ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1222–1227

journal of nuclear materials

Impact behavior of two low activation steels after irradiation to ~67 dpa at 430°C

M.L. Hamilton [a,*], L.E. Schubert [b], D.S. Gelles [a]

[a] Pacific Northwest National Laboratory, MS P8-15, P.O. Box 999, Richland, WA 99352 USA

[b] ARINC, Oklahoma City, OK 73135, USA

Abstract

Miniature CVN specimens of four martensitic steels, GA3X, F82H, GA4X and HT9, have been impact tested following irradiation at 430°C to 67 dpa. Comparison of the results with those obtained previously at lower doses indicates that the GA3X and F82H alloys, two primary candidate low activation alloys, exhibit similar behavior following irradiation at 430°C to ~67 dpa and at 370°C to ~15 dpa. Virtually no shift in either ductile to brittle transition temperature (DBTT) or upper shelf energy (USE) was observed in the F82H alloy at 67 dpa for either notched or precracked specimens. This absence of a shift in DBTT and USE in F82H compares with a slight increase in DBTT and a slight decrease in USE for GA3X, and much larger degradation in both properties in GA4X and HT9. The shifts in DBTT and USE observed in both GA4X and HT9 were smaller after irradiation at 430°C to ~67 dpa than after irradiation at 370°C to ~15 dpa.

1. Introduction

Reduced activation ferritic/martensitic steels are being considered for structural applications in potential fusion energy systems. One of the issues associated with the use of such a steel is the potential for embrittlement during irradiation at relatively low temperatures. This embrittlement is evidenced as an increase in the temperature at which the steel makes a transition from ductile (high energy) to brittle (low energy) fracture, and a drop in the energy required to cause ductile fracture, when loaded under impact conditions.

Two low activation ferritic steels have been identified for application as structural materials in a fusion reactor. These are F82H and GA3X, in the 7–9Cr range, strengthened by additions of W. F82H is a Japanese steel that possesses excellent toughness and radiation resistance, while GA3X is a similar material developed in the United States. The objective of this work was to evaluate the effects of neutron irradiation in these low activation ferritic alloys by examining both the shift of the ductile to brittle transition temperature (DBTT) and the reduction of the upper shelf energy (USE) in miniature Charpy V-notch (CVN) specimens that occurs with irradiation to high dose levels at low temperatures.

2. Experimental procedure

Miniature (one-third size) charpy impact specimens of four alloys were included in irradiation experiments in the FFTF, where they were irradiated in the Materials Open Test Facility (MOTA) to 15 dpa at 370°C and to 67 dpa at 430°C. The alloys included F82H, GA3X, GA4X, and HT9. The first 3 alloys are low activation alloys containing 7.5Cr, 9Cr and 11Cr, respectively. HT9 is the reference 12Cr steel that was included for comparison; it is a similar martensitic steel without reduced activation properties. Nominal alloy compositions are 7.5Cr–2W for F82H, 9Cr–2W for GA3X, 11Cr–2W for GA4X, and 12Cr–1Mo–0.5W for HT9. Each alloy also contains 0.2–0.3V, and F82H also contains nominally a small amount of tantalum. General Atomics supplied a small experimental heat of F82H for this irradiation.

* Corresponding author. Tel.: +1 509 376 3192; fax: +1 509 376 0418; e-mail: ml_hamilton@pnl.gov.

0022-3115/98/$19.00
PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 1 8 9 - 5

Previous reports [1–3] on six low activation ferritic alloys described the experimental procedures. The specimens utilized were about one third the size of the ASTM standard CVN specimen [4]. Specimens of two of the alloys (GA3X and HT9) were fatigue precracked before irradiation. The GA4X was expected to exhibit a duplex microstructure; therefore precracking of the specimens of this alloy was not conducted. The F82H specimens were not precracked prior to irradiation.

Impact testing was performed on these specimens, and the data are presented below. Impact tests were conducted inside a hot cell using a remotely operated vertical drop tower. The fracture energy was calculated from the load versus time record of each impact. The method of calculation and data analysis, as well as the details of the system, have been described previously [3,5–7]. Temperature control for these tests is described in the references cited and is estimated at an accuracy of ±3°C. This value should be doubled for temperatures below −100°C due to difficulties associated with testing at very low temperatures.

3. Results

Tests were conducted on each alloy over a range of temperatures in order to establish full DBTT curves. The data are plotted in Figs. 1–4 along with the data from control specimens, and also with data from the specimens tested after the previous irradiation at 370°C to ~15 dpa. Of these four alloys, the two higher chromium alloys, HT9 and GA4X, exhibited large increases in the DBTT and a significant drop in the USE when compared to the control data, but the degradation exhibited in HT9 and GA4X after irradiation at 430°C was not as severe as was exhibited after irradiation at 370°C. For the two alloys with lower chromium content, the GA3X exhibited the same DBTT as after irradiation at 370°C to ~15 dpa, but it had a somewhat lower USE. The USE determined for the GA3X at the 15 dpa level was ~20% greater than the control data. The USE determined for the GA3X at the 67 dpa level had decreased ~10% from the 15 dpa USE value, but it was still about 10% above the USE value for the unirradiated control specimens. The results obtained on the F82H specimens were qualitatively the same for both irradiation conditions, but since the previously tested specimens were precracked and the current specimens were only notched, quantitative comparison is not possible. The results of the notch-only specimen tests indicate essentially the same behavior both for the unirradiated control specimens and for the specimens irradiated to 67 dpa.

4. Discussion

Impact tests have also been performed on other low activation ferritic alloys and a comparison is shown in Fig. 5 for data obtained on a similar 9Cr–2WVTa alloy irradiated at ~365°C to ~15 dpa [8]. Note that these data were obtained on notched specimens rather than precracked specimens and that the alloy contained ~2–3 times as much tantalum as F82H. The figure shows that while the impact behavior of the alloys was virtually

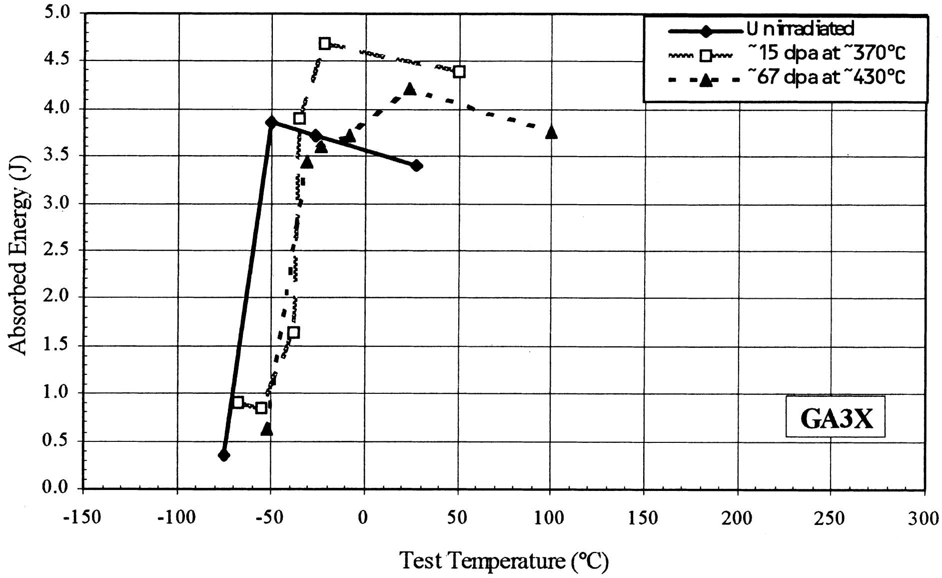

Fig. 1. Test results of impact tests of precracked, miniature CVN specimens of alloy GA3X, Fe–0.15C–9.0Cr–2.0W–0.3V.

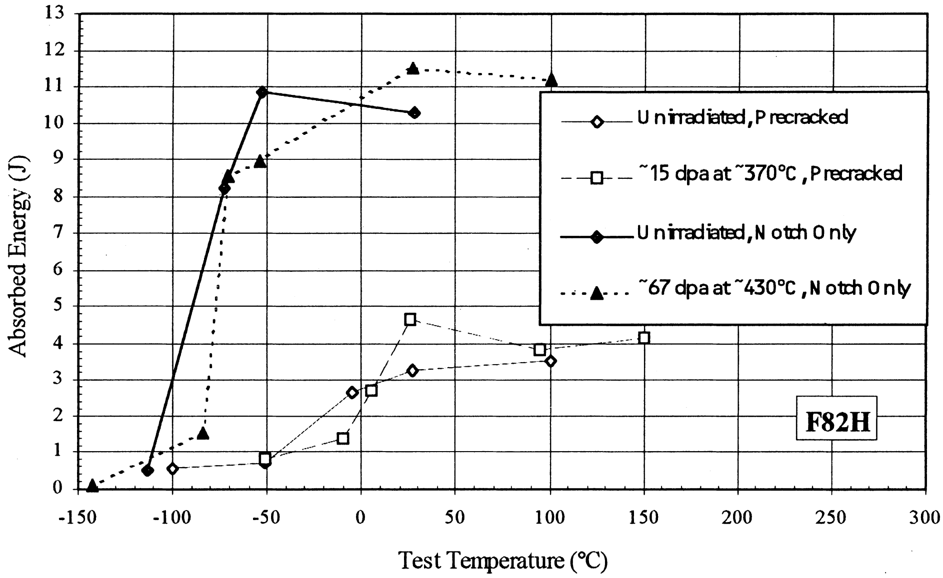

Fig. 2. Test results of impact tests of precracked and notch-only, miniature CVN specimens of alloy F82H, Fe–0.10C–7.8Cr–2.0W–0.5Mn–0.2V.

identical in the unirradiated condition, the 9Cr–2WVTa alloy exhibited a DBTT shift of ~30°C (using notched specimens) while the F82H exhibited virtually no shift (using precracked specimens). The major difference between these two alloys is the increase in the tantalum level in 9Cr–2WVTa. Thus there appears to be reason to speculate that the larger DBTT shift in the 9Cr–2WVTa alloy might result from increased tantalum.

Note that GA3X was designed to be a 9Cr alloy. The current work reports results of tests conducted on a 9Cr heat of GA3X, although the results reported in Ref. [1] were obtained from specimens of an experimental heat of GA3X produced by General Atomics which had only 7.5Cr. Impact data for the unirradiated condition of the 7.5Cr heat of GA3X are compared in Fig. 6 to similar data from the 9Cr heat of GA3X and F82H. The data in

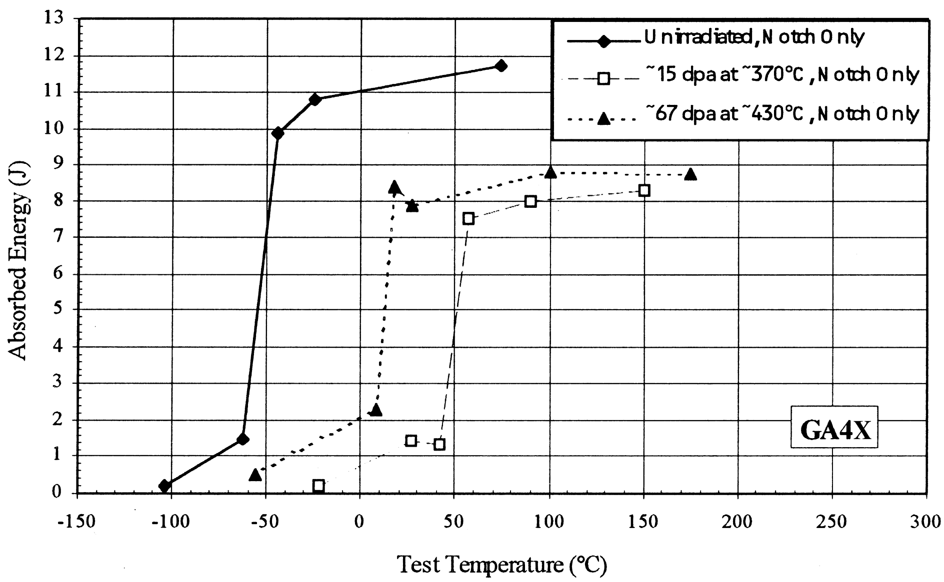

Fig. 3. Test results of impact tests of miniature CVN specimens of alloy GA4X, Fe–0.14C–11.0Cr–2.0W–0.3V

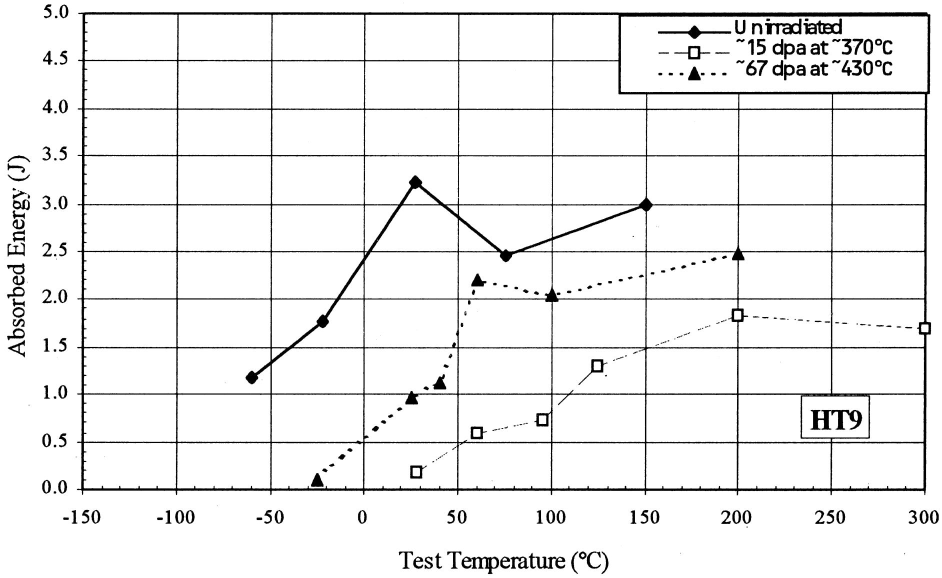

Fig. 4. Test results of impact tests of precracked, miniature CVN specimens of alloy HT9, Fe–0.20C–12.1Cr–1.0Mo–0.6Mn–0.5Ni–0.5W–0.3V.

this figure suggest that the presence of 9Cr will promote a lower DBTT and perhaps a lower USE than 7.5Cr. Data on irradiated specimens of the same alloys are shown in Fig. 7, for previous irradiations of this material conducted below the FFTF core at 370°C to ~15 and also to ~30 dpa. These data support the apparent superiority of 9Cr relative to 7.5Cr.

5. Conclusions

Impact tests were performed on four ferritic alloys irradiated at 430°C to ~67 dpa in order to evaluate changes in the impact behavior of reduced activation alloys. Impact property degradation was no different in the 7–9Cr low activation alloys than had been observed

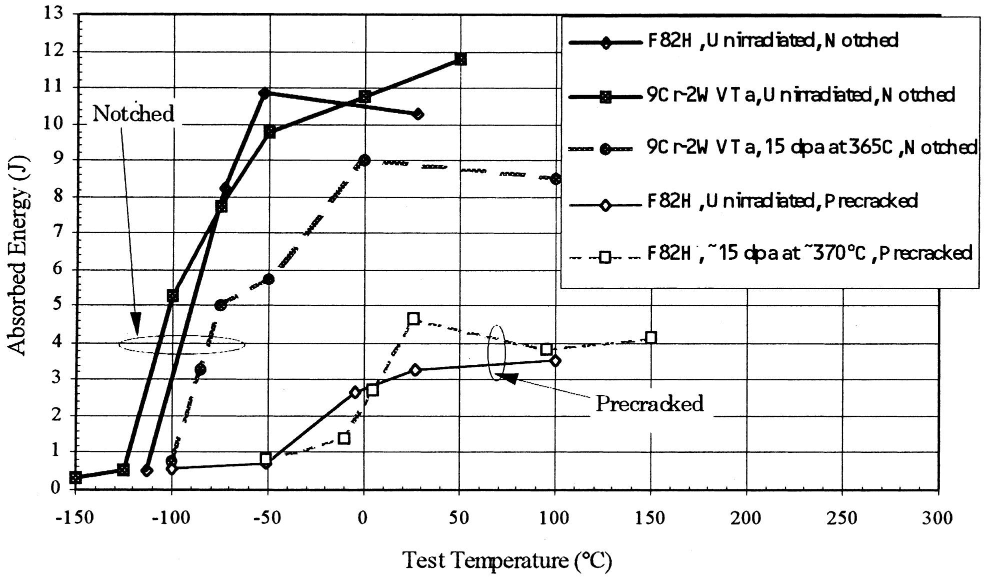

Fig. 5. Comparison between impact data from F82H and 9Cr–2WVTa.

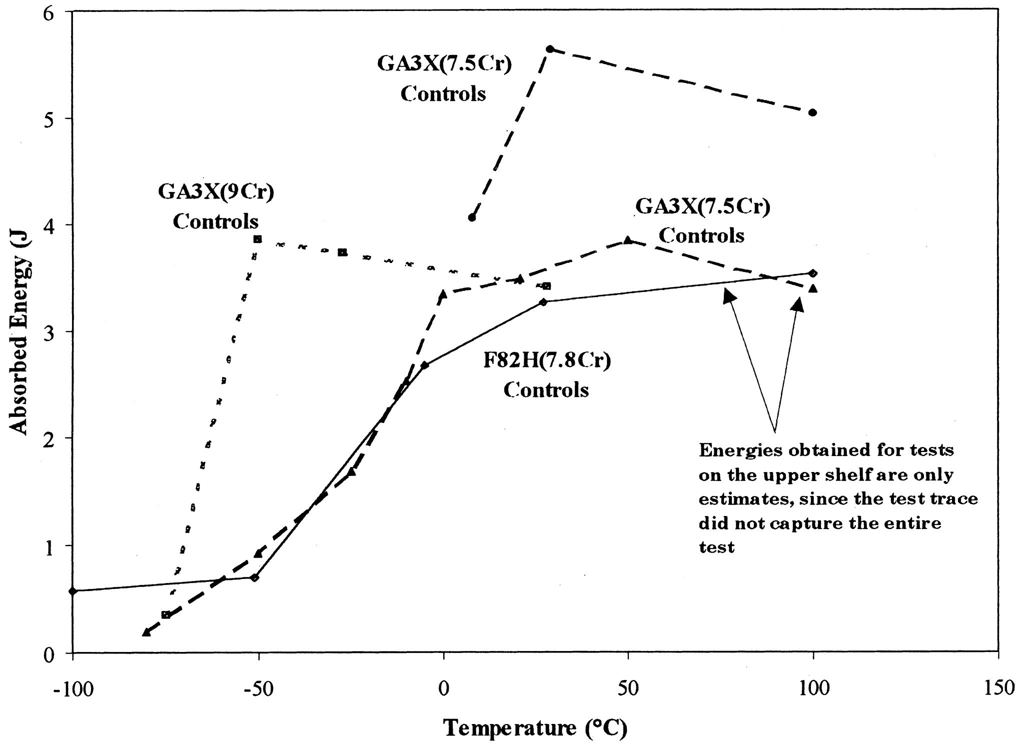

Fig. 6. Effect of chromium level on the impact data of unirradiated GA3X. Note that there are two sets of control data for 7.5Cr GA3X. The smaller USE values are estimates from extrapolated, incomplete traces from tests on the upper shelf. The larger USE values were obtained from more recent tests where the complete trace was obtained. The extrapolated values are included since the same extrapolation technique was used to estimate the USE values for the F82H tests.

after irradiation at 370°C to ~15 dpa, and was minimal. Degradation in the 11–12Cr alloys was more significant, but less degradation was observed than after irradiation at 370°C to ~15 dpa. The results support earlier conclusions that the impact behavior of the GA3X and F82H alloys is superior to that of the GA4X and HT9

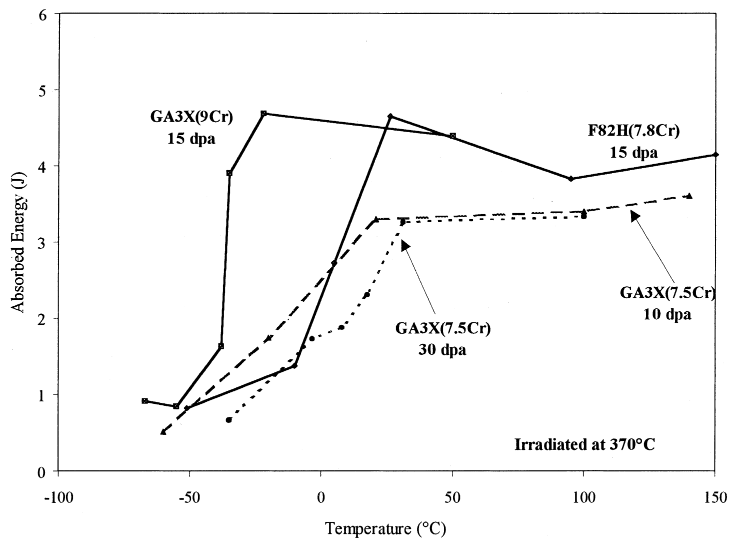

Fig. 7. Effect of chromium level on the impact behavior of irradiated GA3X.

alloys. On the basis of the impact data, both the GA3X and F82H alloys appear to warrant further consideration as potential structural materials in fusion reactors. Finally, a chromium content of about 9% appears to be produce better impact properties than does 7.5Cr for Fe–Cr–W/V ferritic alloys.

References

[1] L.E. Schubert, M.L. Hamilton, D.S. Gelles, Charpy Impact Test Results for Low Activation Ferritic Alloys Irradiated to 30 dpa, Fusion Reactor Materials Semiannual Progress Report for the Period Ending, 31 December 1995, DOE/ER-0313/19, p. 133.

[2] N.S. Cannon, W.L. Hu, D.S. Gelles, Charpy Impact Test Results for Low Activation Ferritic Alloys, Fusion Reactor Materials Semiannual Progress Report for the Period Ending, 31 March 1987, DOE/ER-0313/2, p. 119.

[3] L.E. Schubert, M.L. Hamilton, D.S. Gelles, Charpy Impact Test Results of Four Low Activation Ferritic Alloys Irradiated at 370°C to 15 dpa, Fusion Reactor Materials Semiannual Progress Report for the Period Ending, 30 June 1996, DOE/ER-0313/20, p. 171.

[4] Standard Test Method for Notched Bar Impact Testing of Metallic Materials, Designation: E 23, The American Society for Testing and Materials.

[5] W.L. Hu, N.F. Panayotou, Miniature Charpy Specimen Test Device Development and Impact Test Results for the Ferritic Alloy HT9, Alloy Development for Irradiation Performance Semiannual Progress Report for the Period Ending, 30 September 1981, DOE/ER-0045/7, p. 235.

[6] L.E. Schubert, Effects of Specimen Size Reduction on the Transition Curve of the Charpy V-Notch Impact Test, M.Sc. Thesis, Nuclear Engineering, UMR, May 1995.

[7] W.L. Hu, Miniature Charpy Impact Test Results for Irradiated Ferritic Alloys, Alloy Development for Irradiation Performance Semiannual Progress Report for the Period Ending, 30 September 1982, DOE/ER-0045/9, p. 255.

[8] R.L. Klueh, D.J. Alexander, J. Nucl. Mater. 233–237 (1996) 336–341.