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Irradiation creep and swelling of the US fusion heats of HT9 and 9Cr-1Mo to 208 dpa at ~ 400°C *

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Abstract

The irradiation creep and swelling behaviors of the fusion heats of HT9 and 9Cr-1Mo at ~ 400°C have been measured to exposures as large as 208 dpa, using both diametral and density measurements of helium-pressurized creep tubes. Void swelling was found in both alloys at 208 dpa to occur at rates of 0.012%/dpa or less, with the swelling of HT9 exhibiting a larger degree of stress enhancement than 9Cr-1Mo. The creep rate of HT9 is rather nonlinear in its response to hoop stress level in the range 0-200 MPa, but 9Cr-1Mo exhibits only slightly greater than linear behavior with stress level. The creep compliance and creep-swelling coupling coefficient for 9Cr-1Mo are consistent with values obtained for other steels.

1. Introduction

Ferritic-martensitic steels are being considered for structural applications in fusion reactors. In order to provide data on the response of such steels to radiation, a series of experiments have been conducted in FFTF. One of these experiments involves the simultaneous measurement of irradiation creep and void swelling. Helium-pressurized creep tubes constructed from the ferritic-martensitic alloys HT9 and 9Cr-1Mo (US fusion heats 9607R2 and 30176) have completed their irradiation in the Materials Open Test Assembly (MOTA) in the Fast Flux Test Facility (FFTF) at a nominal temperature of ~ 400°C.

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2. Experimental details

The composition and heat treatment of these two alloys is listed in Table 1. These tubes (2.24 cm long by 0.46 cm diameter) were periodically discharged from the reactor, and prior to reinsertion into reactor, diameter measurements were made using laser profilometry [1]. The tubes were inserted in all MOTA vehicles from MOTA-1B through MOTA-1G and then continued into MOTA-2B. Both alloys were irradiated at hoop stress levels of 0, 60, 100, and 140 MPa, and HT9 was also irradiated at 200 MPa. Irradiation temperatures varied somewhat from one MOTA to the next, but during any one irradiation interval, the temperature was actively controlled within ±5°C of the nominal temperature. Table 2 presents the target temperatures of these tubes in each MOTA irradiation segment. These tubes reached dpa exposure levels as large as 208 dpa. The strains of these tubes were last reported at ~ 150 dpa [2].

Upon termination of the experiment, each tube was

Table 1
Composition of alloys in wt%

	C	Si	Mn	P	S	Cr	Mo	NI	V	W	N	Al	Ti
HT9	0.20	0.17	0.57	0.016	0.003	12.1	1.04	0.51	0.28	0.45	0.027	0.006	0.001
9Cr-1Mo	0.08	0.11	0.37	0.010	0.003	8.61	0.89	0.09	0.21	< 0.01	0.055	0.007	0.004

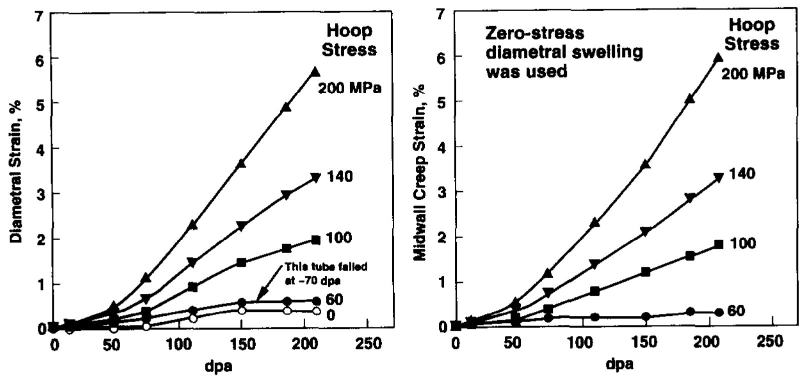

Fig. 1. Total diametral strains and midwall creep strains for HT9.

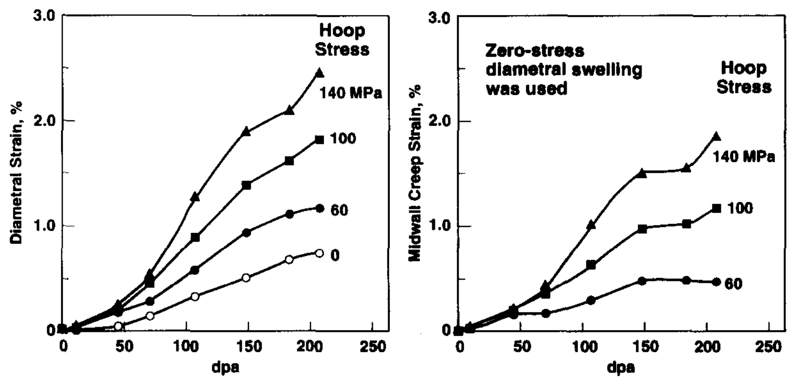

Fig. 2. Total diametral strains and midwall creep strains for 9Cr-1Mo.

Table 2
Irradiation history of pressurized tubes

MOTA	Target temperature (°C)	Incremental dose (dpa)
1B	407	~11
1C	425	~34
1D	406	~26
1E	403	~37
1F	406	~40
1G	420	~35
2B	433	~24

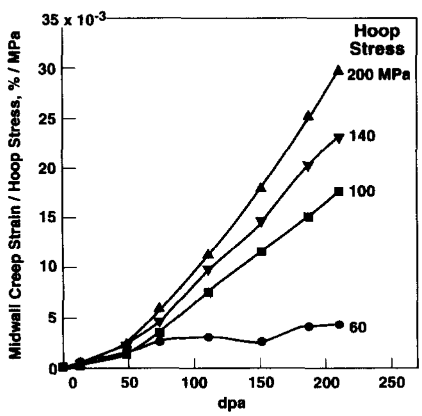

Fig. 3. Stress-normalized midwall creep strains for HT9, ignoring stress-enhancement of swelling.

sectioned to produce two rings approximately 7.5 mm in length, one from each side of the axial center line. Each ring was then sliced in half, and the density of

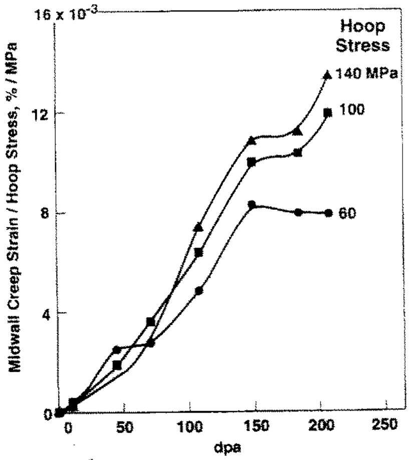

Fig. 4. Stress normalized midwall creep strains for 9Cr-1Mo, ignoring stress-enhancement of swelling.

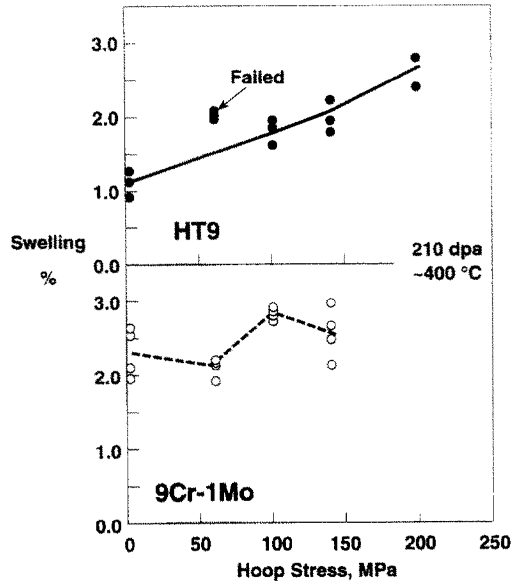

Fig. 5. Swelling measured for individual tube segments at 208 dpa.

each of the four half-sections was determined using an immersion density technique known to be accurate to $\pm 0.2\%$ change in density. Upon sectioning, it was found that the HT9 tube at 60 MPa contained some sodium, indicating that a small unnoticed failure had occurred earlier in the irradiation sequence. Thus, this tube was unpressurized for some unknown period.

3. Results and discussion

Fig. 1 presents both the total diametral strain and midwall creep strain for HT9, and Fig. 2 presents the

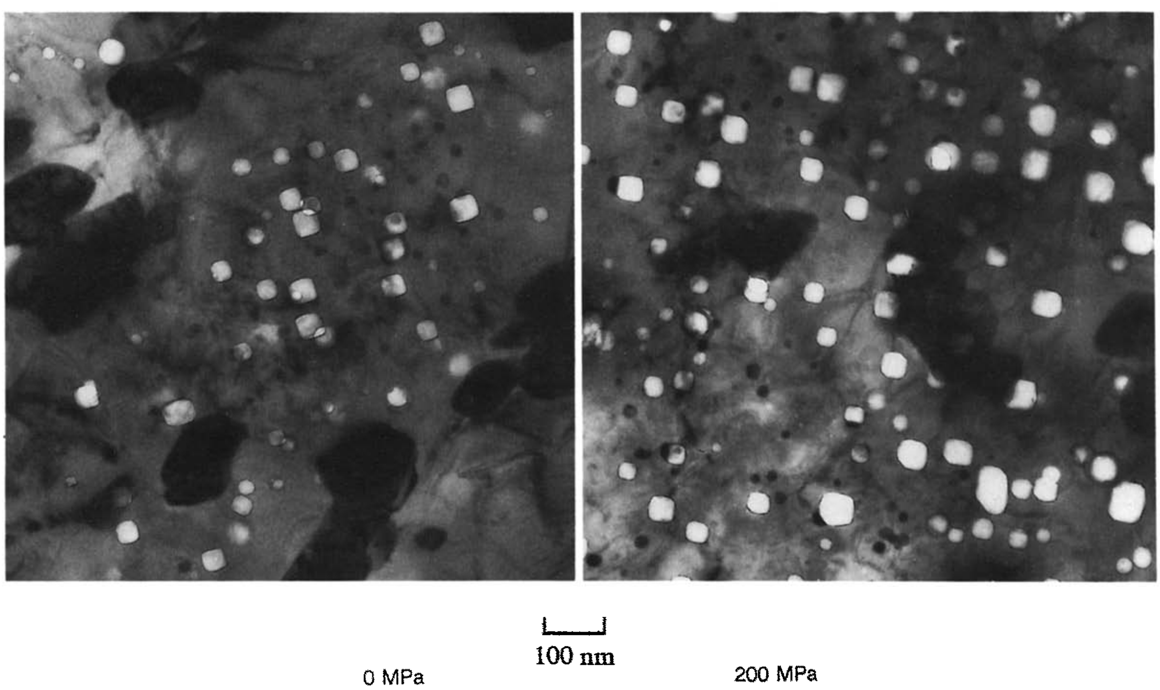

Fig. 6. Void microstructures observed at hoop stresses of 0 and 200 MPa in HT9 after irradiation at ~ 400°C to 208 dpa.

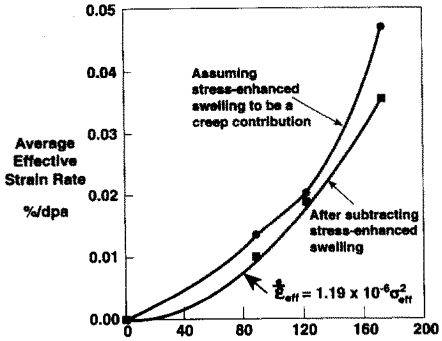

Fig. 7. Comparison of creep strains for HT9 at 208 dpa, calculated using both stress-free and stress-affected swelling.

strains for 9Cr–1Mo. The midwall creep strain is calculated using the traditional assumptions that the strain at zero stress arises only from void swelling, and that swelling is isotropic and unaffected by stress.

The strains observed in 9Cr–1Mo exhibit some complexity, especially at higher fluence. Since such complexity was not observed in HT9, and both sets of tubes were irradiated together, it is assumed that the origin of the complexity is related to a material difference from HT9, rather than some artifact of reactor history. Note that the 0.8% linear swelling strain at zero stress for 9Cr–1Mo is somewhat larger than that of HT9 at 0.35% and implies swelling levels of 2.4 versus 1.1 vol%.

When the midwall creep strains are normalized to their respective hoop stresses and the possibility of stress-enhanced swelling is ignored, it is obvious that the response to stress of HT9 is quite non-linear as shown in Fig. 3. Fig. 4, however, demonstrates that the stress exponent of 9Cr–1Mo is only slightly greater than 1.0 to doses of ≤ 150 dpa. Above 150 dpa the complexity of response mentioned earlier dominates the normalized creep behavior of 9Cr–1Mo.

As shown in Fig. 5, the swelling strains measured by immersion density at 208 dpa show that at zero stress, the swelling strains of 9Cr–1Mo and HT9 are somewhat variable for the four different tube segments, with mean values of $\sim 2.3 \pm 0.3$ and 1.2 ± 0.1 vol%, respectively. The mean values agree very well with the swelling values deduced from diameter changes, however. While the swelling of 9Cr–1Mo appears to be only slightly sensitive to stress level, there is a fairly large effect of stress on the swelling of HT9, increasing from $\sim 1.2\%$ at 0 MPa to $\sim 2.6\%$ at 200 MPa. Since the 60 MPa tube failed, its density was discounted as not being stress-enhanced throughout the irradiation.

Microscopy examination confirmed that void swelling indeed had occurred by 208 dpa and was accelerated by stress, as demonstrated in Fig. 6. If all the density change is ascribed to voids, this implies that the average swelling rates in this experiment were $\leq 0.012\%$/dpa.

Since the influence of stress-enhanced swelling can only be assessed at 208 dpa, it was ignored in deriving the stress-normalized creep rates shown in Fig. 3 and 4. The impact of including the stress enhancement at 208 dpa can be seen to be relatively small, however, as shown in Fig. 7. The stress exponent for HT9 appears to be ~ 2.

If we assume that stress enhancement for 9Cr–1Mo is small enough that it can be ignored, and that the creep rate responds linearly with stress, then we can obtain creep coefficients for the $\bar{\dot{\varepsilon}}/\bar{\sigma} = B_0 + D\dot{S}$ creep model [3], where $\bar{\dot{\varepsilon}}$ is the effective strain rate, $\bar{\sigma}$ is the effective stress, B_0 is the creep compliance, D is the creep–swelling coupling coefficient and $\dot{S}$ is the instantaneous swelling rate. Using this approach, the derived values for B_0 and D are on the order of 0.5×10^{-6} MPa^{-1} dpa^{-1} and $0.7–1.0 \times 10^{-2}$ MPa^{-1}, respectively. This B_0 value agrees rather well with the 0.44×10^{-6} value obtained for the ferritic steels EM10 and EM12 at 400–490°C in the PHENIX reactor [4], and the D coefficient is comparable to the values near 0.6×10^{-2} MPa that are routinely observed in austenitic steels [5].

4. Conclusions

Irradiation of HT9 and 9Cr–1Mo to very high neutron exposure at ~ 400°C confirms the inherent swelling resistance of this class of steels, although the application of high stress levels accelerates swelling somewhat. The irradiation creep rate of 9Cr–1Mo is roughly linear with stress and comparable to that of other ferritic steels. The creep rate of HT9, however, exhibits a stress exponent of ~ 2 at this temperature.

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