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# COMPARISON OF SWELLING AND CAVITY MICROSTRUCTURAL DEVELOPMENT FOR TYPE 316 STAINLESS STEEL IRRADIATED IN EBR-II AND HFIR*

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Comparison of swelling and cavity microstructures for one heat of 20% cold-worked (CW) type 316 stainless steel (316) irradiated at 500–650°C in EBR-II (up to 75 dpa) and HFIR (up to 61 dpa) suggests that void growth and swelling are suppressed by the higher helium generation found in HFIR. Instead of voids, many small bubbles develop in the CW 316 in HFIR and resist conversion to voids. However, similar comparison of solution-annealed (SA) 316 irradiated in EBR-II and HFIR at 500–550°C leads to an opposite conclusion; void swelling is enhanced by helium in HFIR. Many more bubbles nucleate in SA 316 at low fluence in HFIR compared to EBR-II, but bimodal distributions and rapid coarsening eventually lead to high swelling due to high concentrations of matrix and precipitate-associated voids in HFIR. A key to the swelling resistance of the CW 316 in HFIR appears to be the development of a sufficiently cavity-dominated sink system in the early stages of evolution.

## 1. INTRODUCTION

Helium effects on swelling have long been a concern of the radiation effects and reactor design communities for fusion. Recent comparisons of specimens irradiated in HFIR (high helium generation rate of ~20–70 at. ppm He/dpa) and EBR-II (low helium generation rate of ~0.5–1.0 at. ppm He/dpa) have suggested that increased helium generation can (a) suppress void (bias-driven cavity) swelling in 20%-cold-worked (CW) type 316 stainless steel[1,2] (316) but (b) enhance void swelling in solution annealed[1,3] (SA) 316. This work presents additional swelling data and summarizes new microstructural data that confirm and expand upon swelling differences between HFIR- and EBR-II-irradiated specimens.

## 2. EXPERIMENTAL

Irradiation experimental details have been presented previously.[1-4] Samples of the DO heat of 316 were irradiated in EBR-II at 500 to 630°C to fluences ranging from 8.4 to 36 dpa (5–22 at. ppm He) in both SA and CW conditions, and up to 69 to 75 dpa (~44 at. ppm He) only for the CW material. Samples of the same steel (both SA and CW conditions) were irradiated in HFIR at 325 to 755°C to fluences ranging from 5.3 to 68.5 dpa (180–4140 at. ppm He). These HFIR data included dpa and irradiation temperature corrections as compared to previously reported data.[1-4] The dpa values are corrected for additional recoils caused by helium transmutation reactions[5] and the irradiation temperatures corrected by +50 to 75°C, as recommended previously.[4] Fluxes vary from ~0.4 to 1.25 × $10^{-6}$ dpa/s in EBR-II and from 0.5 to 1.1 × $10^{-6}$ dpa/s in HFIR.

Swelling in samples with very large cavities was determined with high voltage electron microscopy (HVEM). For the early, high-fluence HFIR experiments (prior to 1976), the immersion density data on entire tensile specimens are considered unreliable because a large temperature gradient existed from gage to shoulder across the specimens. Because irradiation temperatures were reported for the gage center, transmission electron microscopy (TEM) disks cut from those regions best represent the low swelling.

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## 3. RESULTS

### 3.1 Swelling — SA 316

The temperature and fluence dependencies of cavity volume fraction (CVF) data for SA 316 irradiated in EBR-II (four samples) and HFIR (thirteen samples) are shown in Fig. 1. The HFIR data at 64, 53, and below 17.8 dpa are new. A prominent feature of the data is the high swelling at the higher fluences in HFIR for temperatures below 650°C. In Fig. 1(c), despite scatter in the HFIR data, the EBR-II data fell below the HFIR scatter band, indicating that the SA 316 may be emerging from the low-swelling transient regime more slowly in EBR-II. The higher fluence temperature dependence in HFIR indicates a swelling peak at about 500 to 550°C or below. By contrast, high fluence (66 dpa) EBR-II swelling data on another heat of SA 316 by Kenfield et al.[7] indicates a peak at about 550 to 625°C.

### 3.2 Cavity evolution — SA 316

The fluence dependence of cavity concentration and size distributions for SA 316 irradiated in EBR-II and HFIR at 500 to 550°C are shown in Fig. 2. Matrix cavities were distinguished as voids (bias-driven cavities)[8,9] or bubbles (stable cavities)[8,9] where possible, on the basis of size, size distribution, and comparison to grain boundary cavities, as discussed previously.[1] No matrix bubbles or voids were observed in EBR-II at 8.4 dpa but a few precipitate-associated voids were found. Many matrix cavities were observed in HFIR at 12 and 17.8 dpa with clearly bimodal size distributions Moreover, these cavities coarsened with increased fluence. These observations suggest early conversion of matrix bubbles to voids in HFIR.[8,9] After 47 dpa in HFIR many large matrix voids were found, together with even larger precipitate-associated voids, which were not evident at low fluences. By comparison, fewer voids were found in EBR-II at 31 dpa, with the number of both matrix and precipitate voids progressively increasing with fluence [Fig. 2(a)]. Apparently, the accelerated swelling observed in HFIR [Fig. 1(c)] resulted from the earlier

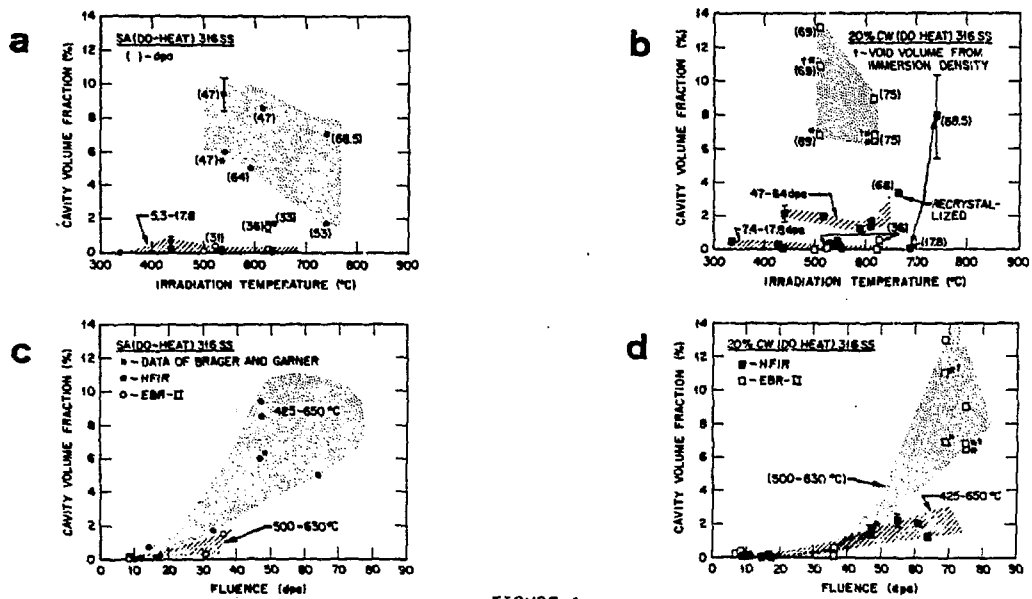


FIGURE 1

Swelling as functions of irradiation temperature (a,b) and functions of fluence (c,d) for SA and CW (DO heat) 316 irradiated in EBR-II and HFIR. Data indicated with (*) were reported by Brager and Garner (ref. 6).

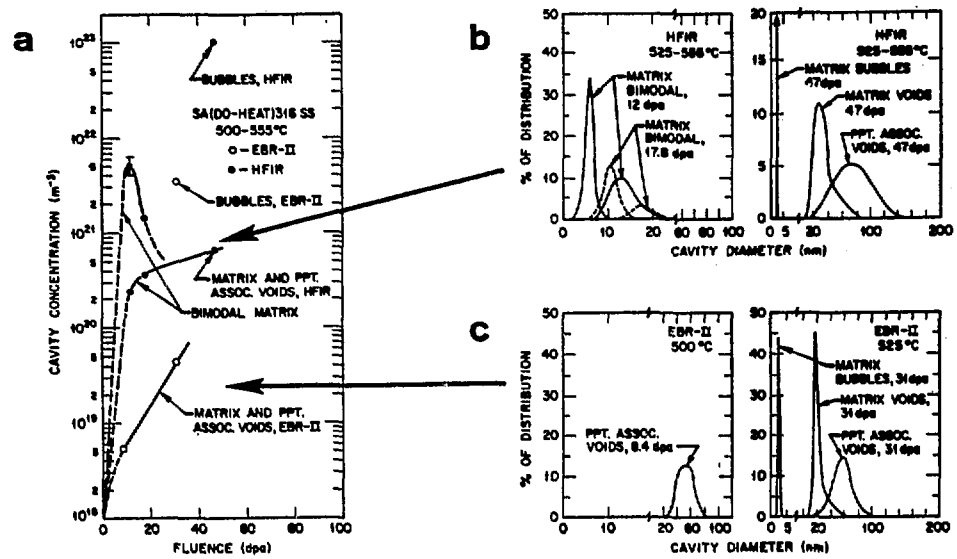


FIGURE 2
Correlated fluence dependence of cavity (a) concentrations and (b) and (c) size distributions for SA 316 irradiated in HFIR and EBR-II at 500–550°C.

development of more, and eventually larger, voids compared to EBR-II.

A perplexing observation was the appearance of dense populations of very fine matrix bubbles (~2 nm in diameter) in SA 316 irradiated in both reactors to higher fluences, particularly when such bubbles were definitely not observed at lower fluences. There were about $10^2$ times more bubbles than voids in both reactors and about 30 to 40 times more bubbles in HFIR than in EBR-II.

3.3 Swelling — 20%-CW 316

The temperature and fluence dependencies of CVF data are shown in Fig. 1(b,d) for EBR-II (six samples) and HFIR (fourteen samples) irradiations of CW 316. High-fluence EBR-II data and the HFIR datum at 64 dpa are also new. In general, below about 30 to 36 dpa, CVFs were low (<1%) and independent of temperature in either reactor at 425 to 650°C [Fig. 1(b)]. Above 30 to 36 dpa, CVFs remain fairly temperature independent and continue to develop at a low rate of ~0.03%/dpa in HFIR to ~64 dpa [Fig. 1(d)]. By contrast, CVFs were quite high in the same temperature range in EBR-II after fluences of 69 to 75 dpa, developing at rates of 0.3 to 0.5%/dpa or more. The high-fluence EBR-II data also indicates greater swelling for 510°C than at 620°C. In HFIR at high fluences, swelling increases dramatically above 650°C due to recrystallization of the originally CW material [Fig. 1(b)] and approaches that found in SA 316 [Fig. 1(a)]. Figure 3 shows that cavity swelling was similar in SA and CW 316 after 68.5 dpa at 730 to 755°C in HFIR. There are no comparable EBR-II data at these temperatures. Recrystallization phenomena under irradiation are treated in more detail in Section 3.5.

3.4 Cavity evolution — 20%-CW 316

The fluence dependencies of cavity concentrations and size distributions for CW 316 irradiated in EBR-II and HFIR at 500 to 550°C and

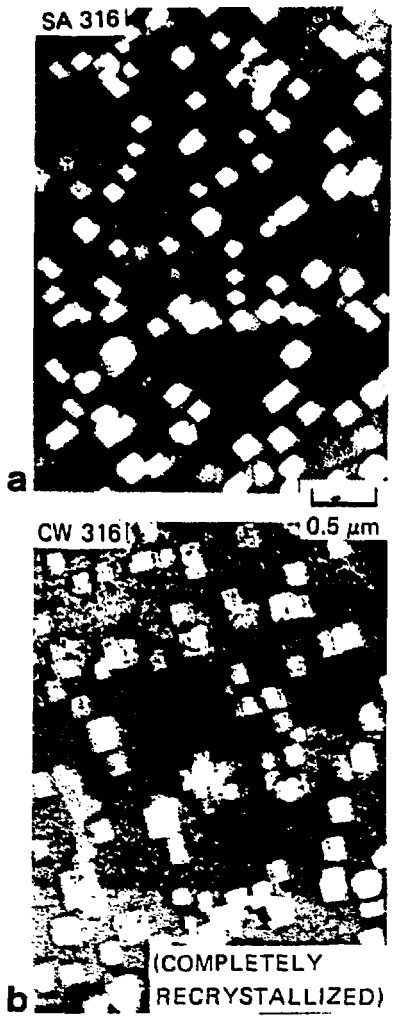


FIGURE 3
A comparison of cavity microstructure in (a) SA 316 and (b) CW 316 after irradiation in HFIR at 730 to 755°C to 68.5 dpa.

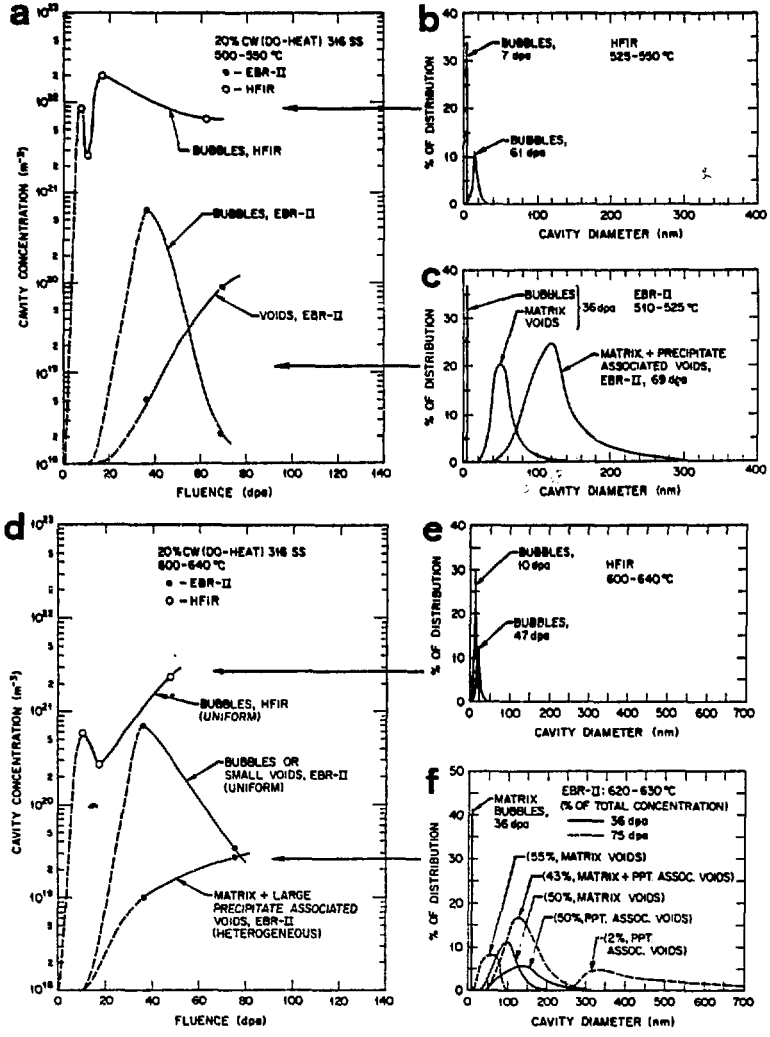


FIGURE 4
Correlation of cavity concentrations (a,d) and size distributions (b,c,e,f) for CW 316 as functions of fluence for irradiations in EBR-II and HFIR at 500 to 550°C (a–c) and 600 to 640°C (e–f).

irradiated in EBR-II and HFIR at 500 to 550°C and at 600 to 640°C are shown in Fig. 4. No bubbles or voids were observed in EBR-II after 8.4 dpa at 500 to 625°C. Thus, Fig. 4(a) and (d) indicate bubble nucleation occurred earlier in HFIR than in EBR-II. A striking feature was that these bubbles remained quite small in HFIR and did not convert to large voids even after 61 dpa [Fig. 4(b) and (e)]. By contrast, fewer bubbles were observed after 36 dpa in EBR-II and these almost completely converted to (or were absorbed by) large matrix voids, and even larger precipitate-associated voids, as fluence increased. These observations are consistent with the suppressed swelling in HFIR compared to EBR-II [Fig. 1(b,d)].

The strongest temperature dependencies were observed for void nucleation and growth in EBR-II and bubble nucleation in HFIR [cf Fig. 4(a) and (d)]. In HFIR, bubble nucleation decreased and became more sluggish as temperature increased. In EBR-II, void nucleation also decreased with increased irradiation temperature [Fig. 4(a) and (d)]. Void sizes separated more distinctly into bimodal and trimodal distribution of matrix and precipitate-associated voids as temperature and fluences in EBR-II increased [Fig. 4(c) and (f)], with precipitate void sizes increasing tremendously with temperature.

### 3.5 Recrystallization of CW 316 under irradiation

Small amounts of recrystallization are found in the DO heat of CW 316 after long-time thermal aging at 650°C (ref. 10). At ~660 to 695°C in HFIR, the CW 316 dislocation structure recovered into polygonalized cell boundaries after 17.8 dpa and a fine grained, completely crystallized structure was found after 67 dpa (ref. 3) [Fig. 5(a,b)]. Compared to thermal aging, recrystallization seemed enhanced under HFIR irradiation, consistent with the similar swelling found between SA and CW 316 in HFIR at these and higher temperatures (see Fig. 3). One isolated, large, recrystallized grain was found after EBR-II irradiation at 620°C to 75 dpa. This seems no more than expected thermally.[9] However, Fig. 5(c) shows that the irradiation-produced precipitates and void structures dissolved at the recrystallization interface in EBR-II in contrast to bubble and precipitate survival during recrystallization in HFIR. This cavity behavior difference during recrystallization supports the distinction made between bubbles in HFIR and voids in EBR-II.

## 4. DISCUSSION

The CW 316 HFIR data indicating suppressed void formation due to very high bubble nucleation rates confirms the early theoretical predictions made for the effects of helium by Odette and coworkers[8,11] in 1974 to 1975. This work indicated that if sufficient bubbles nucleate early in the irradiation in order for these to become the dominant sinks in the system, then the net bias would be reduced. Recent theoretical modeling by Glasgow et al.[12] also points out that it is possible for bubbles not to develop into voids if the net bias is very low.

The SA 316 HFIR data represents the opposite result for increased helium, in that increased bubble nucleation leads to enhanced void formation and swelling. The possibility of helium-enhanced (accelerated) void swelling

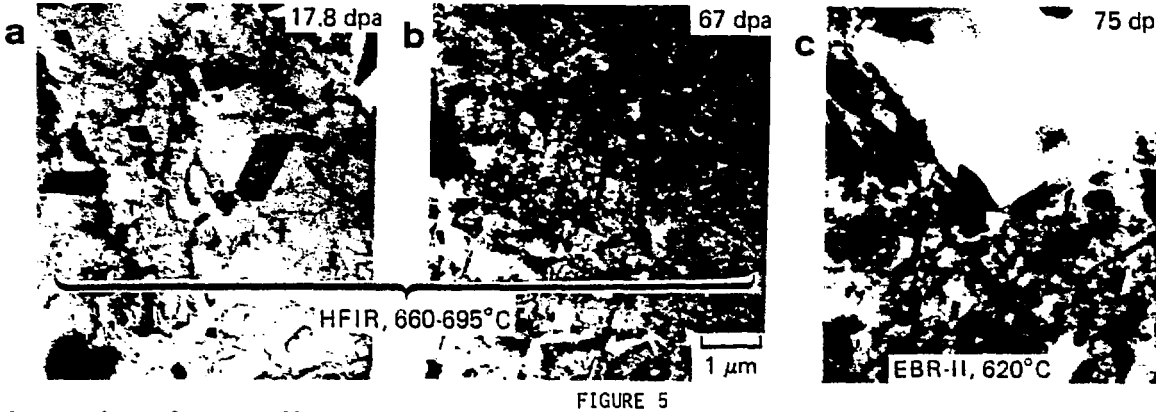


FIGURE 5
A comparison of recrystallization development in CW 316 irradiated in HFIR (a,b) and EBR-II (c) at the conditions indicated.

and the underlying mechanisms are elaborated by recent modeling work of Stoller and Odette.[13] They suggested that if matrix bubbles were not the dominant sinks in the system, then more helium would result in more (and possibly earlier) matrix and precipitate-associated void formation and higher swelling. Despite substantial early bubble nucleation, subsequent cavity evolution suggests that these bubbles are *not* the *dominant* sinks in the SA 316 that they appear to be in the CW 316 in HFIR. This may indicate that some other factor, such as dislocation or precipitation evolution, governs whether bubbles remain stable or convert to voids at higher fluences. The bubble coarsening together with development of bimodal cavity distributions in the SA 316 between 10 and 20 dpa are probably the keys to the divergent swelling behaviors found between SA and CW 316 at higher fluences in HFIR. The development of larger precipitate-associated voids in SA 316, despite the earlier development of matrix voids (early bimodals) indicates faster growth rates for the precipitate-associated voids, consistent with Mansur's theory.[14] Finally, the data presented here are reasonably consistent with rate theory calculations by Ghoniem and Takata[15] of nucleation and growth of voids in SA 316 in HFIR (particularly with revised irradiation temperatures).

It is also noted that Brager and Garner[6] reach different conclusions treating a portion (primarily CW 316) of the EBR-II and HFIR data. However, it is believed that the additional data presented here clearly define the swelling and microstructural differences between AISI 316 irradiated in these reactors.

## 5. CONCLUSIONS

Comparing SA and CW 316 irradiated in EBR-II and HFIR at 400 to 625°C, void swelling appears enhanced for SA 316, but suppressed for CW 316 in HFIR. Increased helium generation results in much more bubble nucleation for both *in HFIR; however, bubbles remain stable in the* CW 316 whereas they convert to voids in SA 316. The key to the swelling resistance of CW 316 in HFIR seems to be achievement of a cavity dominated sink system early in the irradiation history.

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