FRACTOGRAPHIC EXAMINATION OF REDUCED ACTIVATION FERRITIC/MARTENSITIC STEEL CHARPY SPECIMENS IRRADIATED TO 30 DPA AT 370°C - D. S. Gelles and M. L. Hamilton (Pacific Northwest National Laboratory)[a] and L. E. Schubert (University of Missouri, Rolla)

OBJECTIVE

The objective of this research is to assess irradiation embrittlement in reduced activation ferritic/Martensitic steels for first wall applications in a fusion energy system.

SUMMARY

Fractographic examinations are reported for a series of reduced activation ferritic/Martensitic steel Charpy impact specimens tested following irradiation to 30 dpa at 370°C in FFTF. One-third size specimens of six low activation steels developed for potential application as structural materials in fusion reactors were examined. A shift in brittle fracture appearance from cleavage to grain boundary failure was noted with increasing manganese content. The results are interpreted in light of transmutation induced composition changes in a fusion environment.

PROGRESS AND STATUS

Introduction

Charpy impact test results have been recently reported for a series of reduced activation ferritic/Martensitic alloys irradiated in the FFTF at 370°C to 30 dpa.[1] The same alloys had been tested earlier following irradiation to 10 dpa,[2] and fractography previously reported for the earlier test specimens.[3] The purpose of the present work is to extend the interpretation of the most recent impact tests by determination of changes in fracture appearance.

Six alloys were under consideration in this series of tests, one containing 2.5% Cr, three containing 7 to 9% Cr and two containing 12% Cr, all strengthened with V and/or W, and several using Mn additions to control austenite phase stability. The recent impact test results showed that degradation in the impact behavior appears to have saturated by 10 dpa in at least four of the six alloys. The most promising of the alloys, a 7.5Cr-2W alloy referred to as GA3X, exhibited the best impact properties, with no decrease in ductile to brittle transition temperature (DBTT) or upper shelf energy (USE) between 10 and 30 dpa.

Experimental Procedure

Details concerning specimen fabrication, irradiation and testing have been previously reported.[3] Fractographic examination followed procedures developed previously.[2] However, due to space limitations, stereo pairs of fracture surfaces will not be shown, but can be obtained by request from the authors. Specimens selected for examination represent behavior at the ductile to brittle transition temperature (DBTT).

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Results

Fractographs of tested specimens are provided in Figures 1 through 6. Each figure shows the entire fracture surface at low magnification in part (a) and the central portion immediately adjacent to the fatigue precrack at higher magnification in part (b). Figure 1 shows the fracture appearance for specimen L317 of Fe-2.5Cr-1.5V-0.3Mn irradiated at 370°C to 30 dpa and tested at 300°C. The area of Figure 1b can be found in the lower center part of Figure 1a. Fracture is found to be by brittle cleavage adjacent to the fatigue precrack, but by dimple rupture in the final third of the fracture surface. This specimen can be seen to have a very large grain size, as large as 500 μm, and cleaved surfaces containing river pattern features that extend across many of the grains. The cleavage facets are unusually steeply inclined to the plane of the fracture surface. The stretch zone between the fatigue precrack and the cleaved grains is difficult to identify, indicating a very small stretch zone and corresponding crack opening displacement, but cleavage initiates somewhat below the fatigue surface in the area shown in Figure 1b.

Figure 1 Low and higher magnification fractographs of specimen L317 of Fe-2Cr-1.5V irradiated at 370°C to 30 dpa and tested at 300°C.

Figure 2 shows the fracture appearance for specimen L010 of Fe-7.5Cr-2W irradiated at 370°C to 30 dpa and tested at 8°C. Fracture is again found to be by brittle cleavage adjacent to the fatigue precrack but by dimple rupture for the remaining half of the fracture surface. The grain size is much finer, on the order of 100 μm, and a well defined stretch zone, on the order of 25 μm can be identified.

Figure 3 shows the fracture appearance for specimen L508 of Fe-9Cr-1.3V-1.1Mn irradiated at 370°C to 30 dpa and tested at -39°C. Fracture is found to be by a mixture of cleavage fracture and grain boundary decohesion in the brittle region and by dimple rupture in the remaining quarter of the specimen. The grain size is about 100 μm, and grain boundary decohesion occurs with very little surface dimpling. The ratio of grain boundary decohesion to brittle cleavage is about 50% in the area of Figure 3b and deep grain boundary wedge cracking can be seen. Stretch zone formation is probably less than 1 μm.

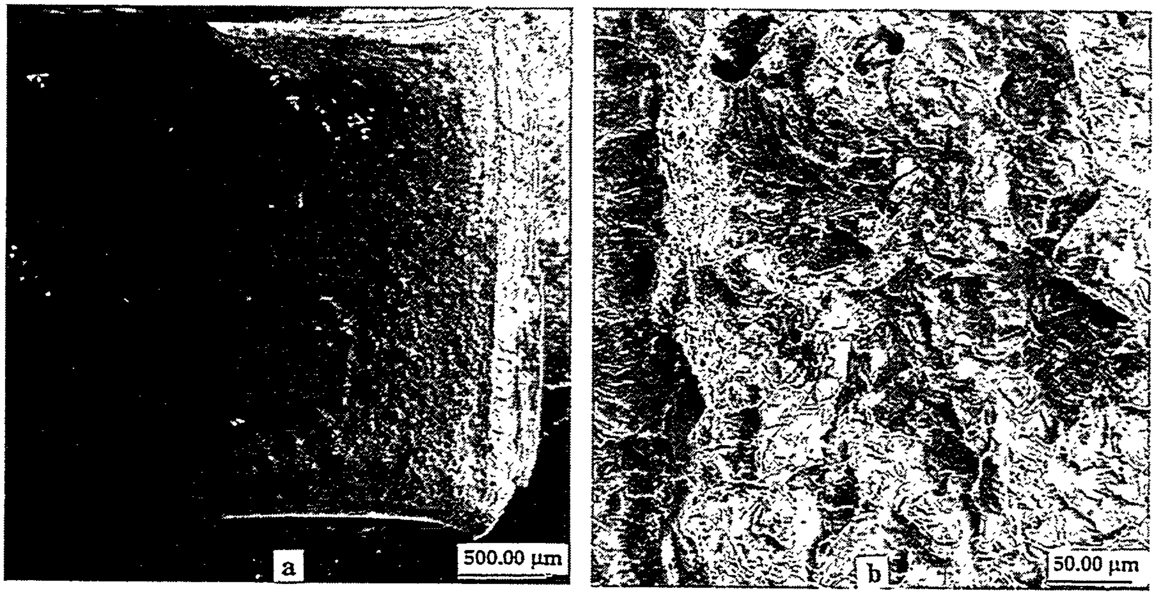

Figure 2 Low and higher magnification fractographs of specimen L010 of Fe-7.5Cr-2W irradiated at 370°C to 30 dpa and tested at 8°C.

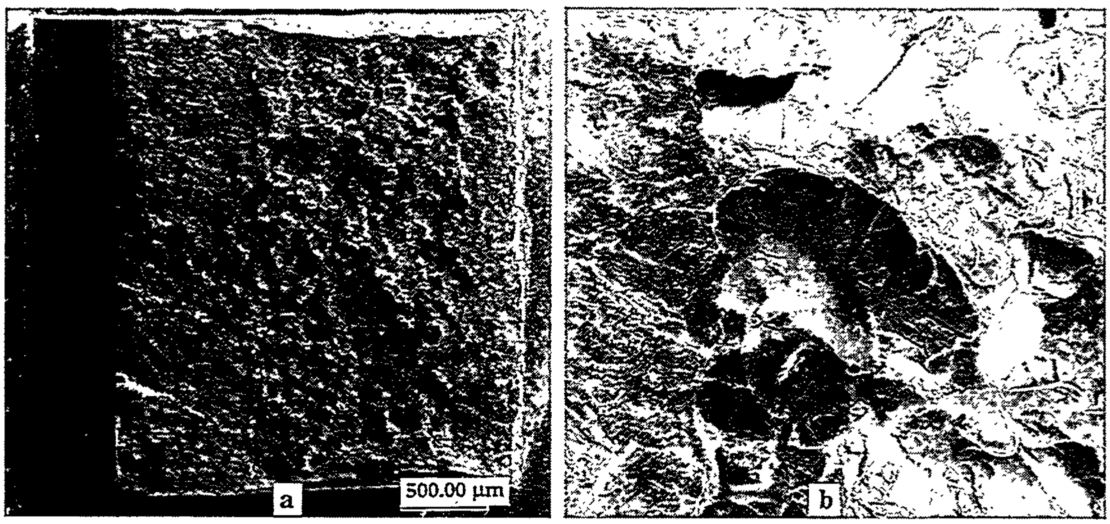

Figure 3 Low and higher magnification fractographs of specimen L508 of Fe-9Cr-1V-1Mn irradiated at 370°C to 30 dpa and tested at -39°C.

Figure 4 shows the fracture appearance for specimen L806 of Fe-9Cr-2.4Mn-1W-0.3V irradiated at 370°C to 30 dpa and tested at 65°C. Fracture is found to be predominantly by grain boundary decohesion in the brittle region and by dimple rupture in the remaining third of the specimen. The grain size is about 100 μm, and grain boundary decohesion occurs with very little surface dimpling. The ratio of grain boundary decohesion to brittle cleavage is about 90% in the area of Figure 4b and deep grain boundary wedge cracking can be seen. The stretch zone is again very narrow, with one example of grain boundary decohesion extending 30 μm back into the fatigue region, in the upper left of Figure 4b.

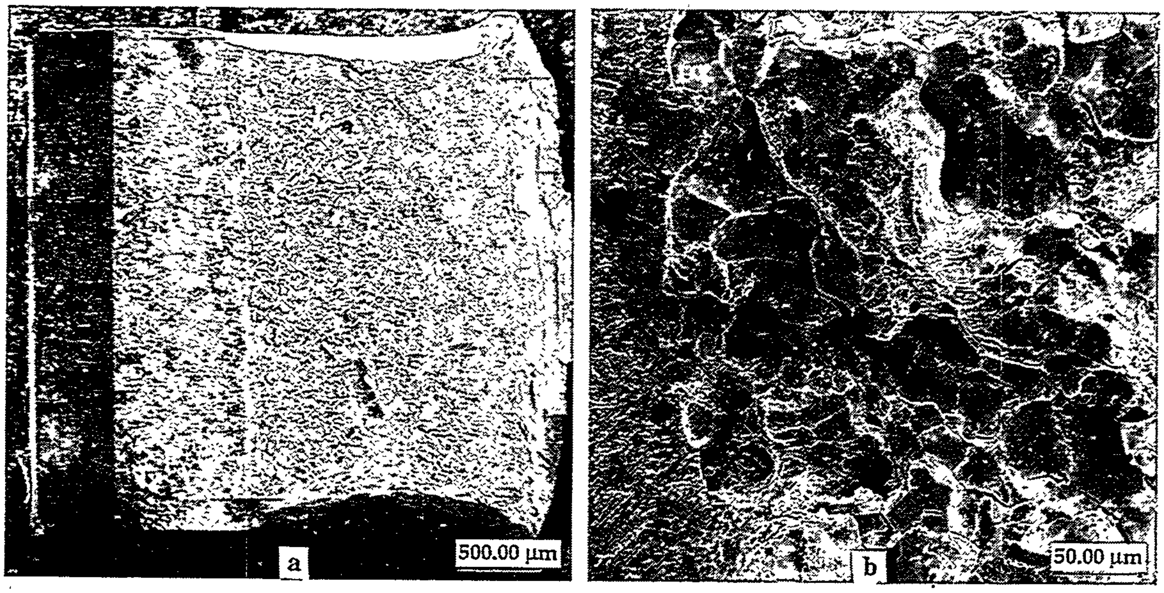

Figure 4 Low and higher magnification fractographs of specimen L806 of Fe-9Cr-1W-2Mn irradiated at 370°C to 30 dpa and tested at 65°C.

Figure 5 shows the fracture appearance for specimen L710 of Fe-12Cr-6.5Mn-1V irradiated at 370°C to 30 dpa and tested at 225°C. Fracture is found to be predominantly by grain boundary decohesion in the brittle region and by dimple rupture over half the specimen, distributed in three regions, two in small regions in the middle of the brittle region. Therefore, in this sample, fracture probably began by grain boundary decohesion, but two central regions actually failed by dimple rupture, possible before brittle fracture continued by grain boundary decohesion, followed by final ligament failure by dimple rupture. Grain boundary decohesion occurs with a fair amount of surface dimpling. The ratio of grain boundary decohesion to brittle cleavage is very high in the area of Figure 5b and deep grain boundary wedge cracking can be seen. The stretch zone is about 20 μm wide.

Figure 6 shows the fracture appearance for specimen L910 of Fe-12Cr-6.5Mn-1W-0.3V irradiated at 370°C to 30 dpa and tested at 200°C. Fracture is found to be predominantly by grain boundary decohesion in the brittle region and by dimple rupture over half the specimen, distributed in two regions, one in a band in the middle of the brittle region. Therefore, fracture probably began by grain boundary decohesion, but a central region actually failed by dimple rupture, possible before a second region failed by grain boundary decohesion. Grain boundary decohesion occurs with surface dimpling. The ratio of grain boundary decohesion to brittle cleavage is very high in the area of Figure 6b and deep grain boundary wedge cracking can be seen. The stretch zone is about 20 μm wide.

Discussion

Comparing the present fractographic results with previous results from specimens irradiated to 10 dpa[2] shows little change in response. The major difference appears to be that for the Fe-9Cr-1.3V-1.1Mn alloy L5, fracture appearance shifts from predominantly grain boundary decohesion at 10 dpa, to about 50% cleavage at 30 dpa. Thus, the reduction in DBTT of about 30°C upon irradiation from 10 to 30 dpa that was observed in this alloy may arise due to a return to cleavage fracture, probably from an overaging process. Also, specimens of Fe-12Cr-6.5Mn-1V alloy L7 and Fe-12Cr-6.5Mn-1W-0.3V alloy L9 developed regions of dimple rupture within regions that failed by brittle grain boundary decohesion following irradiation to 30 dpa that were not found after 10 dpa. However, these last

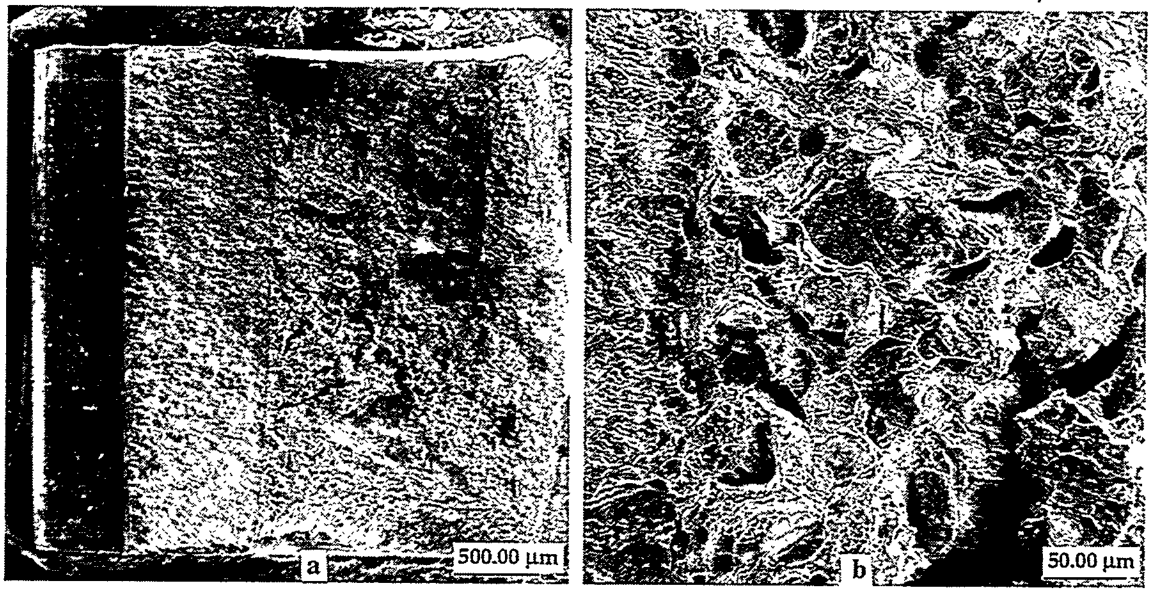

Figure 5 Low and higher magnification fractographs of specimen L710 of Fe-12Cr-6Mn-1V irradiated at 370°C to 30 dpa and tested at 225°C.

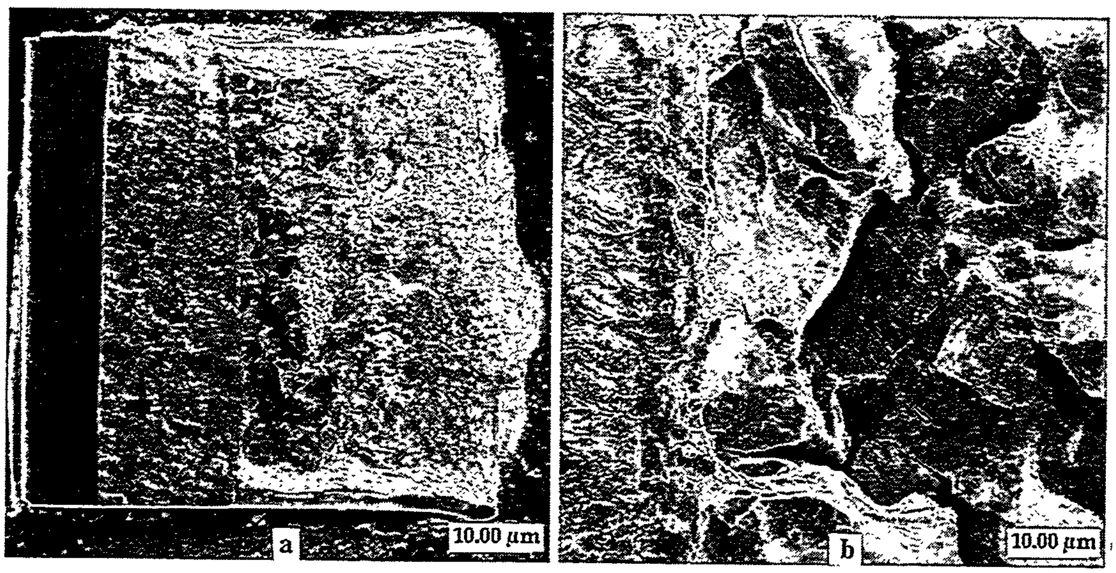

Figure 6 Low and higher magnification fractographs of specimen L910 of Fe-12Cr-6Mn-1W irradiated at 370°C to 30 dpa and tested at 200°C.

observations may arise from specimen to specimen variation and are common observations in welded samples were microstructural variation can occur on a coarse scale.

It is possible to relate change in DBTT due to irradiation in these steels with manganese content. Such a relation is anticipated based on the observation of Fe-Cr-Mn chi phase reported following irradiation.(4) Figure 7 shows shift in DBTT as a function of Mn content for all the higher chromium (7-12%) alloys. From this figure it is apparent that shifts in DBTT of about 100°C can be expected when Mn levels reach about 2% and saturation may be occurring when Mn levels exceed 5%.

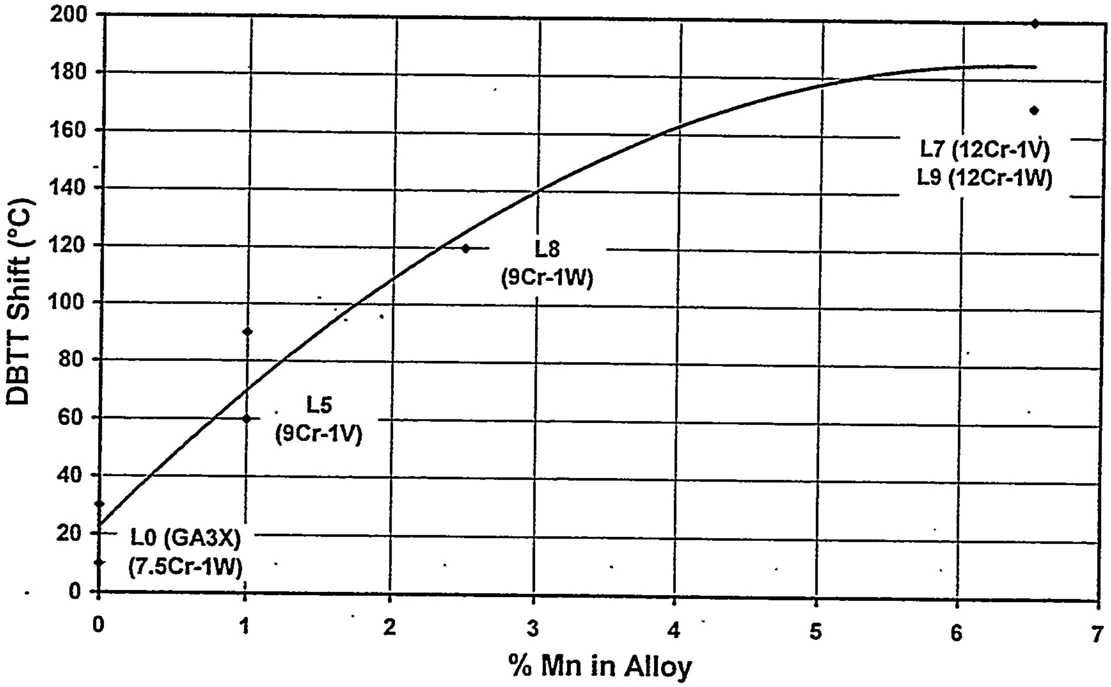

Figure 7 Shift in DBTT following irradiation at 370°C to 10-30 dpa for 7-12Cr alloys as a function of Mn content.

However, it has been predicted that Mn levels will only increase to about 1% Mn by transmutation in a ferritic alloy following irradiation in a fusion device to about 200 dpa.[5] Figure 7 predicts that the consequence will be only a 50°C increase in DBTT.

CONCLUSIONS

Fractographic examination has been performed on charpy specimens of six reduced activation alloys irradiated in the FFTF at 370°C to 30 dpa. Only minor differences were observed in comparison with a similar study following irradiation to 10 dpa, and confirm that radiation-induced embrittlement at 370°C saturates in this alloy class at low dose. Analysis of charpy results also provides a correlation between shift in DBTT and increasing Mn content. Based on this correlation, it is predicted that manganese buildup of 1% following irradiation to 200 dpa in a fusion machine will cause a DBTT shift of only 50°C.

Future work

This work is completed.

REFERENCES

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