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Effect of temperature gradients on void formation in modified 316 stainless steel cladding

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Abstract

Focusing on the effect of temperature gradients across the cladding wall on void formation, observation of void distribution was carried out by means of electron microscopic techniques in the direction of the wall thickness in the irradiated fuel claddings made of P, Ti-modified 316 steel. A deformation analysis was also conducted including irradiation creep and swelling deformation, using a finite element method. At the beginning of swelling a secondary stress occurred at the cladding surface due to non-uniform swelling arising from the temperature gradient. Swelling appears to accelerate by this secondary stress, and the swelling developed a non-monotonic distribution, namely the swelling in mid-wall region was lower than that in the surface regions. This non-monotonic swelling distribution disappears with increasing fluence, however. In the deformation analysis, it became clear that swelling is not continuously accelerated by the secondary stress, because irradiation creep deformation relaxes the stress. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

For energy generated by fission or fusion and removed as thermal energy, the heat must be conducted from fuel to the coolant through the metallic boundary between coolant and fuel, such as fuel cladding in fission reactors and first walls in fusion reactor. Therefore, these boundaries have some temperature gradient in the direction of thickness.

In general, some deterioration in the properties of material such as swelling occurs by radiation damage. It is generally known that the swelling behavior depends on irradiation temperature. Therefore, where the boundary material has a temperature gradient, there is a possibility of swelling gradient in boundary material depending on the temperature gradient. In this case, the swelling gradient generates a secondary stress in the boundary material, and this secondary stress can accelerate the swelling. If the secondary stress increases progressively due to increases of swelling, it is possible that swelling is significantly accelerated. It is obvious that this phenomenon may have large impact on the design and operation of nuclear reactor, if swelling is easily accelerated by stress.

In this paper, the influence of temperature gradient on swelling behavior across the cladding wall is investigated based on both microstructural observation and on analysis of stress history in irradiated fuel cladding.

2. Experimental procedure

Claddings were made of 20% cold-worked P, Ti-modified 316 stainless steels. These chemical compositions are listed in Table 1, and these nominal outer diameter and wall thickness are 6.5 and 0.47 mm, respectively.

These claddings were irradiated with mixed oxide fuel in the JOYO and the FFTF. After irradiation, specimens for examination were cut from some claddings and were defueled. The irradiation conditions of these specimens are shown in Table 2. These specimens were irradiated at an average mid-wall temperature of 773 K,

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Table 1
Chemical composition final heat treatment and cold work level

	Composition (wt%)										Final heat treatment	Cold work level (%)
	C	Si	Mn	P	Ni	Cr	Mo	B	Ti	Nb		
Lot 1	0.048	0.93	1.78	0.031	13.8	16.6	2.51	0.004	0.098	0.073	1358 K × 60s	19.0
Lot 2	0.057	0.79	1.85	0.028	13.7	16.3	2.54	0.004	0.075	0.093	1368 K × 60s	20.6

Table 2
Irraditation condition and results of swelling estimation

Specimen*			Temperature (K)**	Fluence ($\times 10^{26}$ n/m^2; $E > 0.1$ MeV)	Reactor	Swelling (vol.%)
Lot 1	A	I	802	15.4	JOYO	0.09
		M	786	[77.0 dpa]		
		O	771			
	B	I	801	17.3	JOYO	0.99
		M	783	[86.5 dpa]		
		O	766			
	C	I	804	17.8	JOYO	1.46
		M	786	[89.0 dpa]		
		O	769			
Lot 2	D	I	794	20.9		
		M	775	[104.5 dpa]	FFTF	5.2
		O	757			

* I; Inner surface, M; Mid-wall, O; Outer surface.
** Irradiation temperature is average value during irradiation term on each position.

and each had temperature gradients of ~40 K. And the temperature of these specimens fell slowly during irradiation, dropping about 30 K over the lifetime.

Density measurement of these specimens was carried out at first. After that, for the purpose of investigation of swelling distribution across the wall thickness of specimen, specimens for TEM and SEM observation were prepared from the same specimens as those used for density measurement. TEM observation was carried out on thin foil specimens that were sectioned from three regions in the direction of thickness, i.e. near-inner surface region, mid-wall region and near-outer surface region. One specimen was also observed across the entire cross-section of the cladding wall by means of SEM.

3. Experimental results

3.1. Density measurement

The swelling estimated from density change is shown in Table 2. It appears that specimen A, B and C are in the swelling transient period, and that specimen D is beyond the transient period.

3.2. TEM observation

Fig. 1 exhibits typical microstructures of specimens. From the microstructures of specimen A, irradiated to the lowest fluence, it is clear that void formation started first at the near-outer surface region. With increasing fluence, void formation began next at the near-inner surface region, and the mid-wall region swelled last. In specimen D, irradiated to the highest dose, the void structure was developed even in the middle region.

Fig. 2 shows void swelling estimated from the number density and mean diameter of voids in each region. The distribution of void swelling, void number density and void mean size in the direction of wall thickness are different from the initial stage of swelling transient period, e.g. specimens A, B and C, and the post-transient regime of specimen D. In the initial stage of transient, there is a peculiar non-monotonic difference of void structure in the direction of thickness. On the other hand, this difference becomes smaller near the final stage of transient.

3.3. SEM observation

The microstructure across the wall of specimen D was also observed by means of SEM. In this exam-

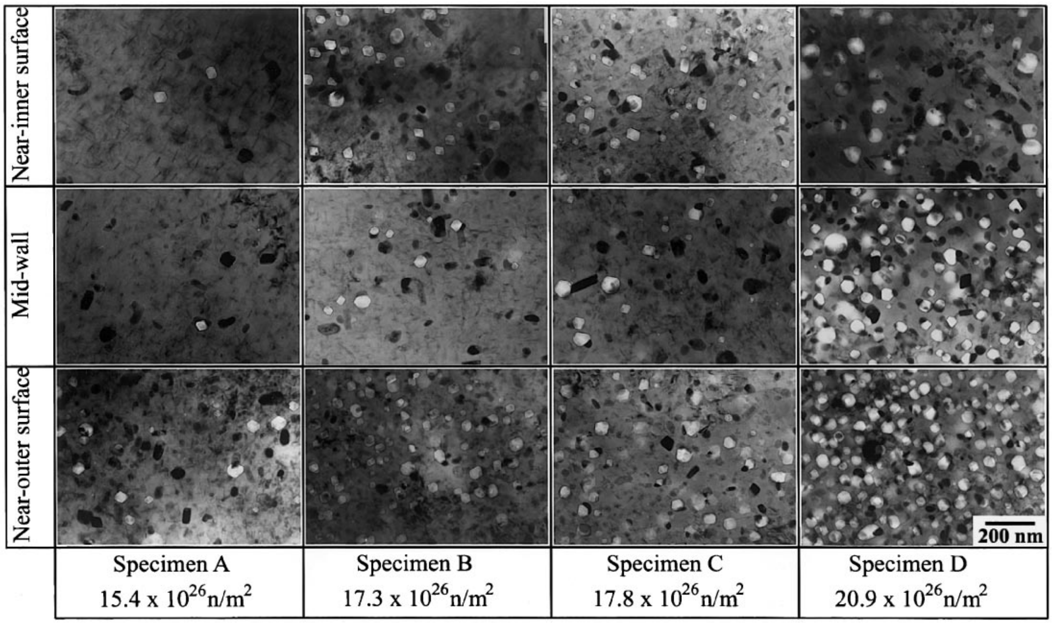

Fig. 1. Microstructure of several regions of all specimens.

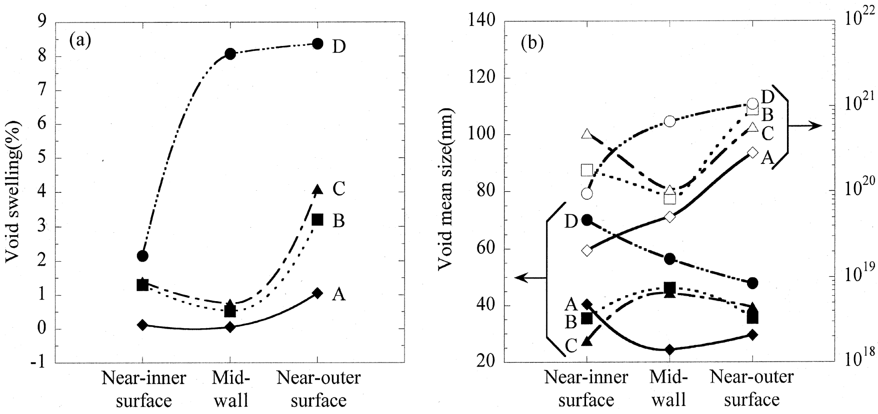

Fig. 2. (a) Void swelling and (b) void mean size and void number density at each region of all specimens.

ination, SEM images show many holes, which indicate positions where voids have been intersected on the cross-section surface of cladding. The distributions of hole mean size and hole surface density in the direction of wall thickness of specimen D are shown in Fig. 3. The distribution of hole surface density roughly follows the temperature gradient, although there are local density fluctuations. The distribution of hole mean size also roughly follows the temperature gradient, too. It seems, however, that the hole size at near-inner surface grew larger than at other regions.

4. Discussion

The temperature gradients examined in this study are estimated to be about 40 K. The difference in thermal expansion at the outer and inner surfaces of the cladding causes compressive and tensile stress, respectively. Another factor leading to an occurrence of a secondary stress is the difference in swelling across the cladding, which is originally due to the temperature dependency of swelling. It is also generally known that stress leads to accelerate swelling [1–6], primarily by shortening of the incubation period [5,6].

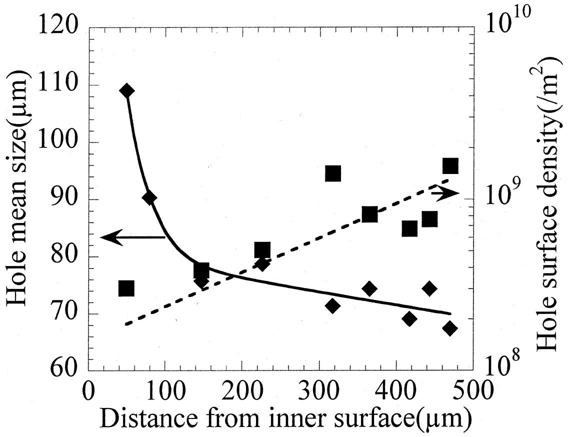

Fig. 3. Distribution of hole mean size and surface density across the wall thickness of specimen D.

Focusing on the influence of stress on swelling within the cladding during irradiation, analyses of deformation caused by stress history and swelling behavior was carried out by means of finite element method. The analytical model is composed of 51 sections of quadrangular-axis symmetrical-elements in the direction of wall thickness. The analytical conditions used were as follows:

- Each node was assigned an initial temperature condition of 293 K and an initial stress condition of 0 MPa before reactor start-up.
- Temperature of each node was calculated assuming a linear temperature gradient of 758 and 788 K between outer and inner surfaces.
- Fast neutron flux was 2.3×10^{19} n/m^2 s.
- Temperature and flux conditions were constant.
- The equation of irradiation creep was assumed SIPA and CCG models.
- The equation of swelling was assumed bilinear model.
- Parameter of stress induced swelling was derived from previous studies [4,5].

The results of analyses by the finite element method are shown in Fig. 4 for the fluence dependence of hoop stress and swelling. At the initial stage of the reactor operation, the hoop stress caused by the thermal expansion difference within the cladding is relaxed by the irradiation creep deformation. The hoop stress increases later due to swelling in the outer region. This stress then accelerated the onset of swelling not only in the outer surface region but also the inner surface and middle regions according to value of hoop stress. The stress is then relaxed, saturating at some value determined by irradiation creep when the differences of swelling in all regions are fixed in the steady state swelling regime. It is obvious that the swelling of cladding made of modified 316 stainless steel is not accelerated continuously by the temperature gradient within the cladding during irradiation, because the stresses due to the temperature and swelling gradient are relieved by irradiation creep.

5. Conclusion

Focusing on effect of temperature gradient across the cladding wall on void formation in modified 316 stainless steel, the influence of generated hoop stress on swelling behavior was investigated from both microstructural observations and FEM deformation analysis.

At the beginning of swelling, secondary stresses develop at the outer and inner surface of cladding due to

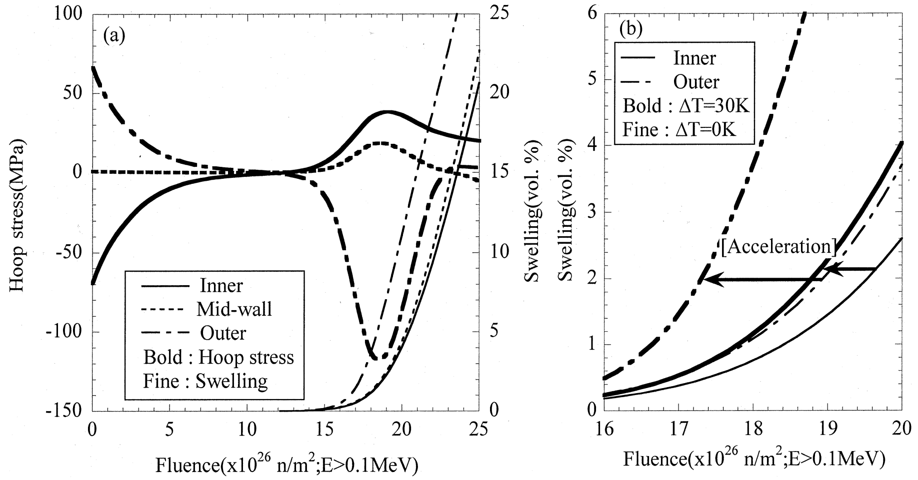

Fig. 4. Results of FEM deformation analysis: (a) fluence dependence of hoop stress and swelling, and (b) comparison of swelling behavior with and without temperature gradient.

the swelling gradient inducing the temperature gradient. Therefore, the swelling of each region is accelerated by this secondary stress, and the swelling gradient becomes non-monotonic. But the swelling of cladding is not continuously accelerated by the secondary stress since these stresses are eventually relieved by irradiation creep.

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