INFLUENCE OF CARBON AND DPA RATE ON NEUTRON-INDUCED SWELLING OF Fe-15Cr-16Ni-0.25Ti IN FFTF at ~400°C - T. Okita and N. Sekimura (University of Tokyo), F. A. Garner (Pacific Northwest National Laboratory)* and W. G. Wolfer (Lawrence Livermore National Laboratory)

OBJECTIVE

The purpose of this effort is to determine the influence of dpa rate and composition on the void swelling of simple austenitic Fe-Cr-Ni alloys.

SUMMARY

Contrary to the swelling behavior of fcc Fe-15Cr-16Ni and Fe-15Cr-16Ni-0.25Ti alloys irradiated in the same FFTF-MOTA experiment, Fe-15Cr-16Ni-0.25Ti-0.04C does not exhibit a dependence of swelling on dpa rate at ~400°C. The transient regime of swelling is prolonged by carbon addition, however.

Introduction

In an earlier report it was shown that two simple, annealed austenitic alloys, Fe-15Cr-16Ni and Fe-15Cr-16Ni-0.25Ti, when irradiated in FFTF-MOTA at ~400°C over a wide range of dpa rates, exhibited a very strong influence of dpa rate on void swelling (1). While the steady state swelling rate of ~1%/dpa was unaffected by dpa rate, the transient regime was strongly affected, with a progressive shortening of the transient duration as the dpa rate decreased, as shown in Figure 1. This counterintuitive dependence was shown to be mirrored in other previously published experiments conducted on more complex commercial alloys. (2-4).

Also contained in the FFTF-MOTA experiment was Fe-15Cr-16Ni-0.25Ti-0.04C, also in the annealed condition. This allows the possibility to study the possibly synergistic effects of two important variables, dpa rate and carbon.

Experimental Details

Relatively pure Fe-15Cr-16Ni, Fe-15Cr-16Ni-0.25Ti and Fe-15Cr-16Ni-0.25Ti-0.04C (at %) with no added solute were prepared by arc melting from high purity Fe, Ni, Cr and Ti. The binary alloys was rolled to sheets of 0.25 mm thickness, cut into 3 mm disks and annealed for 30 minutes at 1050°C in high vacuum.

Two sets of identical specimens are placed in sealed, helium-filled packets at each of seven different capsule positions of the Materials Open Test Assembly (MOTA), ranging from below the core to above the core of the Fast Flux Test Facility (FFTF). The packets in general contained four identical specimens of each of the two alloys. The three alloys were located side-by-side in the same packet. Two or more identically-loaded packets were placed in each capsule, with the dpa rate dependent on the axial location in MOTA.

With the exception of the below-core canister, the temperatures in MOTA capsules are actively controlled to ±5°C of the nominal target, although the nominal target temperatures varied a little from capsule to capsule.

The first irradiation sequence occurred in Cycle 11 of MOTA-2A for 2.58×10^{7} sec, and a subset of specimen packets was then removed. Other identical specimen packets continued in Cycle 12 of MOTA-2B for 1.71×10^{7} sec. The dose rates in the various capsules ranged from 8.9×10^{-9} to 1.7×10^{-6} dpa/sec. The dose levels attained by the specimens varied from 0.23 to 43.8 dpa in Cycle 11 and an additional

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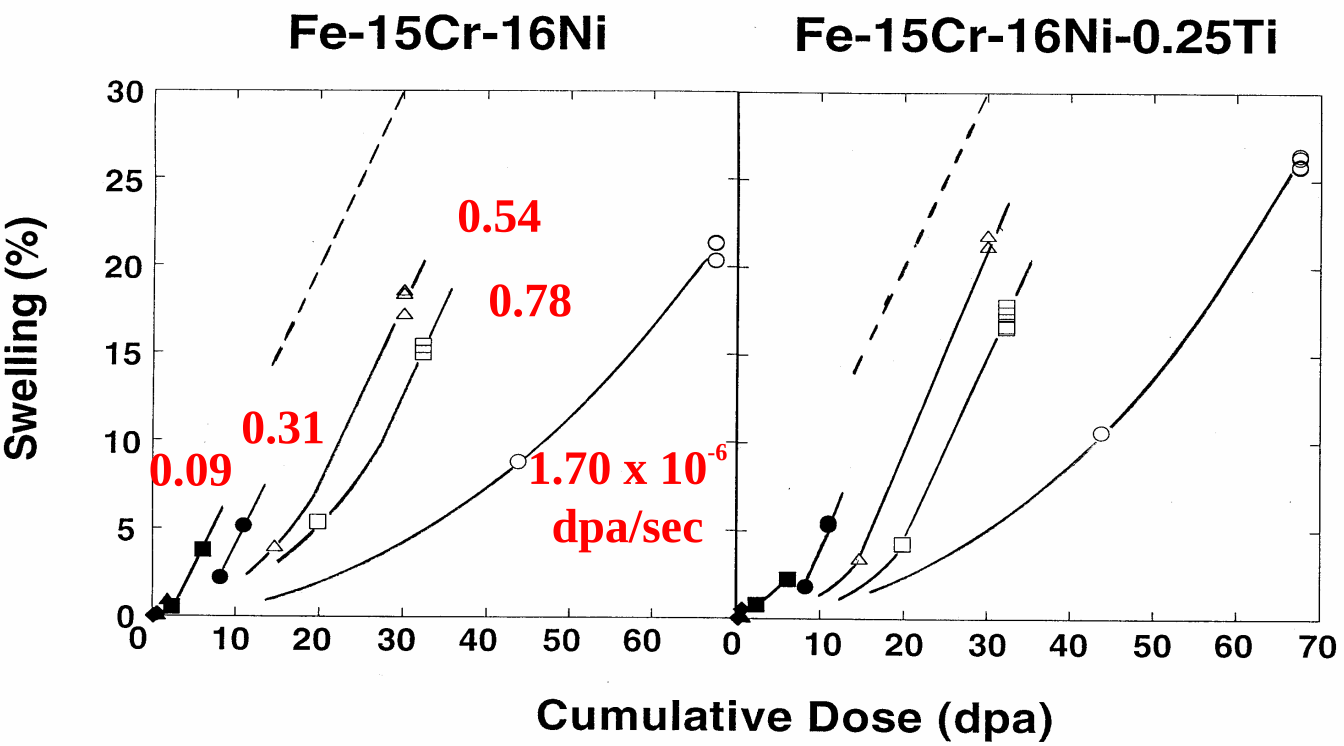

Figure 1. Swelling of simple model f.c.c. Fe-Cr-Ni alloys in FFTF-MOTA at ~400°C, as observed by Okita and coworkers (1), showing that the transient regime of swelling increases progressively as the dpa rate increases.

0.38 to 24.0 dpa in Cycle 12. Table 1 summarizes the irradiation conditions for the fourteen combinations of temperature, dpa and dpa rate.

The starting and post-irradiation densities were measured using an immersion density technique known to be accurate to ±0.2 % change in density. In some cases it was not possible to clearly identify and retrieve all four specimens, but in general there were at least two identical specimens measured in each capsule. Determination of microstructural evolution in the specimens using a transmission electron microscope has been completed for the ternary and quaternary alloys, but has not yet been initiated for the carbon-doped alloy from MOTA-2B. An earlier study by Sekimura and Ishino addressed the microstructure of some of the MOTA-2A specimens, however (5). Both the current density change and earlier microscopy data are presented in Figure 2.

Results

As shown in Figure 2, the swelling of the carbon-doped alloy at ~400°C appears to show no obvious influence of the dpa rate. As observed in the two simple undoped alloys, the range of swelling between identical specimens is relatively small, indicating the reproducibility of the swelling phenomenon. Surprisingly, the swelling of the fourteen data ensemble appears to be following a general, lower-swelling trend somewhat characteristic of the undoped alloys at the highest dpa rate.

Discussion

There are two major features of these results. First, carbon additions clearly suppress the onset of swelling at ~400°C, an effect not observed to result from the addition of Ti alone. Second, carbon additions suppress the early termination of the transient regime, especially at lower dpa rates where the

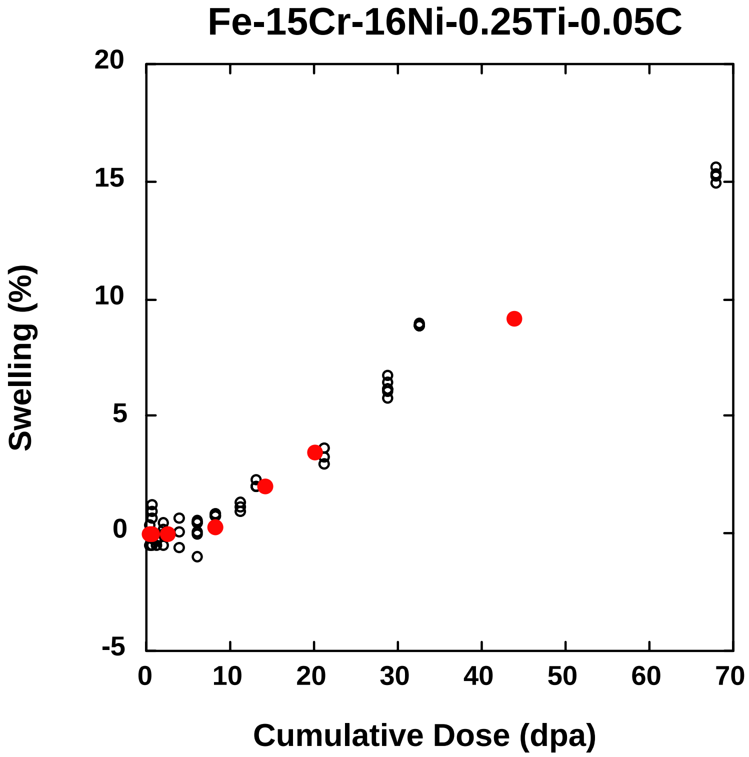

Figure 2. Swelling of simple model f.c.c. Fe-15Cr-16Ni-0.25Ti-0.05 in FFTF-MOTA at ~400°C, showing that the swelling is relatively independent of dpa rate. The red data were obtained from irradiation in MOTA-2A only and the black data from irradiation in both MOTA-2A and 2B.

undoped alloys exhibited very short transient durations.

Currently, there are no microstructural observations for the MOTA-2B carbon-doped specimens to determine the origins of this surprising result. In the undoped alloys microstructural observations of both 2A and 2B specimens showed that the flux sensitivity of the transient regime arose primarily from the flux sensitivity of Frank loop evolution (1). Higher dpa rates produced higher densities of smaller loops which were more resistant to unfaulting and network formation, thereby delaying the development of a dislocation network. Attainment of a stable network was found to be coincident with the termination of the transient regime in these carbon-free alloys (1).

As shown in Figure 3, Sekimura and Ishino (5) earlier examined by microscopy another set of the MOTA-2A specimens at three irradiation temperatures including the ~400°C specimens discussed in this report. Note that the influence of Ti addition is very small at ~400°C but increases at higher temperatures, while carbon additions to the Ti-modified alloys suppress swelling at all temperatures in the range 400-600°C.

Sekimura and Ishino did not address the effect of carbon on Frank loop characteristics at ~400°C for MOTA-2A specimens, so we can not at this point invoke a specific role for carbon's possible influence to delay swelling via its action on the evolution on Frank loops. Microstructural examination of the MOTA-2B specimens may allow the identification of such a role for carbon.

Table 1. Irradiation conditions experienced by carbon-doped specimens in FFTF cycles 11 and 12 (MOTA-2A and MOTA-2B). Note that in three of the seven cases the specimens irradiated in both cycles did not experience completely identical conditions with single cycle packages.

Dose Rate, dpa/sec		Dose, dpa		Temperature, ˚C	
# 11	#12	#11	#11 & #12	#11	#11 & #12
1.7 x 10^{-6}	1.4 x 10^{-6}	43.8	67.8	427	408
7.8 x 10^{-7} *1	9.5 x 10^{-7}	20.0 *1	32.4	390	387
5.4 x 10^{-7}	8.4 x 10^{-7}	14.0	28.8	430	424
8.2 x 10^{-7}	-----	21.1	-----	430	-----
3.2 x 10^{-7} *2	3.5 x 10^{-7}	8.22 *2	13.1	373	373
3.1 x 10^{-7} *3	3.0 x 10^{-7}	8.05 *3	11.1	411	410
1.5 x 10^{-7}	1.3 x 10^{-7}	3.87	6.12	430	431
9.1 x 10^{-8}	2.1 x 10^{-7}	2.36	6.36	430	431
4.6 x 10^{-8}	4.2 x 10^{-8}	1.18	1.91	434	437
2.7 x 10^{-8}	6.6 x 10^{-8}	0.71	1.87	434	437
1.4 x 10^{-8}	1.4 x 10^{-8}	0.37	0.61	436	444
8.9 x 10^{-9}	2.2 x 10^{-8}	0.23	0.61	436	444

Note: The swelling data of the underlined irradiation conditions come from TEM observation, while the other are density measurements.

*1: 6.0 x 10^{-7} dpa/sec and 15.6 dpa for #11 in 2 cycle irradiation specimens
*2: 2.7 x 10^{-7} dpa/sec and 6.90 dpa for #11 in 2 cycle irradiation specimens
*3: 2.2 x 10^{-7} dpa/sec and 5.69 dpa for #11 in 2 cycle irradiation specimens

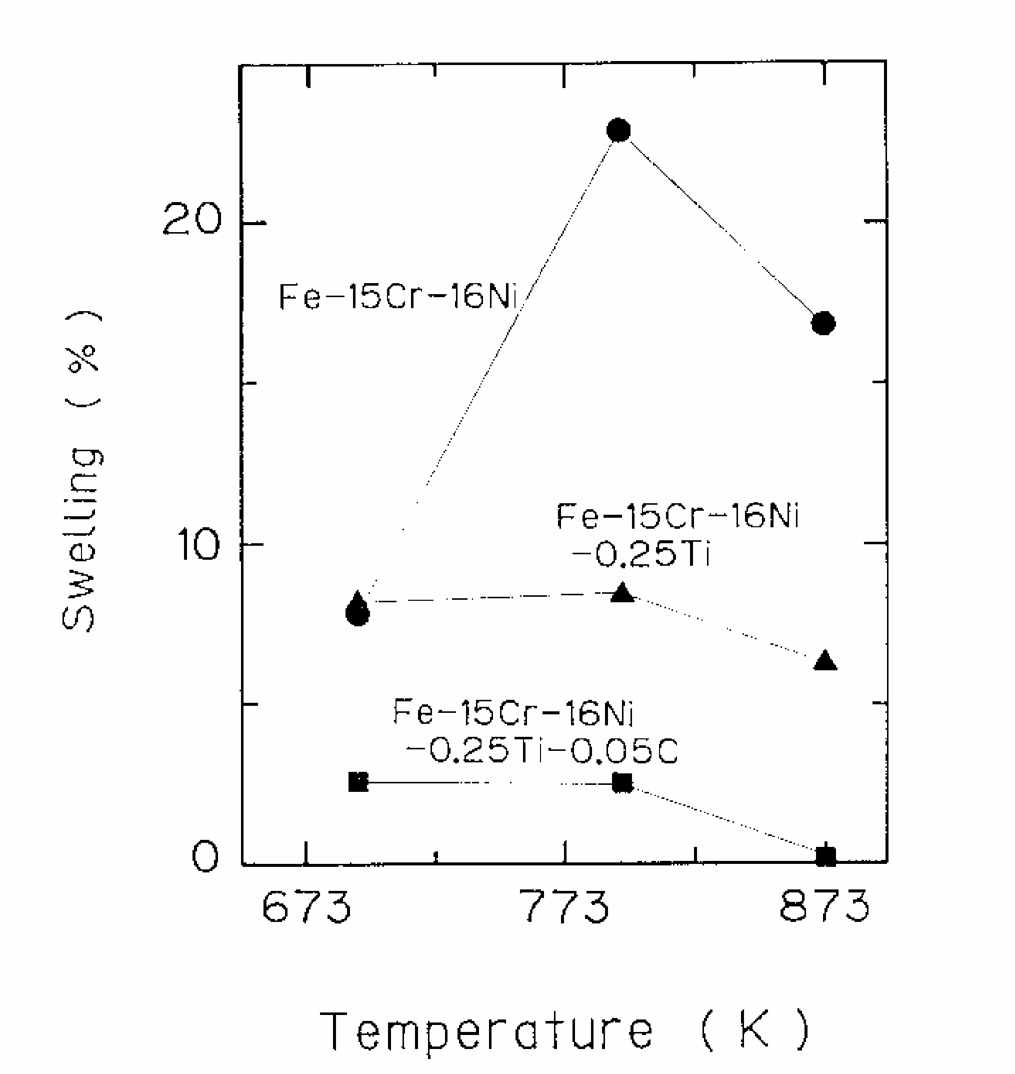

Figure 3. Cavity volume fraction determined by microscopy of three simple austenitic alloys after irradiation in FFTF-MOTA-2A at three different temperatures (5).

Conclusions

The addition of 0.04% carbon to Fe-15Cr-16Ni-0.25Ti leads to a reduction of neutron-induced swelling at ~400°C. Another consequence of carbon addition is that the strong influence of the dpa rate observed in the carbon-free alloy completely disappears in the carbon-doped alloy. The microstructural reasons for this behavior are not yet clear.

REFERENCES

[1] Okita, N. Sekimura, F. A. Garner, L. R. Greenwood, W. G. Wolfer and Y. Isobe, "Neutron-Induced Microstructural Evolution of Fe-15Cr-16Ni Alloys at ~ 400°C During Neutron Irradiation in the FFTF Fast Reactor," 10th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, 2001, issued on CD format, no page numbers. Also in Fusion Materials Semiannual Progress Report for Period Ending June 30, 2001, vol. 30, pp. 148-164.