

## EFFECTS OF STRESS ON SWELLING IN REACTOR FUEL CLADDING

J. F. BATES, E. R. GILBERT

*Hanford Engineering Development Laboratory, Westinghouse Hanford Company,  
P.O. Box 1970, Richland, Washington 99352, U.S.A.*

## SUMMARY

The purpose of this report is to describe the effect of stress on swelling in both annealed and 20% cold worked 316 stainless steel. An effect of stress on swelling in irradiated metals has been postulated for some time. Low fluence data confirmed that indeed a tensile stress can increase swelling in irradiated annealed 316 stainless steel and that the maximum swelling occurs at an intermediate stress level which is approximately equal to the proportional elastic limit of the material. The specimens discussed above were examined by transmission electron microscopy and an effect of stress on the microstructure of the annealed and 20% cold worked 316 specimens has been observed. However, as yet, copious swelling had not occurred in the 20% cold worked material. Specimens of 20% cold worked 316 fabricated from the same heat of material as those described above have now been irradiated to sufficiently high neutron fluences that swelling has occurred in both the annealed and cold worked conditions.

The specimens were 2.5 cm long, biaxially pressurized tubes, with an OD of 0.58 cm and ID of 0.51 cm. Stress levels ranged from 0 to ~400 MPa. Specimens were irradiated in EBR-II to maximum fluences ~53 dpa. Swelling in the specimens was evaluated by pre- and post-irradiation immersion density measurements.

The results of immersion density measurements indicate that stressing above the yield stress causes deformation which reduces swelling in the annealed material. A typical set of data for annealed 316 specimens irradiated at stresses from 0 to ~200 MPa at 430°C to fluences of ~20 dpa shows that maximum swelling occurs at an intermediate stress level ~138 MPa. For two stress levels, 138 and 200 MPa, the swelling is substantially less at the higher stress level. The high fluence data generated in the present experiment are consistent with the low fluence data generated earlier in that maximum swelling occurs at an intermediate applied stress rather than the maximum applied stress.

The cold worked data indicate that the swelling does not decrease after 138 MPa has been reached but in fact increases. In this respect, the effects of stress on the swelling behavior of the solution annealed and 20% cold worked 316 SS material appear to be different. Swelling in both 20% CW and solution annealed 316 stainless steel is increased by biaxially applied tensile stresses. Swelling increases linearly with stress for both materials. However, for solution annealed 316, swelling reaches a maximum at ~138 MPa, whereupon further increases in stress result in reduced swelling.

It is felt that this reduction in swelling is related to the onset of plastic yielding in the material. The swelling observed in the 20% CW 316 and the solution annealed 316 below the maximum swelling stress can be adequately described by an equation of the form:  $S = S_0(1 + P\sigma)$ . No strong effect of stress on changing the incubation period associated with void nucleation was found.

## 1. Introduction

An effect of stress on swelling in irradiated metals has been postulated for some time. Recently, experimental data confirmed that indeed a tensile stress can increase swelling in irradiated annealed 316 stainless steel [1]. It was also shown that the maximum swelling occurs at an intermediate stress level which is approximately equal to the proportional elastic limit of the material [1]. This effect has also been reported for pure nickel, i.e., maximum swelling occurred at a stress below the maximum experimentally applied stress [2]. The specimens discussed in reference [1] were examined by transmission electron microscopy and an effect of stress on the microstructure of the annealed and 20% cold worked 316 specimens has been described [3]. However, as yet, copious swelling had not occurred in the 20% cold worked material. Specimens fabricated from the same heat of material as those described in references [1] and [3] have now been irradiated to sufficiently high neutron fluences that swelling has occurred in both the annealed and cold worked conditions. The purpose of this report is to describe the effect of stress on swelling in both annealed and 20% cold worked 316 stainless steel.

## 2. Experimental Details

The experimental details of this experiment have been described previously [1,3] and only a description of the specimen geometry will be repeated here. The specimens were 2.5 cm long, biaxially pressurized tubes, with an OD of 0.58 cm and ID of 0.51 cm. Specimens were irradiated in EBR-II to maximum fluences around  $10^{23}$  n/cm<sup>2</sup> ( $E > 0.1$  MeV). Swelling in the specimens was evaluated by pre- and postirradiation immersion density measurements.

## 3. Results

Results from immersion density measurements of both the annealed and cold worked specimens are presented in Table I. The results listed in Table I indicate that stressing above the yield stress causes deformation which reduces swelling in the annealed material. The cold worked specimens were not stressed above the yield stress and hence show only increasing swelling with increasing stress. A typical plot of the annealed data is shown in Figure 1 for the specimens irradiated at 430°C to fluences of around  $4.0 \times 10^{22}$  n/cm<sup>2</sup> ( $E > 0.1$  MeV). Maximum swelling occurs at an intermediate stress level,  $\sim 138$  MPa. For the two stress levels, 138 and 200 MPa, the swelling is substantially less at the higher stress level. A least squares fit to the first three data points of Figure 1 results in a slope of  $\sim 0.006\%$ /ksi. At lower neutron fluences, the initial slope is steeper with the maximum in the swelling occurring at a lower stress, 70 MPa. This shift in maximum and initial higher slope may reflect an influence of stress on void nucleation which precedes steady state swelling. The slope of 0.006%/ksi provides a nominal fit for the first three stressed data points of the low fluence data set, as shown in Figure 2. The high fluence data generated in the present experiment, therefore, are consistent with the low fluence data generated earlier in that maximum swelling occurs at an intermediate applied stress rather than the maximum applied stress.

A plot of all the data in Table I is presented in Figure 3. Once the stress of  $\sim 138$  MPa has been exceeded in each of the sets of annealed data, the swelling is reduced. This is true for all of the annealed data sets. However, the cold worked data indicate that the

swelling does not decrease after 138 MPa has been reached but in fact increases. In this respect, the effects of stress on the swelling behavior of the solution annealed and 20% cold worked 316 SS material appear to be different.

#### 4. Discussion

In general, typical applied stresses in fuel pins and core components are below 138 MPa. Based on the data, it is reasonable to assume that the swelling is linear with the hoop stress to 138 MPa. If swelling is modeled in this manner, a formula similar to that used in reference [1] can be applied:

$$\frac{S}{S_0} = 1 + \frac{P\sigma_{\text{Hoop}}}{2}, \quad (1)$$

where  $\sigma_{\text{Hoop}}/2$  = hydrostatic stress.

If  $S/S_0$  is plotted versus  $\sigma_{\text{Hoop}}$ , the slope, in accordance with eq. (1), is equal to the coefficient  $P/2$ . Therefore, for plots of  $S/S_0$  versus stress, the  $P$  coefficients can be evaluated from the different slopes of the data sets. This was done directly for those data sets which include a zero stress data point, as shown in Figure 4. For those data sets which did not have a zero stress specimen included in the set, the extrapolated values of  $S_0$  were used.

There is a suggestion that the cold worked material may exhibit a higher  $P$  coefficient than the solution annealed material, as the slope of the cold worked data lies near the upper value of the slopes obtained from the annealed data. Equation (1) adequately represents all the data. The slope for the cold worked material is  $0.021 \text{ ksi}^{-1}$  ( $0.003 \text{ MPa}^{-1}$ ) and the slopes for the annealed material range from  $0.001$  to  $0.027 \text{ ksi}^{-1}$ , as shown on Figure 5. Thus, for 20% CW 316,  $P = 0.042 \text{ ksi}^{-1}$  ( $0.006 \text{ MPa}^{-1}$ ) and for solution annealed 316,  $P = 0.002$  to  $0.054 \text{ ksi}^{-1}$  ( $0.0002$  to  $0.0078 \text{ MPa}^{-1}$ ).

It has been suggested that stress can affect both void nucleation and void growth rate [4]. The development, represented by eq. (1), would be indicative of stress affecting primarily the swelling rate; however, this may not be the only operative mechanism. Certainly, the available immersion density data must be substantiated by transmission electron microscopy (TEM) to clearly define whether stress affects nucleation or both nucleation and growth. Transmission microscopy examination of low fluence solution annealed 316 specimens revealed that the void number density had increased with the applied stress [3]. In addition, the maximum void diameter had increased slightly with applied stress, while the mean void diameter had decreased due to the presence of a large number of small voids. The former observation indicates stress had increased the void swelling rate, and the latter indicates that stress had increased the void nucleation rate. The major effect was attributed to the nucleation phase of the swelling phenomenon. However, the specimens described both in references [1] and [3] were irradiated to relatively low fluences ( $0.28$  to  $2.7 \times 10^{22} \text{ n/cm}^2$ ,  $E > 0.1 \text{ MeV}$ ), and it is not surprising that a stress effect noticed in these specimens should be manifested in the nucleation phase. In all probability, the stress is affecting both the void nucleation and the swelling rate of the material.

In addition to a stress enhanced swelling rate as described in eq. (1), a prediction was made [5] that stress reduces the incubation period for swelling in accordance with the following equation:

$$\tau_e = \frac{\tau_0 + Q \sigma_{HYD} \tau_1}{1 + Q \sigma_{HYD}}, \quad (2)$$

where  $\tau_e$  = effective incubation fluence for swelling,

$\tau_0$  = stress-free incubation fluence,

$\tau_1$  = a postulated high stress limit for the incubation fluence,

$Q$  = material coefficient, and

$\sigma_{HYD}$  = hydrostatic stress =  $(\sigma_1 + \sigma_2 + \sigma_3)/3$ .

The maximum reduction, due to applied stress, in the fluence required for the onset of steady state swelling is given by  $\tau_0 - \tau_1$ . In reference [5], this value of  $\tau_0 - \tau_1$ , derived from fuel pin data, is  $2 \times 10^{22}$  n/cm<sup>2</sup> (E>0.1 MeV).  $\tau_0$  can be determined from the present stress-free data in Figure 5. Using  $\tau_0 - \tau_1 = 2 \times 10^{22}$  n/cm<sup>2</sup> (E>0.1 MeV),  $\tau_e$  was calculated, and is represented by the dashed line on Figure 5 for solution annealed 316 stainless steel.

The swelling predictions utilizing eq. (1) and (2) with  $P = 0.02$  psi<sup>-1</sup> (0.0029 MPa<sup>-1</sup>) and using the value of  $\tau_0 - \tau_1$  and the  $Q$  recommended in reference [5] are plotted in Figure 5 for a hoop stress of 63.4 MPa and for stress-free swelling. It appears that the model of eq. (2) over-predicts the effects of stress on the incubation fluence prior to the onset of steady state swelling. The effect of stress on swelling for these data can be adequately represented through a swelling rate modification in accordance with eq. (1).

The other item of significance inherent in this set of data is the reduction of swelling in the annealed material at high stresses. A mechanism for this reduction has been proposed [1]. Once the applied stress exceeds the stress required for plastic yielding, additional dislocations are generated which in turn act as additional sinks for reducing the vacancy super-saturation and hence reduce the swelling. [It is of interest to note that Harbottle's results (reference 2) were also for annealed material.] However, in the 20% CW material the dislocation density is already quite high. The generation of a few more dislocations would not significantly affect the total dislocation line length (sink density) and hence would not significantly influence the swelling.

## 5. Conclusions

(a) Swelling in both 20% CW and solution annealed 316 stainless steel is increased by biaxially applied tensile stresses.

(b) Swelling increases linearly with stress for both materials. However, for solution annealed 316, swelling reaches a maximum at ~138 MPa, whereupon further increases in stress result in reduced swelling. It is felt that this reduction in swelling is related to the onset of plastic yielding in the material.

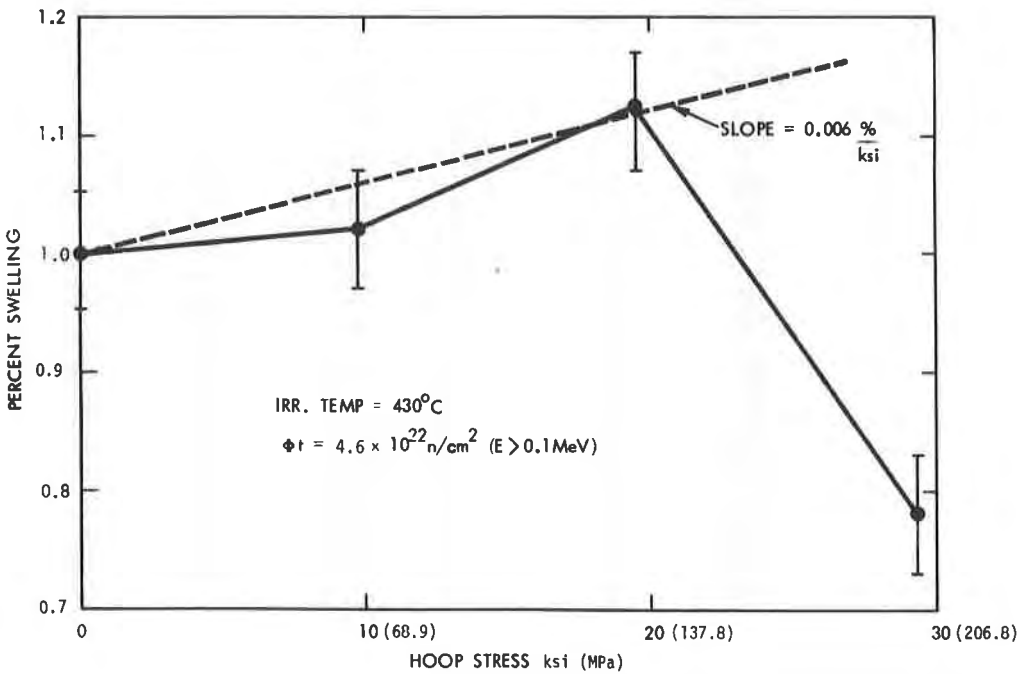
(c) The swelling observed in the 20% CW 316 and the solution annealed 316 below the maximum swelling stress can be adequately described by an equation of the form

$$S = S_0 (1 + P\sigma)$$

(d) No strong effect of stress on changing the incubation period associated with void nucleation was found.

References

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- [2] HARBOTTLE, J. E., Int'l Colloquium on Irradiation Creep, Petten, The Netherlands, May 5-6, 1975.
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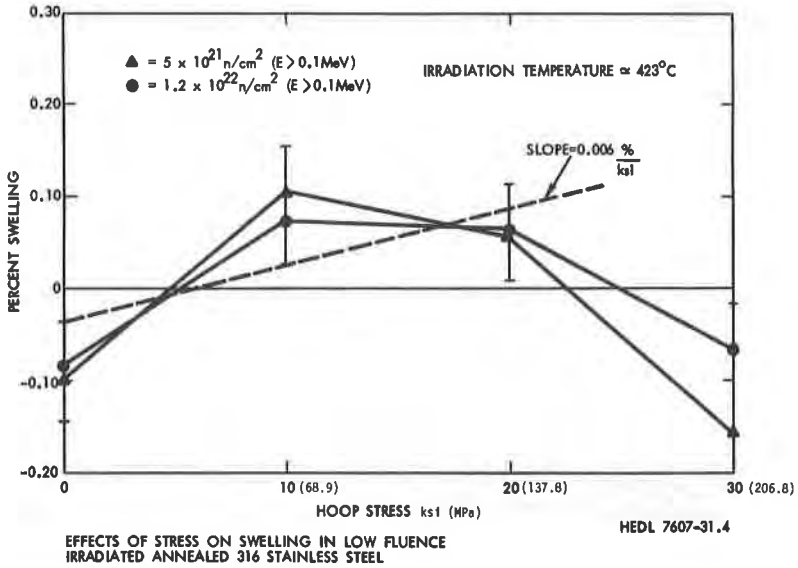
EFFECTS OF STRESS ON SWELLING IN ANNEALED 316 STAINLESS STEEL

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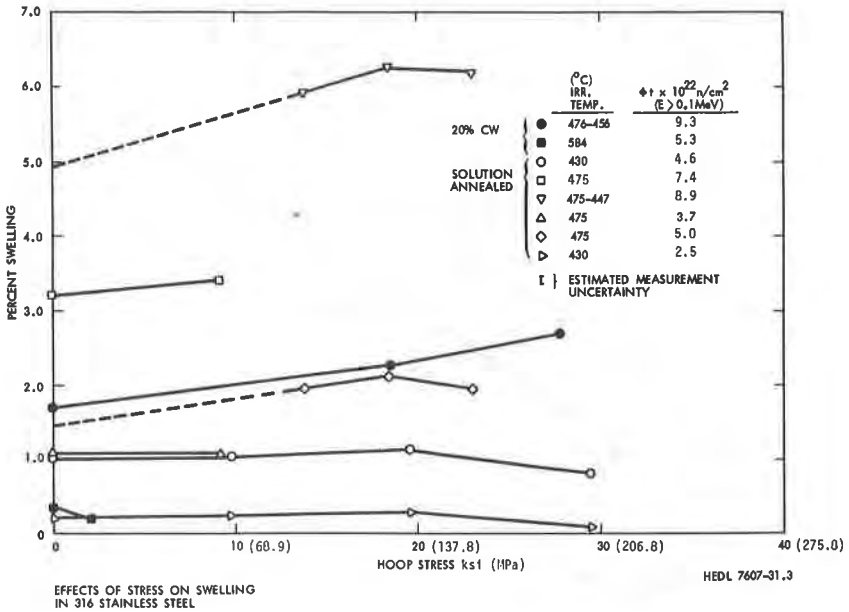
1. Effects of Stress on Swelling in Annealed 316 Stainless Steel.

TABLE I. DENSITY CHANGE DATA FROM X-157 FOR SOLUTION ANNEALED AND 20% COLD WORKED 316 STAINLESS STEEL

	Irradiation Temp. (°C)	Fluence $10^{22}$ n/cm <sup>2</sup> (E>0.1 MeV)	EBR-II Core Location		$\sigma_{\text{Hoop}}$ (ksi)	$-\Delta\rho/\rho_0$ (%)
			r (cm)	z (cm)		
<u>20% Cold Worked:</u>	377	3.1	13.5	-30	0	-0.019
	377	3.1	13.5	-30	40	-0.054
	377	3.1	16.5	-30	58.4	-0.003
	447	3.4	16.5	27.2	0	-0.031
	428	4.6	16.5	-23.6	34.2	0.038
	447	1.9	14.3	27.2	0	-0.046
	447	1.8	17.7	27.2	10	0.016
	419	3.5	17.7	-17.3	58	0.005
	477-472	4.7	17.7	8.1	0	-0.019
	477-472	4.7	17.7	8.1	18.5	-0.046
	477-472	4.7	17.7	8.1	27.7	-0.10
	528-518	4.6	17.7	-10.9	0	0.13
	587-582	5.2	17.7	1.8	0	0.36
	584	5.4	15.1	1.8	2.1	0.20
	477-456	9.3	13.5	8.1	0	1.69
	474-459	6.9	17.2	14.5	2.3	2.33
	477-456	9.3	13.5	8.1	18.5	2.27
	477-456	9.3	13.5	8.1	27.7	2.69
	508-480	6.6	16.5	-17.3	0	0.95
	<u>Solution Annealed:</u>	429	2.4	17.7	-23.6	0
428		2.5	14.3	-23.6	9.8	0.26
447		1.9	14.3	27.2	15.1	-0.036
429		2.4	17.7	-23.6	19.6	0.28
429		2.4	17.7	-23.6	29.4	0.080
419		3.6	15.1	-17.3	58.0	0.17
475		3.7	17.7	14.5	0	1.06
475		3.7	17.7	14.5	9.2	1.06
475		5.0	14.3	8.1	13.8	1.96
475		5.0	14.3	8.1	18.4	2.11
475		5.0	14.3	8.1	23.0	1.96
429		4.6	13.5	-23.6	0	1.00
428		4.6	16.5	-23.6	9.8	1.02
447		3.4	16.5	27.2	15.1	0.12
429		4.6	13.5	-23.6	19.6	1.12
429		4.6	13.5	-23.6	29.4	0.78
419-408		6.4	17.2	-17.3	58.0	1.32
475-471		7.4	13.5	14.5	0	3.21
475-471		7.4	13.5	14.5	9.2	3.42
475-447		8.9	16.5	8.1	13.8	5.93
475-447		8.9	16.5	8.1	18.4	6.26
475-447		8.9	16.5	8.1	23	6.20

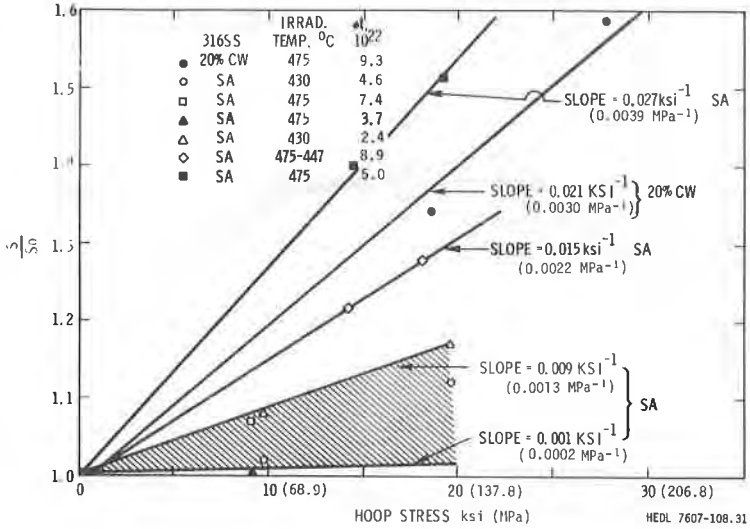


2. Effects of Stress on Swelling in Low Fluence Irradiated Annealed 316 Stainless Steel.

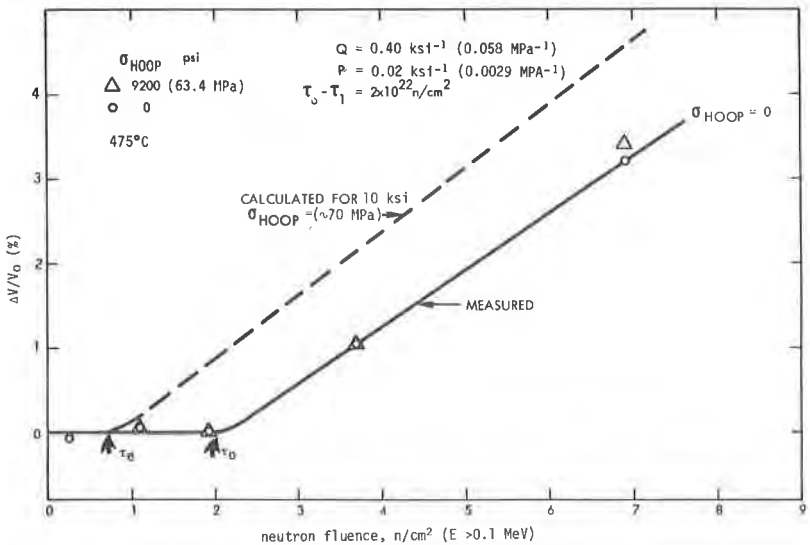


3. Effects of Stress on Swelling in 316 Stainless Steel.

**EVALUATION OF "P" COEFFICIENT IN 316 STAINLESS STEEL**



4. Evaluation of "P" Coefficient in 316 Stainless Steel.



EFFECT OF STRESS ON SWELLING  
SA 316 SS (HEAT V87210)

HEDL 7609-255.1

5. Effect of Stress on Swelling in SA 316 SS (Heat V87210)