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STUDIES OF VOID FORMATION
IN
PROTON-IRRADIATED TYPE 316
AND
TITANIUM-MODIFIED 316
STAINLESS STEELS

AEC Research and Development Report

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**STUDIES OF VOID FORMATION
IN
PROTON-IRRADIATED TYPE 316
AND
TITANIUM-MODIFIED 316
STAINLESS STEELS**

By
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ABSTRACT

Void formation was studied as a function of helium content in annealed Type 316 stainless steel irradiated with 1-MeV protons at 500°C. Increasing the helium content resulted in an increased void density, with a concurrent decrease in void size. Swelling was unaffected by changes in helium between 0.28 and 28 appm. In a sample containing no helium, the onset of observable voids was delayed to much higher displacement damage. The effect of periodic increases in helium content in a sample irradiated at 500°C was also studied. This procedure altered the void size and density from that observed in singly-injected samples. Below ~20 displacements per atom (dpa), the swelling was also affected.

Void formation was studied in annealed Type 316 stainless steel irradiated at 400, 500, and 600°C for amounts of damage up to 50 dpa. The volume increase at each temperature varied exponentially with displacement damage, and the exponent increased with temperature. Volume increases exceeding 20% were associated with 50 dpa at 500°C and 20 dpa at 600°C; no limits on volume increases were apparent at any temperature. Void number density decreased, and average void size increased, with increasing temperature for a constant damage.

A titanium-modified Type 316 stainless steel developed a very inhomogeneous void distribution when proton irradiated at 600°C. However, the addition of titanium did not appear to diminish the volume increase at damages between 5 and 10 dpa, when compared to ordinary Type 316 stainless steel.

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1. INTRODUCTION

The nucleation of voids in reactor-irradiated metals is generally assumed to be assisted by the presence of helium generated by transmutations. According to this point of view, small clusters of helium atoms serve as sites to which vacancies migrate; the helium prevents the collapse of the resulting vacancy agglomerate into a two-dimensional defect. The effect of helium on void formation has been tested by Bloom, who found that pre-injection of helium by means of a cyclotron resulted in a greatly increased void density, with concurrent decrease in void size, in neutron-irradiated Type 304 stainless steel.⁽¹⁾

Similarly, helium, pre-injected into metals subjected to accelerator irradiation, has been observed to enhance nucleation of voids. For example, Nelson *et al.*⁽²⁾ have found that pre-injection of helium significantly increased the void density in carbon ion - irradiated nickel and Type 316 stainless steel. We have observed a similar effect in our work on proton-irradiated Type 316 stainless steel.⁽³⁾ In the present work, we obtained quantitative information on the effect of varying amounts of pre-injected helium on void formation in proton-irradiated Type 316 stainless steel. The effect of periodic helium injection during the course of proton irradiation was also studied.

This report also includes studies of the effects of displacement damage and irradiation temperature on void formation in Type 316 stainless steel. Data obtained from samples irradiated at 400, 500, and 600°C are presented. Further, we investigated possible effects of a titanium addition to Type 316 stainless steel. Specimens of Type 316 stainless steel plus 0.2 wt % titanium were injected at room temperature with ~5 appm helium and irradiated with 1-MeV protons. Data obtained from 600°C irradiations of the modified alloy, in annealed and ~20% cold-worked conditions, are compared with 600°C data from Type 316 stainless steel.

II. EXPERIMENTAL

The heat treatments used in preparing the specimens are listed in Table 1. Note that the treatments include 12 hr at 650°C, during which time the specimens are diffusion bonded to copper plates. These plates serve as heat conductors during irradiation.⁽⁴⁾ The treatment used for Type 316 stainless steel results in austenitic grains, 20 to 30 μm in size, with M_{23}C_6 carbides in grain boundaries and, to a much smaller extent, on dislocations.

TABLE 1
HEAT TREATMENTS

Alloy	Heat Treatment
Type 316 Stainless Steel	1 hr at 980°C + 8 hr at 760°C + 12 hr at 650°C*
Type 316 Stainless Steel + 0.2 wt % Ti, Annealed	1 hr at 1050°C + 12 hr at 650°C*
Type 316 Stainless Steel + 0.2 wt % Ti, Cold Worked	1 hr at 1050°C + 20% reduction + 12 hr at 650°C*

*The final 12 hr at 650°C is due to the bonding of the samples to copper plates.

The titanium-modified alloy contains a high number density of M_{23}C_6 precipitates in grain and twin boundaries.[†] In addition, large cuboidal TiC particles occur within the grains. Neither type of carbide particle has been observed in the solution-annealed state, and their presence in our specimens is attributable to the bonding operation. The 20% cold-worked specimens contain a low and inhomogeneous distribution of precipitates, the identity of which has not been established. The bonding treatment has resulted in no detectable recrystallization of the cold-worked structure.

Our experimental technique has been described in a prior publication, and will not be treated in detail here.⁽⁴⁾ However, a few experimental features have been altered somewhat. The temperature control system has been modified, and

[†]The modified alloy was kindly furnished to us by E. E. Bloom, of Oak Ridge National Laboratory.

accelerator beam stability has been improved, so that we now are able to control the temperature within $\pm 5^\circ\text{C}$ during irradiation. Prior to irradiation, the specimen surface is electropolished to give a smooth planar surface. Electron-microscope foils are extracted from selected positions along the proton path. Electropolishing techniques and specimen thickness monitoring by an x-ray attenuation method have been improved, so that our accuracy in determining foil position is estimated to be within $\pm 1000 \text{ \AA}$.

A detailed review of calculations of the number of atom displacements has been made.⁽⁵⁾ For protons in the energy range used in our work, we believe that the Kinchin-Pease model, with a small modification to take into account dissipation of knock-on atom energy in electronic encounters, gives the best value for the number of defects created per unit proton fluence. We have made no attempt to determine the fraction of defects which survives close-pair recombination. This, along with consideration of the disposition of surviving defects, will eventually become necessary, if our results are to be compared in detail with those obtained by neutron irradiation.

Figure 1. Type 316 Stainless Steel, Injected at Room Temperature With 5.8 appm Helium (Note presence of carbides on grain and twin boundaries and on dislocations. At sufficiently high magnification, a low density of "black spot" defects can be observed.)

15-196

III. RESULTS

A. EFFECTS OF PRE-INJECTED HELIUM

In Figure 1, we show an electron photomicrograph of a Type 316 stainless steel sample which has been injected at room temperature with 5.8 ppm helium. With the exception of a low density ($\sim 10^{12}/\text{cm}^3$, in some regions) of "black spot" defects, which are observable at a higher magnification than that used in the photograph, the microstructure of this sample is typical of samples which have been heat treated and diffusion bonded only. Note the presence of carbides decorating boundaries and dislocations.

A photomicrograph of an uninjected Type 316 stainless steel specimen, which was irradiated to 13 displacements per atom (dpa) at 500°C, is shown in Figure 2. The void density in this sample is very inhomogeneous, and the figure is representative of regions having the highest density, $\sim 10^{14}$ voids/cm³. These regions represent only a small fraction of the foil area viewed; in fact, only about one third of the foil contains any voids at all.

In Table 2 are results obtained on samples injected to various helium contents and irradiated at 500°C. The total number of atom displacements and displacement rates were kept approximately constant in all of the samples. It is particularly important that the displacement rate be kept fixed, since we have previously observed a strong dependence of void density on the rate of damage production at 500°C.⁽³⁾ In Table 2, an increase in helium content leads to an increase in void density, with a concurrent decrease in void size. This can also be seen in Figures 3a and 3b. Changing the initial helium content has no detectable effect on the swelling obtained; all the swelling values for the helium-containing samples in Table 2 are in agreement with our results on samples containing between 2 and 9 appm helium (see the 500°C data in Figure 5).

In terms of the deposition of helium, our usual experimental technique, in which the entire helium content is injected prior to irradiation, does not accurately simulate a reactor irradiation, where helium is continuously produced at a relatively low rate. In an effort to simulate more closely the reactor condition, and to study the effects of periodic increases in helium content during

Figure 2. Type 316 Stainless Steel, Proton Irradiated at 500°C to 13 dpa Without Pre-Injection of Helium (Area shown is representative of regions having highest void density, $\sim 10^{14}/\text{cm}^3$)

21-189

a. 0.28 appm Helium (Sample 88)

2-208

b. 28 appm Helium (Sample 29)

14-207

Figure 3. Voids in Type 316 Stainless Steel, Proton Irradiated at 500°C to 11 dpa, Illustrating Dependence of Void Size and Density on Helium Concentration

a. Section 2 — 0.55 appm Helium and 6.9 dpa 16-194

b. Section 3 — 3.0 appm Helium and 24 dpa (Note areas which have transformed to ferrite) 2-196

Figure 4. Voids in Type 316 Stainless Steel, Proton Irradiated at 500°C (Specimen 117)

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TABLE 2
EFFECT OF HELIUM CONTENT ON VOID FORMATION AT 500°C

Sample Number	Helium Content (appm)	Displacements per Atom	Displacement Rate (dpa/sec)	Void Density (/cm ³)	Average Void Diameter (Å)	Swelling (%)
116	0	13	0.74×10^{-3}	$\sim 0^*$	-	~ 0
88	0.28	11	1.4×10^{-3}	2.8×10^{15}	280	3.7
56A	5.9	15	1.2×10^{-3}	7.2×10^{15}	260	6.0
29	28	11	1.2×10^{-3}	1.3×10^{16}	170	4.0

*Isolated groups of voids, in which the void density was $\sim 10^{14}/\text{cm}^3$, were observed.

proton irradiation, we have injected and irradiated Type 316 stainless steel (Sample 117) according to the following schedule (see Table 3):

- 1) The whole sample was injected at room temperature with 0.001 appm helium, and proton irradiated at 500°C to produce 1 dpa.
- 2) Section 1 of the sample was shielded with a heavy copper plate, and the exposed portion of the sample received additional helium at room temperature, raising the concentration to 0.5 appm. A second proton irradiation at 500°C raised the damage in the exposed portion to 6.9 dpa.
- 3) Sections 1 and 2 were shielded, and the final section received additional helium, raising the concentration to 3.0 appm, and additional proton irradiation raising the damage to 24 dpa.

Electron microscope foils were extracted from closely the same proton penetration depth in all three sections. The results can thus be compared at a constant displacement rate of $\sim 1.2 \times 10^{-3}$ dpa/sec. The microstructures obtained in Sections 2 and 3 are shown in Figures 4a and 4b.

6506-4722

Figure 5. Swelling as a Function of Displacement Damage for Proton-Irradiated Type 316 and Titanium-Modified 316 Stainless Steels (Average swelling for annealed modified alloy given by ◇)

TABLE 3
EFFECT OF ALTERNATE HELIUM INJECTION AT
ROOM TEMPERATURE AND PROTON
IRRADIATION AT 500°C

Section Number	Total Helium Injected (appm)	Total Displacements per Atom	Displacement Rate (dpa/sec)	Void Density (/cm ³)	Average Void Diameter (Å)	Swelling (%)
1	0.001	1.0	1.2×10^{-3}	0	-	0
2	0.55	6.9	1.2×10^{-3}	4.3×10^{14}	230	0.52
3	3.0	24	1.2×10^{-3}	1.6×10^{15}	400	7.1

B. VOIDS IN TYPE 316 STAINLESS STEEL

In Figure 5, we show the dependence of swelling in Type 316 stainless steel on displacement damage for irradiation temperatures of 400, 500, and 600°C. Swelling is defined here as $\Delta V/V$, where ΔV is the volume of voids in the total volume, V , of the sample. The lines through the data are drawn according to least squares fitting, and can be expressed analytically as:

$$400^\circ\text{C}: \Delta V/V (\%) \approx 0.24 (\text{dpa})^{0.68} \quad \dots (1)$$

$$500^\circ\text{C}: \quad \quad \quad = 0.14 (\text{dpa})^{1.3} \quad \dots (2)$$

$$600^\circ\text{C}: \quad \quad \quad = 0.0013 (\text{dpa})^{2.9} \quad \dots (3)$$

Note that Equation 1 is based on only a few data.

The data in Figure 5 were obtained from foils extracted from various positions along the proton path in samples irradiated to several different fluences. The foils which were used in obtaining the data underwent atom displacement rates which varied between $\sim 2 \times 10^{-4}$ to 12×10^{-4} displacements per atom per sec (dpa/sec). Although, as will be discussed later, the void density can be dependent on the displacement rate, we have observed no dependence of swelling on displacement rate. In addition, we have sufficient data at each temperature, for an approximately constant displacement rate, to assure us of the correctness of the lines shown in Figure 5. The vertical bars in the figure represent data obtained on the modified alloy; these will be dealt with later.

a. 4.5 appm Helium, Irradiated
at 400°C to 9.2 dpa

19-177

12-152

b. 3.5 appm Helium, Irradiated
at 500°C to 9.2 dpa

17-205

c. 4.5 appm Helium, Irradiated
at 600°C to 11 dpa

Figure 6. Typical Void Distribution for Type 316 Stainless Steel, Injected
With Helium at Room Temperature and Proton Irradiated

Typical void distributions for Type 316 stainless steel for the three irradiation temperatures are given in Figures 6a, b, and c. These photomicrographs are of foils in which the displacement rates ($\sim 10^{-3}$ dpa/sec) and numbers of displacements (~ 10 dpa) are approximately the same. The swelling values obtained from these photomicrographs are ~ 0.5 , 3 , and 0.2% for 400 , 500 , and 600°C , respectively.

The changes in average void diameter with number of atom displacements for Type 316 stainless steel irradiated at 400 , 500 , and 600°C are shown in Figure 7. The lines through the data are drawn according to least squares fits. The void size increases with increasing irradiation temperature, as does the rate at which the void size changes with number of atom displacements. Again, the bars refer to data obtained on the modified alloy.

The void number density in Type 316 stainless steel as a function of number of displacements for 500 and 600°C is shown in Figure 8. Insufficient 400°C data are available for presentation. The data which are plotted were selected at approximately constant displacement rates. As we have discussed earlier, the void density obtained at 500°C is relatively independent of the number of displacements, but is sensitive to the displacement rate.⁽³⁾ Although the 600°C data in Figure 8 are badly scattered, the void density clearly increases with increasing damage. Insufficient 600°C data are available at significantly different displacement rates to determine whether the void density is dependent on the displacement rate, as well as the number of displacements.

C. VOIDS IN TYPE 316 STAINLESS STEEL PLUS 0.2 wt % TITANIUM

The void distributions in both the annealed and cold-worked modified alloys are very inhomogeneous. As a result, the 600°C swelling data for this alloy vary over a much wider range than those from our standard Type 316 stainless steel. The vertical bars in Figure 5 represent the variation in swelling obtained from photomicrographs which exhibited voids. Since large areas of the foil from the annealed material contained no voids at all, an average swelling value was calculated by taking into account the relative fractions of foil area which exhibited "high," "medium," "low," and no swelling. This crude average for the annealed alloy is shown as a diamond in Figure 5. Because of the even greater inhomogeneity in void distribution in the cold-worked sample, no averaging was attempted.

72-M27-4-10

Figure 7. Average Void Diameter as Function of Displacement Damage for Proton-Irradiated Type 316 and Titanium-Modified 316 Stainless Steels

72-M27-4-11

Figure 8. Void Number Density as Function of Displacement Damage for Proton-Irradiated Type 316 Stainless Steel at 500 and 600°C

a. Annealed Steel

16-190

b. ~20% Cold-Worked Steel

1-187

Figure 9. Void Distribution for Titanium-Modified Type 316 Stainless Steel, Proton Irradiated at 600°C

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Photographs of microstructures observed in the annealed and cold-worked modified alloy after 600°C irradiation are shown in Figures 9a and b. The inhomogeneity in void distribution for the cold-worked alloy can be seen in Figure 9b. Additional noteworthy observations are as follows: (1) the angular precipitates present in the annealed specimens prior to irradiation are not present after irradiation — those precipitates which are observed are much smaller in size, and similar to those found in Type 316 stainless steel after proton irradiation, (2) the specimens do not have a particle-void association, as in the case in the neutron-irradiated alloy,⁽⁶⁾ and (3) the general dislocation structure of the ~20% cold-worked specimen does not appear to have changed due to irradiation.

IV. DISCUSSION

A. EFFECTS OF PRE-INJECTED HELIUM

A thorough examination of a specimen injected with 5.8 appm helium has revealed only a very low density of "black spot" defects. The remainder of the microstructure is unaffected by the injection of helium, and is typical of samples which have been heat treated and diffusion bonded to, and subsequently removed from, the copper plates. Thus, prior to irradiation, there are no observable microstructural features of our helium-injected stainless steel specimens which might affect subsequent void formation.

In Table 2, the void density for the sample containing no helium is given as ~ 0 for 13 dpa. Isolated areas containing voids are present in this sample. In these areas, which make up only a small fraction of the total area viewed, the void density is $\sim 10^{14}/\text{cm}^3$. In another portion of this sample, where the damage is 20 dpa, the void array has become more homogeneously distributed, and the overall density has increased. Thus, void formation is clearly possible in samples which contain no helium, but the nucleation process is drastically delayed to higher levels of damage. The inhomogeneity in void distribution at low damage levels suggests that nucleation may be assisted, at least partly, by a low and inhomogeneous distribution of residual gas impurities. Inhomogeneity in microstructure or composition can possibly affect void nucleation as well.

Comparing Samples 88 and 29 in Table 2 and Figure 3, we see that an approximately one hundred-fold increase in helium content leads to about a five-fold increase in void density. Thus, increasing the number of helium atoms leads to more void nuclei (i. e., helium atom clusters). However, the probability of nucleus formation at any given time during an irradiation decreases with increasing number of nuclei already present, and the relationship between the numbers of voids and helium atoms is not one-to-one. Note that, in Sample 88, the partitioning of 0.28 appm helium among 2.8×10^{15} voids/ cm^3 leads to ~ 8 helium atoms per void. This estimate is based on the assumption that all the helium participates in void nucleation. In Sample 29, the number of helium atoms per void is ~ 180 . This relatively large number of helium atoms per void suggests that helium may continue to arrive at a void over a long period of time, compared to the time needed to form a stable nucleus.

In Sample 117, which was alternately injected and irradiated, the initial injection yielded an unintentionally low helium content, and no voids were observed in the section irradiated to 1 dpa. "Black spot" damage and precipitates decorating dislocations were observed.

As can be seen in Figure 4a, voids were observed in Section 2, which had received a total of 0.55 appm helium and 6.9 dpa. Precipitates on dislocations again were present, along with a low density of very large faulted dislocation loops. The results given in Table 3 and Figure 4a for this section can be compared with those in Table 2 and Figure 3a for Sample 88. (Recall that the latter was injected and irradiated in a single step.) The average void size obtained in the two samples is approximately the same, while the swelling in Section 2 is less than that in Sample 88. The difference in swelling is due to the fact that, despite a slightly higher helium content, the void density in Section 2 is significantly less than that in Sample 88. It appears that the damage introduced during the initial irradiation of Section 2 inhibited void nucleation during the second irradiation. Presumably, such inhibition results from a lower vacancy supersaturation, induced by the presence of large numbers of vacancy sinks. Despite the lower void density in Section 2, the average void size is comparable to that in Sample 88. This is contrary to the usual observation that lower void densities result in larger void sizes for equal amounts of damage. As will be seen in the discussion of Section 3, this latter condition eventually develops upon further irradiation.

In Section 3 of Sample 117, the void density, void diameter, and swelling have increased significantly over the values obtained in Section 2. Injection of additional helium into the third section has resulted in nucleation of more voids, while those voids which were already present have increased in size. The additional nucleation contrasts with results we have obtained previously on samples whose entire helium content was injected prior to irradiation.⁽³⁾ In the latter, void nucleation was complete at a very low damage level. On the other hand, the swelling in this section of Sample 117 is in excellent agreement with that shown in Figure 5 for ~ 25 dpa at 500°C . The voids are less numerous, but are now somewhat larger, than those obtained in samples which were injected and irradiated in single steps.

The dependence of swelling on displacement damage in Sample 117 (compare Sections 2 and 3) is quite different from that obtained for comparable changes in damage in singly-injected samples (see Figure 5). Although the initial irradiation, in which damage was created but no voids were formed, undoubtedly had an effect on subsequent swelling results, the periodic injection of helium may have also influenced the magnitude of swelling. In any case, these results emphasize the sensitivity of void formation to microstructure and helium content.

In previous work, we have noted that proton irradiation of Types 316 and 321 stainless steels at 500°C can lead to the transformation of austenite to ferrite.^(3,7) This transformation, which can be seen in Figure 4b, occurred to an even greater extent in Section 3 of Sample 117 than it has in previous irradiations of singly-injected samples. Also, the transformation occurred principally in the course of the third irradiation (i. e., between 6.9 and 24 dpa). The cause of the acceleration of the transformation in Sample 117 over that detected in previous samples is not apparent at this time.

B. VOIDS IN TYPE 316 STAINLESS STEEL

In reaching the damage states shown in Figure 6, the microstructures progress through series of changes which are similar at all three irradiation temperatures. Faulted dislocation loops form first, along with a low-density array of irradiation-produced precipitates. As has been discussed by Katz and Wiedersich, if there are initially insufficient sinks to reduce the interstitial concentration, void nucleation must be preceded by nucleation of interstitial agglomerates.⁽⁸⁾ As irradiation proceeds, voids become visible and grow; usually, the first observable voids are arrayed inhomogeneously. Concurrent with the development of the void population, the dislocation loop structure rapidly gives way to a tangled dislocation array. Voids grow, and the dislocation density increases, as the irradiation proceeds still further. Although no quantitative measurements of the dislocation density have been made, it appears that the dislocations reach a maximum density very early in the irradiation. We have seen no evidence that this density ultimately decreases with increasing irradiation.

The dependence of swelling on number of atom displacements is shown in Figure 5 for the three irradiation temperatures. Since few data have so far been obtained at 400°C, we will concentrate the following discussion on comparisons of the 500 and 600°C data. It appears likely that similar comparisons can be made between the 400°C data and those at 500 and 600°C.

Our swelling results at 500°C can be summarized as follows:

- 1) Swelling increases at a rate somewhat greater than linear with number of atom displacements, and continues to do so, up to a volume increase of over 20% at 50 dpa. No limit to swelling, as obtained in carbon ion - irradiated stainless steel⁽⁹⁾ and selenium ion - irradiated nickel⁽¹⁰⁾ has been observed here.
- 2) The void density is established early in the irradiation, and the increase in swelling with damage is due to void growth only.

The characteristics of our 500°C data are in good agreement with results obtained by Taylor and McDonald on Type 304 stainless steel proton irradiated at 525°C.⁽¹¹⁾ However, their results were obtained on samples which had not been injected with helium. The reason for this difference in the two sets of data is not clear at this time, but it should be recalled that the propensity of Type 304 stainless steel to swelling is greater than that of Type 316 stainless steel.

The important aspects of our 600°C data are as follows:

- 1) Swelling increases much more rapidly with damage than it does at 500°C.
- 2) The average void size, and the increase in void size with damage, are greater than at 500°C.
- 3) The void density is less than at 500°C, but increases with damage.

The more rapid increase of swelling with damage at 600°C than at 500°C can be explained by considering the relative behavior of the void size and density at the two irradiation temperatures. Note that swelling is low initially at 600°C, but eventually becomes quite large, exceeding that at 500°C at ~15 dpa. Extrapolating the high-temperature data in Figure 7, we see that the average void size at 600°C exceeds that at 500°C for dpa in excess of ~1; so the lower swelling

at 600°C, up to ~15 dpa, must be attributed to the lower void density. As irradiation at 600°C continues, however, the void density increases. This increase, coupled with a faster growth rate, ultimately leads to higher swelling at 600°C than at 500°C. The dependence of $\Delta V/V$ on dpa can be expressed in the following way. Let us assume that $\Delta V/V \sim \rho_v (d_{\text{avg}})^3$, where ρ_v is the void number density, and d_{avg} is the average void diameter. From least squares fitting, at 600°C, $d_{\text{avg}} \sim (\text{dpa})^{0.66}$ and $\rho_v \sim (\text{dpa})^{0.60}$, so we can write that $\Delta V/V \sim (\text{dpa})^{0.60} [(\text{dpa})^{0.66}]^3 \sim (\text{dpa})^{2.6}$. In view of the scatter in all of the data, this approximation is in agreement with Equation 3 for the fit to the swelling data in Figure 5 - $\Delta V/V \sim (\text{dpa})^{2.9}$. Clearly, the increase in ρ_v with dpa must be included in the analysis, in order to obtain consistency between swelling and displacement damage. On the contrary, at 500°C, $\Delta V/V \sim \rho_v (d_{\text{avg}})^3 \sim \rho_v [(\text{dpa})^{0.36}]^3 \sim \rho_v (\text{dpa})^{1.1}$. This agrees with Equation 2 - $\Delta V/V \sim (\text{dpa})^{1.3}$ - for ρ_v independent of dpa.

Because of the complicated mechanism for void formation, particularly in a complex alloy such as stainless steel, we will at this time only speculate briefly on the reasons for differences in void nucleation and growth at 500 and 600°C. This speculation is based on theoretical work described in References 8, 12, and 13. First, we note that the supersaturation of vacancies, as well as interstitials, decreases with a rise in irradiation temperature. This will decrease the probability of void nucleation and lower the void density at a given number of atom displacements. Also, the onset of observable swelling will be delayed until a greater damage level is reached. Apparently, a reduction in defect supersaturation extends the irradiation time over which nucleation can occur. Since we have observed an enhancement of void growth rate at 600°C, we must assume that the relative probability of vacancy annihilation at voids has been increased. This is due to a reduction in interstitial-vacancy recombination with decreasing defect supersaturation.

In the preceding discussion, we have ignored the possible effect of temperature on the disposition of helium in the lattice, as well as microstructural changes which might be occurring. We know that a transformation of austenite to ferrite is taking place at 600°C, even at relatively low damage levels. This has also been observed at 500°C, but to a lesser extent.⁽³⁾ The effect of such a transformation on void formation, growth, and stability is not known.

Increases in the dependence of swelling on damage with increasing temperature have been observed by Bloom in neutron-irradiated Type 304 stainless steel.⁽¹⁾ In the neutron case, however, the temperature dependence of swelling resulted only from an increase in the dependence of void density on damage. The void size was found to be relatively insensitive to the damage level.

C. VOIDS IN TYPE 316 STAINLESS STEEL PLUS 0.2 wt % TITANIUM

The swelling obtained in both the annealed and cold-worked titanium-modified alloy is comparable to, and sometimes higher than, that obtained in the standard Type 316 stainless steel. This is shown in Figure 5, where the vertical lines represent the variation in swelling obtained from photographs containing void distributions. It must be remembered, of course, that the lines actually extend to $\Delta V/V = 0$, since some areas were found to contain no voids at all. In those regions containing voids, neither the void size nor the number density in the modified alloy is significantly different from that observed in standard Type 316 stainless steel.

The reason for the great inhomogeneity in void density in the modified alloy is not clear. Inhomogeneity in the titanium distribution may produce microstructural variations which will influence void nucleation and growth. For example, the titanium will affect the distribution of interstitial carbon in solution. It has already been suggested that the effect of carbon on void formation is substantial.^(14,15)

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