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A THIRD STAGE OF IRRADIATION CREEP INVOLVING ITS CESSATION AT HIGH NEUTRON EXPOSURES

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1.0 Objective

The object of this effort is to determine the mechanism by which radiation affects the properties and dimensions of reactor components.

2.0 Summary

As swelling approaches 5-10% in AISI 316, the creep rate appears to rapidly decline and eventually vanish. There may be some correlation between this phenomena and changes in failure mode that also appear to be related to void swelling.

3.0 Program

Title: Irradiation Effects Analysis (AKJ)
Principal Investigator: D. G. Doran
Affiliation: Hanford Engineering Development Laboratory

4.0 Relevant Program Plan Task/Subtask

Subtask II.C.14 Models of Flow and Fracture Under Irradiation
Subtask II.C.16 Composite Correlation Models and Experiments

5.0 Accomplishments and Status

5.1 Introduction

It is generally accepted that in structural steels at fusion-relevant temperatures that there is one minor stage of irradiation creep followed by two major stages.⁽¹⁻³⁾ The minor stage is transient in nature and is found only in cold-worked steels very early in the irradiation. It results from an initial reduction in dislocation density. The first major stage is characterized by a steady-state creep rate which appears to be athermal in nature and which is independent of void swelling. In the second major stage the creep rate is accelerated and appears to be proportional to the swelling rate, at least for relatively low swelling levels (<5%). In this stage the creep rate therefore has the same parametric sensitivities as those associated with the swelling rate.

Analysis of creep data extracted from components with higher levels of swelling now shows that coincident with 5-10% swelling levels, a third major stage of creep evolves in which the creep rate begins to rapidly decline with further exposure and eventually vanish.

5.2 Fuel Pin Data

This third stage was first brought to light when the measured creep strains of highly irradiated 20% cold-worked fuel pin cladding fell substantially below the levels predicted by a correlation developed from

creep tube data at lower fluence.^(4,5) An example is shown in Figure 1 for a pin with a high fluence to burn-up ratio and a very high neutron exposure.

FIGURE 1. Comparison of predicted and measured diametral strains of 20% cold-worked AISI 316 FFTF Core-4 cladding for a fuel pin irradiated to a peak fluence of 1.7×10^{23} n/cm² ($E > 0.1$ MeV).^(4,5) Note that the measured diameter changes appear to arise primarily from the swelling-related strains.

It is important to note that the creep prediction shown in Figure 1 is that of an older correlation which did not include either of the insights of a swelling rate which approached 1%/dpa or creep rates proportional to swelling rates.⁽¹⁾ Thus the creep strains predicted by more recent correlations would be even larger, emphasizing once again the difference between measured and predicted creep strains.

Examination of the strains of other fuel pins at lower exposure levels provides some additional insight. Figure 2 shows the strains measured in a fuel pin at lower fluence and for which the fluence to burn-up ratio is relatively high but not as high as that of the pin shown in Figure 1. Note once again that the measured creep is significantly less than predicted. Figure 3 shows the strains of a pin in which the fluence to burn-up ratio is much lower but in this case the measured creep is comparable to or greater than the predictions. The agreement is best at temperatures where pressurized tube data were available in this fluence range. Otherwise an under-prediction of creep strains would be anticipated. In general the trends of these two pins are reproduced in other pins, with the difference between creep predictions and measurements being somehow dependent on the fluence to burn-up ratio.

The fluence to burn-up ratio is largely determined by the enrichment of the fuel. In pins where the fluence is large but the burn-up is low swelling gets started without the presence of significant stress. The stress arises from the generation of fission gases and therefore increases monotonically with neutron exposure. Thus when creep begins in such a pin swelling is already rather advanced. In pins which have higher enrichments and therefore higher burn-up rates creep gets a head start on swelling and the predictions based on pressurized tube data are comparable to that actually observed in the fuel pins. Thus it appears that the level of swelling may be related to the short-fall observed in creep.

Since fuel pins are subject to complex histories of stress, temperature and chemical environment, the possibility can not be ruled out that the unexpectedly low creep strains might have arisen as a result of some previously unsuspected history dependence of microstructural evolution.

5.3 Pressurized Tube Data

In order to investigate the sources of these sometime low creep strains it is better to analyze the deformation of non-fueled creep tubes at constant pressure. By comparing the strains of tubes at different

FIGURE 2. Comparison of measured strains and predictions for pin P-14A-30 clad with FFTF Core-1 20% cold-worked AISI 316. This high fluence to burn-up ratio pin reached a peak of $11 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) and 9.0% burn-up. The volumetric swelling at the position of maximum strain is 9.4%.

FIGURE 3. Comparison of measured and predicted strains for pin P-14-29 clad with FFTF Core-1 20% cold-worked AISI 316. The low fluence to burn-up ratio pin reached a peak of $8 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) and 11.5% burn-up.

internal pressures one can get some idea of the relationship between stress, swelling and creep. If one uses measurements along the length of relatively long pressurized tubes data at a given stress can also be obtained as a function of neutron flux and fluence.

Helium-filled tubes of this type have been irradiated in EBR-II for both AISI 304 and AISI 316 steels and data from these have been reported elsewhere.^(6,7) In this study we will concentrate on tubes of AISI 316 (N-lot heat) irradiated at 550°C ($\pm 10^\circ\text{C}$) in each of the following conditions; annealed, 10% cold-worked, 20% cold-worked and a Garafolo-type cold-worked and aged condition (Heat Treat D, fully carbide precipitated). The latter condition is known to induce early swelling. It should be noted that the 10% cold-worked condition was achieved by first annealing a 20% cold-worked tube and then reworking it. Thus the two cold-work conditions do not have the same starting state since the original 20% cold-worked material was annealed using another technique in an industrial laboratory.

These tubes have a 10 inch (0.25 m) pressurized section located above the core centerline and the temperature was maintained by preheating the sodium coolant with a solid tantalum heater in that section of the tube which is below the core centerline. The end-of-life internal gas pressure of each tube was measured when the tube was removed from the reactor for the final examination. Creep strains were measured at both core center and other axial positions during interim examinations. Some tubes were sectioned into axial increments upon removal from the reactor and immersion density measurements were performed on them.

Figure 4 shows the total diametral strains measured at core centerline for three 10% cold-worked tubes at different stress levels. As the stress increases the creep and swelling strains also increase but together they do not exceed the strain rate (0.33%/dpa) that one would expect from steady-state swelling alone (1/3 of 1%/dpa). The increase in strain rate between tubes at 15 and 30 ksi is surprisingly small, however. Figure 5 shows the strain for the cold-worked and aged Heat Treat D condition which is known to swell sooner than cold-worked steel. Note that while the transient regime of diametral deformation decreases in duration with increasing stress, the post-transient deformation rate does not appear to change. Even more significantly, the total deformation rate does not exceed the 0.33%/dpa expected from steady-state swelling alone. Indeed it appears that the well-known stress dependence of creep rate has disappeared somewhere between hoop stress levels of 0 and 15 ksi. A similar behavior is shown in Figure 6a for the 20% cold-worked condition. Note that both the Heat Treat D and the 20% cold-worked condition swell sooner in the stress-free condition than does the 10% cold-worked condition. This is probably a reflection of the different starting conditions for the 10 and 20% cold-worked steels.

FIGURE 4. Diametral strain at 550°C observed at core centerline of EBR-II for three pressurized tubes of N-lot AISI 316 in the 10% cold-worked condition.

When the swelling and creep strains are separated, it becomes more obvious why the total strain rate appears to saturate at a level independent of the stress and starting condition. Figure 6b shows the results of density change measurements performed along the length of the 30 ksi tube. Comparison of the stress-affected swelling strains with those of the stress-free tube indicates a relatively small influence of stress in accelerating the onset of steady-state swelling. However, when the stress-affected swelling strains are subtracted from the total deformation at 30 ksi it can be seen that the creep strains indeed

FIGURE 5. Diametral strains at 550°C observed at core centerline of EBR-II for three pressurized tubes of N-lot AISI 316 in the Heat Treat D condition.

begin to saturate coincident with swelling levels of 7-10%. The stress-dependence of creep disappears because creep itself disappears.

Further insight can be obtained on this phenomenon by measuring the strains of three Heat Treat D tubes removed at a lower level of irradiation. Note that the strains of these tubes are compared in Figure 7 with those of the nominally identical tubes at higher fluence shown in Figure 5. These lower fluence pins were sectioned in axial increments and density change measurements made. Note in Figure 8 that if one uses the stress-free swelling strain, the onset of creep saturation is camouflaged somewhat. This may explain why this phenomenon has not yet been observed in the shorter pressurized tubes used for the U.S. breeder reactor studies. It is the practice in those studies to calculate creep using the stress-free strains in order to avoid sacrificing a valuable stress-free tube at low and intermediate fluence levels. Thus the stress-enhanced portion of the swelling strain is included as a creep contribution which thereby obscures the observation of the third stage of creep.

The annealed tubes from this experimental series were not used in this analysis because these tubes after removal from the reactor were found to have lost their gas pressure, indicating that they failed sometime during irradiation. These tubes start to swell sooner than do tubes in either the cold-worked or Heat Treat D conditions. Note in Figure 9 that the 30 ksi tube failed somewhere before a diametral strain of >2% was attained. Judging from the stress-free strain behavior, most of this strain is associated with swelling, indicating a swelling level probably on the order of >5%. While the annealed tubes cannot be confidently used to study the postulated third stage of creep, they do suggest another ramification of the swelling-creep interaction. In another recent paper it has been suggested that if large levels of void swelling tend to interfere with irradiation creep, it might be expected that ex-reactor deformation and failure modes may also be affected.⁽⁵⁾ It was shown in that paper that large changes in fracture mode indeed occur for swelling levels on the order of 5-10%.⁽⁵⁾ Perhaps then, the in-reactor failure modes are also affected by swelling. While the failure of the annealed tubes cannot be taken as proof of a causal relationship between the reduction of irradiation creep and the subsequent failure of the tube, it does signal that additional attention should be paid to the potential for such a relationship. It is difficult to imagine how the applied and swelling-generated stresses (particularly at stress risers and triple points) are being relieved when the macroscopic creep rate seems to disappear.

5.4 Discussion

The microstructural origins of this phenomenon are not at all obvious and are currently under study. Some observations can be made, however, that may at least partially explain the observed results. First of all, at these swelling levels the overwhelming majority of dislocations terminate at void surfaces, a situation in which the climb rate of dislocations can be strongly affected by pipe diffusion of defects into the

FIGURE 6. a) Deformation observed in pressurized tubes of 20% cold-worked AISI 316 irradiated in EBR-II at 550°C. Note that the total strain rate does not exceed 0.33%/dpa, even at very high stress levels. b) Density measurements on the 30 ksi pressurized tube show that stress accelerates the rate of swelling and its approach to 1%/dpa, but also causes the creep rate to approach zero at high swelling levels.

voids. This will tend to change the bias of the dislocation network. Second, the glide distance of dislocations will be decreased as the voids become the dominant obstacle. This will reduce the amount of creep that can occur for a given level of irradiation. Third, if the creep process is now restricted primarily to irradiation-induced climb of dislocations, one can envision a situation in which the SIPA creep mechanism⁽⁸⁾ may no longer operate effectively. This mechanism requires that the climb of dislocations lying on some planes is enhanced by the applied stress state while other less favorably oriented dislocations are inhibited in their climb rate. In short, this mechanism requires that dislocations lie on different planes with different Burgers vectors. Gelles and coworkers have recently shown that large applied stresses lead to an anisotropy of dislocations such that unfavorably oriented dislocations exist at substantially reduced densities while favorably oriented dislocations increase in density.^(9,10) Similar stress-induced anisotropies have been observed in the Frank loop population.^(11,12) Hence, the SIPA creep mechanism may not function very effectively after the stress state has substantially altered the dislocation and loop microstructure.

Since the diametral creep rate does saturate at approximately one-third of 1%/dpa, the latter being the steady-state swelling rate, this implies that stress-affected swelling itself is isotropic. Increases in volume require dislocation motion but the apparent disappearance of creep implies greatly reduced mobility

FIGURE 7. Comparison of the strains at 550°C of three pressurized tubes in the Heat Treat D condition with those at higher fluences shown in Figure 5.

FIGURE 8. Calculated creep strains for two pins shown in Figure 7, showing how the use of stress-free swelling camouflages the onset of the third major stage of creep.

of dislocations, or at least a reduction in their ability to sense and react to the stress state. This apparent paradox awaits the acquisition of more data before it can be resolved.

5.5 Conclusions

Coincident with the attainment of swelling levels in the range 5-10%, irradiation creep in AISI 316 appears to decline in rate and eventually vanish. There may be some relationship between this phenomenon and that of changes in failure mode that also appear to be related to swelling.

FIGURE 9. Creep Strains observed in annealed AISI 316 tubes irradiated at 550°C in EBR-II. All of these pins were found to have lost their gas pressure somewhere prior to their final examination.

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7.0 Future Work

This effort will continue, particularly in the area of possible relationships between swelling, creep and ex-reactor deformation.

8.0 Publications

None