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Tensile response of low activation ferritic steels irradiated in ORR at temperatures in the range 60–400 °C

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Abstract

Post-irradiation tensile test results are reported for a series of low activation steels containing manganese following irradiation in the Oak Ridge Reactor at 60, 200, 330 and 400 °C to ~10 dpa. Alloy compositions included 2Cr, 9Cr and 12Cr steels with V to 1.5% and W to 1.0%. Strengths are higher in all alloys for irradiation conditions below 400 °C, with peak hardening occurring following irradiation at 200 °C. The 9Cr alloy class exhibited the smallest increases in hardening. Test results were consistent with previous results obtained on fast flux test facility-irradiated specimens. Manganese does not appear to play a role in the hardening observed at these low irradiation temperatures.

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1. Introduction

Low activation martensitic steels are being considered for structural applications in fusion reactors. Significant hardening results from irradiation of these steels at temperatures of 400 °C following irradiation in fast reactors, but few tests are available for material irradiated at lower temperatures. Post-irradiation tensile test response has been reported for the present series of ferritic/martensitic steels containing manganese following irradiation in fast flux test facility (FFTF), Richland, WA at 420 and 585 °C to 15 and 45 dpa [1]. That work investigated the response of a series of alloys including 2% Cr alloys with V additions, and 9% and 12% Cr alloys containing Mn with V and W additions. It was found that irradiation at 420 °C to 15 dpa produced significant hardening in the 2Cr alloys whereas the other alloys were unaffected, and irradiation at 585 °C produced softening for all alloys. Further irradiation to 45 dpa resulted in either little change or in softening. Similar specimens irradiated in the Oak Ridge Reactor (ORR), Oak Ridge, TN at 60, 200, 330 and 400 °C to 10 dpa were recently retrieved and provide excellent basis for comparison with that work, given a similar irradiation dose and an overlap in the temperature range of 400 °C, but allowing extension to significantly lower temperatures.

2. Experimental procedure

Compositions and identification codes for specimens irradiated in the ORR-MFE 6J and 7J tests are provided in Table 1. Specimens were of SS-3 flat tensile geometry, with nominal gauge dimensions of 0.3″ × 0.030″ × 0.060″ (7.62 mm × 0.76 mm × 1.5 mm). Tests were performed at both room temperature and the nominal irradiation temperatures. The initial strain rate was 4×10^{-4}/s. The 6J test for irradiation at 60 and 200 °C accumulated a midplane fluence of 2.4×10^{22} n/cm^2 (total) or 8.8×10^{21} n/cm^2 ($E > 0.1$ MeV) and the 7J test for irradiation at 330 and 400 °C accumulated a midplane fluence of 2.7×10^{22} n/cm^2 (total) or 9.5×10^{21} n/cm^2 ($E > 0.1$ MeV) [2,3]. This corresponds to damage levels of 6.6– 6.8 and 7.1–7.3 dpa, respectively, variations corresponding to lower or higher chromium levels. Predicted helium levels are 2.1–2.3 appm for both tests, with

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Table 1
Compositions and identification codes for specimens irradiated in the ORR-MFE 6J and 7J tests with commercial alloy information included for comparison [1]

ID code	Heat # or alloy name	Composition (w/o)								
		Cr	V	W	Ta	Mo	C	Mn	Nb	Ni
TE	V02262	2.32	0.50	–	–	–	0.086	–	–	–
TZ	UC-19	2.46	1.50	–	–	0.2	0.11	0.30	–	–
	2.25Cr1Mo	2.25	0.03	–	–	1.0	0.1	0.5	–	–
TR	V02268	8.82	0.27	0.89	–	–	0.101	2.44	–	–
TM	V02264	9.13	0.52	–	–	–	0.096	–	–	–
TP	V02266	9.02	0.51	–	–	–	0.097	2.68	–	–
TN	V02265	9.14	1.23	–	–	–	0.197	1.08	–	–
	9Cr1Mo	8.75	0.2	–	–	0.9	0.1	0.5	0.08	–
TT	V02702	12	0.2	0.8	–	–	0.1	6.5	–	–
TU	V02269	11.81	0.28	0.89	–	–	0.097	6.47	–	–
TW	V02754	12	0.3	1.0	0.2	–	0.1	6.5	–	–
TL	V02267	12.19	1.05	–	–	–	0.089	6.47	–	–
TF	V02700	12	1.0	–	–	–	0.1	6.5	–	–
TX	V02755	12	1.0	0.2	0.2	–	0.1	8.0	–	–
	HT9	12	0.3	0.5	–	1.0	0.2	0.6	–	0.5

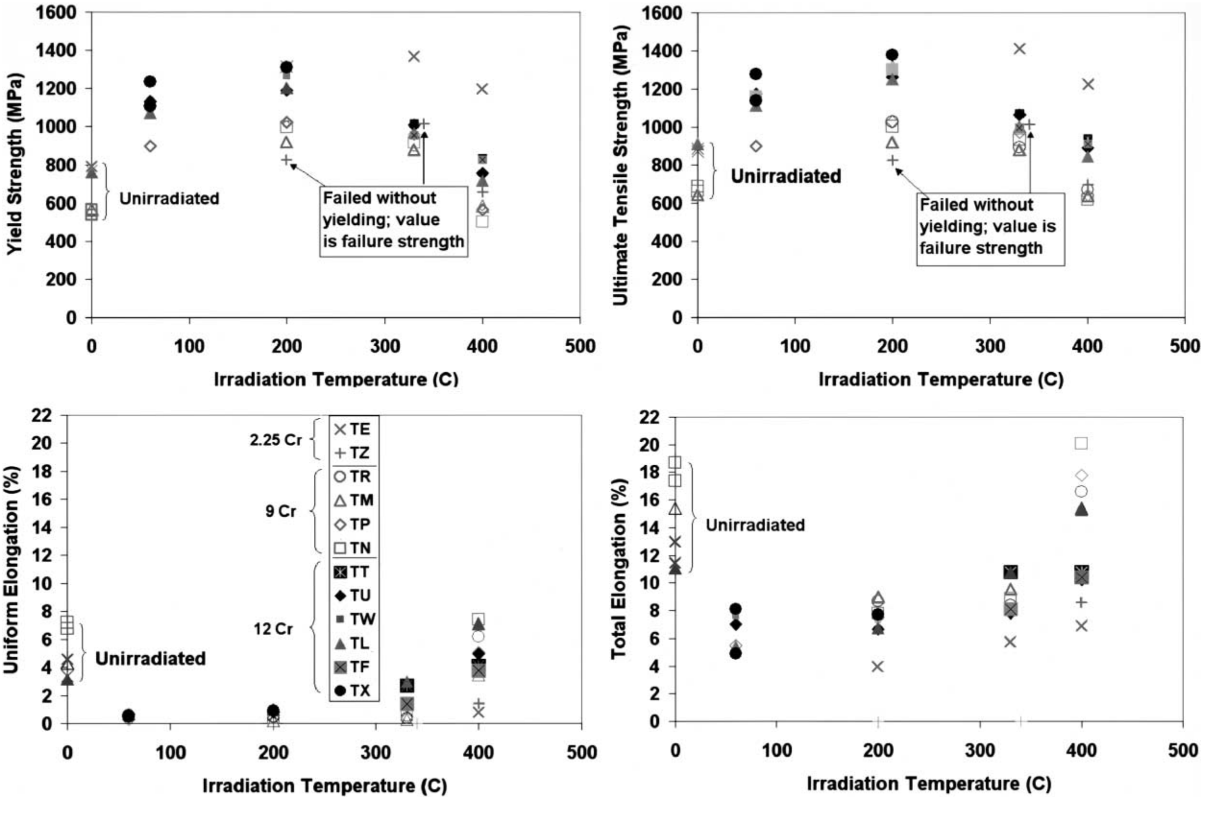

Fig. 1. Mechanical properties of low activation alloys at room temperature after irradiation in ORR.

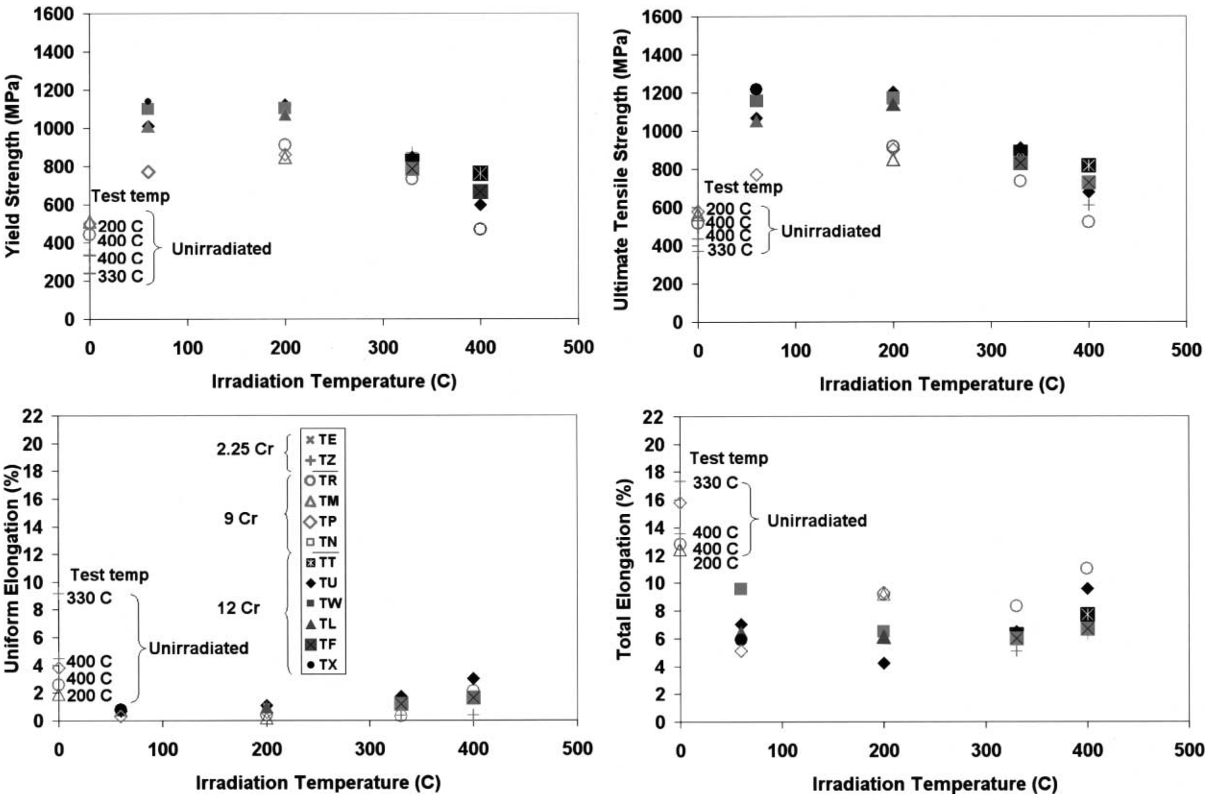

Fig. 2. Mechanical properties of low activation alloys at the irradiation temperature after irradiation in ORR.

variations due to higher or lower chromium levels, respectively.

3. Results

The tensile results can be found tabulated in Ref. [4] and are plotted in Figs. 1 and 2. Fig. 1 shows behavior for room temperature tests and Fig. 2 gives results for tests at the irradiation temperature with control tests marked to indicate test conditions. Several plots have been annotated to show behavior more clearly as a function of Cr content. Significant hardening and loss of ductility were observed at room temperature in all three alloy classes for irradiation at 330 °C and below. Relative trends as a function of Cr match behavior prior to irradiation except for low Cr alloys irradiated at 330 and 400 °C where hardening can be very large. Similar trends were observed in tests conducted at the irradiation temperature, although the results are less well-defined because of the paucity of data on unirradiated material. From these figures, it can be concluded that irradiation induced hardening appears worst following irradiation at 200 °C but elongation values are worse following irradiation at 60 °C.

4. Discussion

Tensile data obtained on FFTF-irradiated specimens are comparable to the data obtained for specimens irradiated in ORR under similar conditions. A number of materials were duplicated in those experiments at about 400 °C to 10 dpa and tested at room temperature. Yield and ultimate tensile strengths, and uniform and total elongations, were essentially the same following irradiation in FFTF and ORR for two of the 2Cr alloys (TE[V02262] and TZ[UC-19]), four of the 9Cr alloys (TN[V02265], TR[V02268], TP[V02266] and TM[V02264]), and a single 12Cr alloy (TU[V02269]) [1]. Therefore, spectral differences between the two reactors do not appear to have any effect. As a class, the 9Cr alloys exhibit the most stable properties. However, irradiation in ORR demonstrates that significant hardening can occur following irradiation at low temperatures. Property degradation is worse following

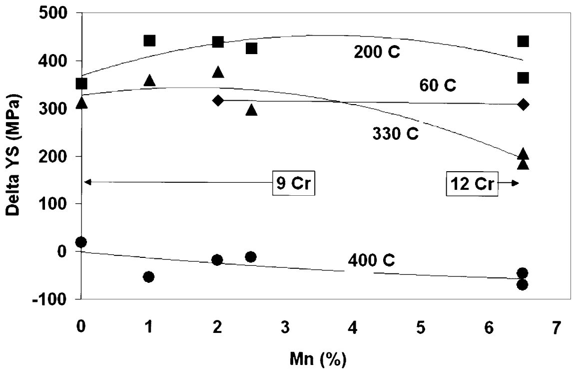

Fig. 3. Effect of Mn on hardening as an increment to yield stress observed in low activation alloys at room temperature after irradiation in ORR.

irradiation at 200 °C, but irradiation at 60 °C produces similar behavior for the 12Cr alloys. However, it can be anticipated that irradiation to higher dose at 60 °C can be expected to degrade properties further [5], and therefore it appears worthwhile to continue this work by testing identical specimens from ORR that were further irradiated in the high flux isotope reactor.

The results of this study can be used to define the consequences of transmutation induced Mn on mechanical properties. It has been noted that the alloy series being studied in this effort contains manganese additions for austenite stabilization, that manganese is created by transmutation during irradiation and that manganese additions are understood to cause chi phase formation during irradiation at about 400 °C [6], leading to embrittlement as evidenced by an increase in the DBTT and a change in fracture mode from transgranular to intergranular [7]. It was therefore expected that the hardening observed in the 9 and 12Cr alloys at 330 °C and below that appears in Fig. 1 could also be due to precipitation of chi phase. Further evaluation of the results are provided in Fig. 3, showing change in yield strength as a function of Mn content. No direct correlation is apparent between irradiation hardening and Mn content. The differences in behavior between 9 and 12Cr alloys following irradiation at low temperatures therefore correspond to differences present prior to irradiation. Chi phase formation does not lead to hardening at low irradiation temperatures and the correlation of DBTT with Mn content is only due to the effect of chi phase on grain boundary degradation rather than hardening. In fact, the observed differences in hardening were present prior to irradiation.

5. Conclusions

ORR and FFTF irradiations under comparable conditions (400 °C, to ∼10 dpa) appear to produce similar changes in tensile behavior for a series of low activation alloys containing Mn additions. Significant hardening and loss of ductility resulted from irradiation at temperatures ranging from 60 to 330 °C. The hardening cannot be attributed directly to Mn additions, indicating that chi phase does not cause the hardening.

References

[1] D.S. Gelles, M.L. Hamilton, J. Nucl. Mater. 148 (1987) 272.

[2] L.R. Greenwood, Fusion Reactor Materials, Semiannual Progress Report for Period Ending 31 March 1989, DOE/ER-0313/6, Oak Ridge National Laboratory, Oak Ridge, TN, 1989, p. 23.

[3] L.R. Greenwood, Fusion Reactor Materials, Semiannual Progress Report for Period Ending 31 March 1990, DOE/ER-0313/8, Oak Ridge National Laboratory, Oak Ridge, TN, 1990, p. 34.

[4] M.L. Hamilton, D.S. Gelles, Fusion Reactor Materials, Semiannual Progress Report for Period Ending 30 June 1999, DOE/ER-0313/26, Oak Ridge National Laboratory, Oak Ridge, TN, 1999, p. 102.

[5] W.L. Hu, D.S. Gelles, in: F.A. Garner, C.H. Henager Jr., N. Igata (Eds.), Influence of Radiation on Material Properties: 13th International Symposium, ASTM STP 956, American Society for Testing and Materials, Philadelphia, PA, 1987, p. 83.

[6] D.S. Gelles, W.L. Hu, Fusion Reactor Materials, Semiannual Progress Report for Period Ending 31 September 1986, DOE/ER-0313/1, Oak Ridge National Laboratory, Oak Ridge, TN, 1987, p. 251.

[7] M.L. Hamilton, L.E. Schubert, D.S. Gelles, in: R.K. Nanstad, M.L. Hamilton, F.A. Garner, A.S. Kumar (Eds.), Effects of Radiation on Materials: 18th International Symposium, ASTM STP 1325, American Society for Testing and Materials, W. Conshohocken, PA, 1999, p. 931.