can be used to evaluate irradiation-induced stress relaxation behavior. The obtained irradiation creep rates and the calculated irradiation-induced stress relaxation will be compared with those of SUS 316L (Japanese version of AISI 316L) steel.

2. Experimental procedure

The new in-beam creep apparatus, schematically shown in Fig. 1, permits us to apply torsion loading. Controlled torque is applied to a thin wire specimen through the mechanism of an analog current meter with a movable coil and a permanent magnet. A small mirror is attached to a thin quartz rod which is connected to the bottom of a coil frame. This mirror rotates as the specimen is deformed and sheared. The rotation of this mirror is continuously followed by an optical tracking device which consists of a photocell sensor and a high-sensitivity laser encoder attached directly to the axis of a servomotor-driven rotation stage. Angular resolution of the tracking device is 0.001° which corresponds to a shear strain of about 7×10^{-8} in a typical thin-wire specimen. Shear stress and strain quoted in the following were averaged values calculated using the method given in Ref. [3].

Irradiation creep tests were performed for the F82H IEA-heat material (C: 0.09, Cr: 7.82, W: 1.98, V: 0.19, Ta: 0.04, Ti: 0.004, Si: 0.07, Mn: 0.1, P: 0.003, S: 0.001 in wt.%), from which thin wires of 0.7 mm diameter were fabricated through a repetition of annealing at 780 °C in vacuum and swaging at room temperature. These wires were normalizing at 940 °C for 40 minutes followed by tempering at 750 °C for 1 h. Reduced gauge section with a minimum diameter of about 0.15 mm was formed by electro-chemically polishing a 12 mm section at the center of a wire specimen of 0.7 mm diameter and 40 mm length.

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doi:10.1016/j.jnucmat.2008.12.108

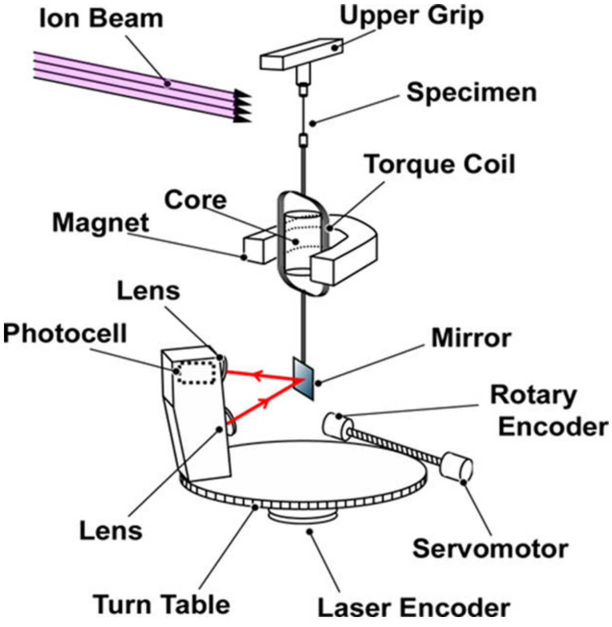

Fig. 1. Schematic illustration of the torsion creep apparatus.

Irradiation experiments were carried out with 17 MeV protons using the cyclotron accelerator at National Institute for Materials Science. The atomic displacement rate averaged through the thickness direction was 2×10^{-7} dpa/s according to the calculation using the TRIM 2003 code for the present experimental condition, and its variation along the bean direction was about 10%. During experiments, the specimen temperature was held at 300 °C with accuracy of ±1 °C by a jet of high temperature helium gas which was continuously purified by a Ti getter system. The specimen temperature was monitored by an infrared pyrometer with a spot size of 0.25 mm. It was also monitored by type K thermocouples of about 0.15 mm diameter positioned close to the specimen and within the proton beam and the helium jet. The total accumulated atomic displacement was about 0.2 dpa throughout the present experiment.

3. Results and discussion

When the stress was 30 MPa, i.e., the lowest stress applied in the present investigation, the direction of specimen rotation was opposite to that of the applied torque up to 0.2 dpa, except for the very beginning of irradiation, as shown in Fig. 2. This means that the strain had been reduced under irradiation although the specimen was kept stressed. Above 30 MPa, measured creep rates were positive and became reasonably constant after a few hours from the start of irradiation, indicating the creep was basically stationary. Such a 'negative creep' at 30 MPa has been reported for austenitic stainless steels [4–6], and it was attributed to the irradiation-induced microstructure changes such as precipitation, defect clustering and/or consequent solute segregation. Since torsion creep is insensitive to volumetric changes, increase in elastic modulus particularly at the surface region of the cylindrical specimen by irradiation-induced segregation should play a significant role and lead to a reduction of elastic strain in the present case.

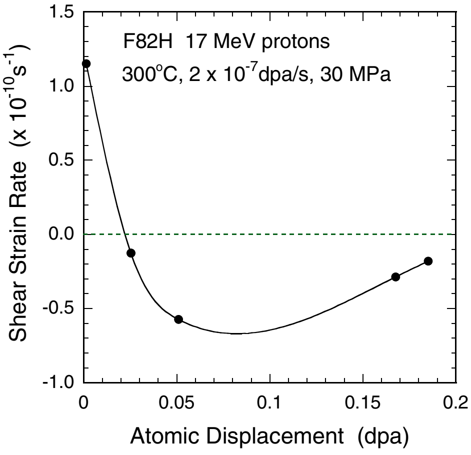

Fig. 2. 'Negative' irradiation creep rate versus dpa.

Although the specimen rotation under stresses above 30 MPa had been in the direction of applied torque, the measured creep rates should have included the decreasing rate of elastic strain due to the modulus increase, because all measurements had been carried out with irradiation damage less than 0.2 dpa. It is, therefore, necessary to compensate for the decrease in elastic strain during each creep rate measurement. The elastic response of the specimen had been measured by recording its rotation as the applied torque was increased continuously from zero to a rather low torque and then decreased back to zero during intermissions in the present investigation. The elastic modulus was evaluated from the slope of this rotation-torque response and it was found

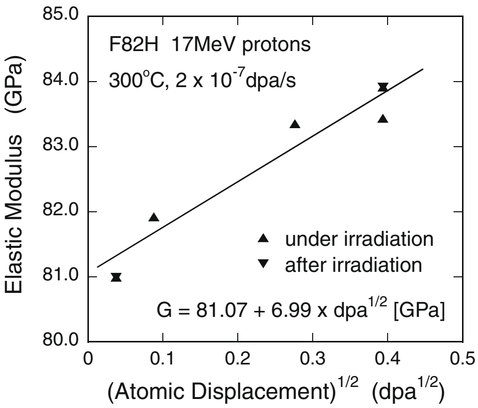

Fig. 3. Change of elastic modulus versus dpa$^{1/2}$.

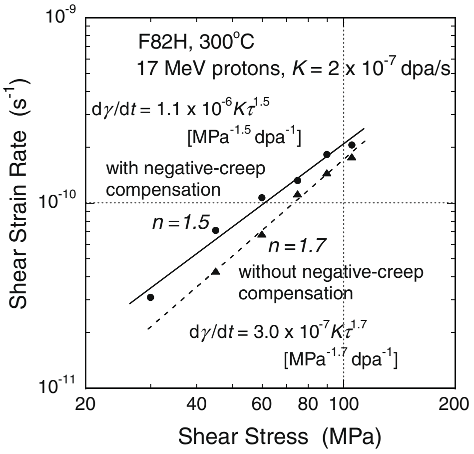

Fig. 4. Stress dependency of strain rate with and without negative-creep compensation.

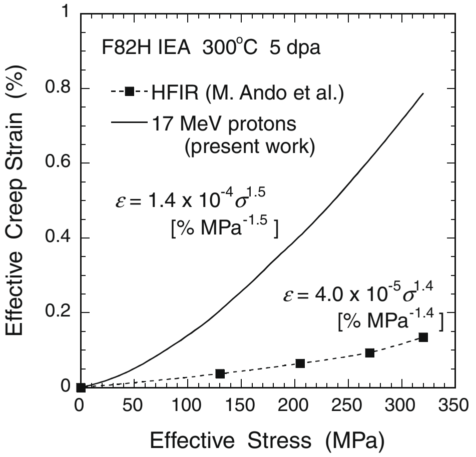

Fig. 5. Irradiation creep strain versus stress for the two irradiation conditions.

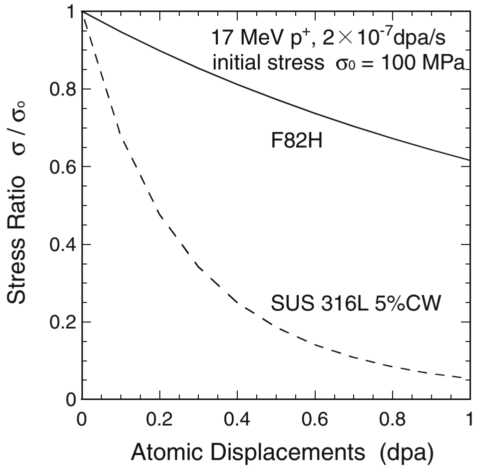

Fig. 6. Irradiation-induced stress relaxation for F82H and SUS 316L 5%CW.

to increase proportionately to a square root of the accumulated dpa as shown in Fig. 3. The apparent reduction of creep rate due to the 'negative creep' was calculated based on this relation for a specific dpa value, below 0.2 dpa, at which each creep measurement was carried out including the measurement with 30 MPa. The revised irradiation creep rates are plotted in Fig. 4 together with those before compensation. Stress exponent *n* of the power law expression was 1.5 after the modulus compensation. This *n* value was very close to that of creep strain at 5 dpa of the F82H pressurized tubes irradiated in HFIR [2]. Creep strain at 5 dpa was calculated as a function of stress based on the stress dependence of creep rates obtained in the present experiment. The calculated relationship between applied stress and creep strain is compared with the aforementioned in-reactor result in Fig. 5, where both stress and strain in the two experiments, shear in the present torsion case and biaxial tension in the in-reactor case, have been converted to the effective values following Ref. [7]. Although the stress dependence is almost the same, the magnitude of strain is quite different, i.e., several times larger in the present proton irradiation. Such difference, however, can be understood from the difference in defect production efficiency between protons and reactor neutrons and also from the clustering of point defects at cascades in the latter, both of which reduce the point defect fluxes [8]. The obtained exponent of 1.5 is larger than that of SUS 316L, close to unity. Such difference in the stress dependence of an irradiation-induced creep leads to a rather significant difference in the irradiation-induced stress relaxation as will be discussed below.

Stress relaxation reflects a decrease in stress associated with the conversion from elastic to plastic strain while the total strain is kept constant. When creep rate is expressed in a form of power law, stress relaxation can be expressed by the equations [9],

$$\sigma/\sigma_0 = \exp(-\mathrm{E}Ct);\ n = 1, \tag{1}$$

$$\frac{\sigma}{\sigma_0} = \exp\left[-\frac{1}{n-1} \times \ln\{1 + (n-1)\mathrm{E}C\sigma_0^{n-1}t\}\right];\ n > 1, \tag{2}$$

where σ is the stress, σ_0 is the initial stress, *E* is the elastic modulus, *C* and *n* are the coefficient and the stress exponent of the power-law creep rate equation, respectively. These two equations indicate that stress relaxation tends to be larger when the stress exponent *n* is smaller and closer to unity. Calculated stress–relaxation curve is shown as a function of dpa in Fig. 6, where that of 5% cold-worked SUS 316L [10] is also plotted for comparison. Stress relaxation predicted for F82H is slower than that for SUS 316L. This difference mainly results from that of *n* between the two steels, i.e., smaller and closer to unity in the latter.

On the one hand, the prevailing mechanism of the irradiation-induced deformation in SUS 316L 5%CW at 300 °C has been attributed to the SIPN (stress-induced preferential nucleation of interstitial loops) [11] following previous experimental and computer simulation studies [10,12]. Contributions from other two major mechanisms, i.e., SIPA (stress-induced preferred absorption of point defects) climb [13] and the glide of network dislocations enabled by SIPA-climb [14], appear to be smaller for the rather low network dislocation density of $3.1 \times 10^{14}\ \mathrm{m}^{-2}$. As a result, stress exponent of irradiation-induced creep rates in SUS 316L 5%CW is expected to be about unity as has been shown by experiments [10]. On the other hand, the stress exponent *n* of F82H is 1.5 that is higher than unity so that it is hard to explain its irradiation creep simply by SIPN or SIPA. In BCC (body centered cubic) metal dislocations can glide rather easily by cross-slip. This may enhance a climb-assisted glide mechanism, which gives *n* values of 2 or higher, simultaneously with SIPN or SIPA. Combination of these mechanisms could increase *n* to 1.5. Much higher dislocation density in the tempered martensite structure of F82H, compared to SUS 316L, should support the active contribution of a dislocation glide. More experiments are needed to clarify the mechanism of irradiation-induced deformation in F82H.

4. Conclusions

Irradiation creep of F82H IEA-heat steel was examined at 300 °C under 17 MeV proton irradiation (damage rate: 2×10^{-7} dpa/s, maximum dose: 0.2 dpa). Stress relaxation was also predicted using the obtained creep rate data. The results are summarized as follows.

(1) 'Negative creep', i.e., deformation in the direction against applied stress, was observed at 30 MPa, and it was attributed to the increase in elastic modulus due to irradiation. Such an effect was compensated for each measurement based on the modulus data measured during irradiation in order to evaluate effective irradiation-creep rates.

(2) Stress exponent *n* of irradiation creep rates was 1.5, very close to that of creep strain at 5 dpa of pressurized tubes. Stress relaxation was predicted slower than that for 5% cold-worked SUS 316L, resulting mainly from the difference in *n*, smaller and closer to unity in the latter.

Acknowledgements

This work was financially supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology, based on the screening and counseling by the Atomic Energy Commission.

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