THEORETICAL AND EXPERIMENTAL ANALYSES OF CLADDING STRAIN PRODUCED BY EXPANSION OF CRACKED FUEL PELLETS

M. NAKATSUKA

*Energy Science and Technology Laboratory, Toshiba Research and Development Center
Toshiba Corporation, 1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki-city, Kanagawa 210, Japan*

T. SAKUYAMA

*Nuclear Engineering Department, Toshiba Corporation,
3-13-12 Mita, Minato-ku, Tokyo 108, Japan*

Fuel pellets should crack into small pieces due to the thermal expansion, when power is increased. These cracked pellets could cause stress and strain concentrations in the cladding tube, as a result of pellet-cladding mechanical interaction (PCMI), sometimes leading to cladding tube failure.

Analytic studies of the strain concentration in the cladding have been carried out by several investigators so far, using the assumptions of no gap between the cladding and pellet and the axisymmetric deformation of the cladding.

This paper presents a simplified equation for the strain concentration, taking the pellet-cladding gaps and non axisymmetric cladding deformation into consideration. The membrane and the bending strain were calculated individually, in order to evaluate the circumferential strain distribution in elastic analysis. Membrane hoop strains were obtained from a simple equilibrium condition. The bending strain, which is caused by differences in the radius of curvature between the pellet and the cladding, was obtained in this study, based on the bending theory for uniformly loaded plates with built-in edges.

The strain in the cladding, at a position facing the crack, was shown as follows;

$$\epsilon_{\max} = \frac{\mu\pi/N(r_{c2}-r_{c1})}{1 - \exp(-\mu\pi/N)r_{c1}} + 4h \left[\frac{(r_{c2}-r_{c1}+\delta)\sin^2(\pi/N)}{\cos(\pi/N)} + \delta \{ \cos(\pi/N) - 1 \} \right] \left(\frac{N}{\pi r_{c1}} \right)^2$$

where μ , N , h , δ , r_{c1} and r_{c2} are friction coefficient between fuel and cladding, number of cracks, thickness, radial gap and inner radius of cladding before and after deformation, respectively. The results of proposed equation showed good agreement with that proposed by G. Roberts, when the pellet-cladding gap equaled zero.

The fuel cladding used for the PCMI simulation tests are typical Zircaloy-2 tube. Pellets, with a copper tube in the center hole, were inserted in the cladding to form the test specimen. The copper tube was inflated by means of internal oil pressurization to expand the pellets and the cladding. Strain distribution on an external surface of the cladding was measured with 20 wire strain gauges.

The comparison of the experimental results with the calculated values derived from the proposed equation, showed relatively good agreement. The results of this study suggested that the bending of the cladding exerted a more dominant effect on the strain concentration than friction, unless there was a very high friction coefficient, or fuel-cladding bonding.

1. Introduction

Fuel pellets should crack into small pieces, due to thermal expansion, when reactor power is increased. These cracked pellets would cause stress and strain concentrations in the cladding tube as a result of pellet-cladding mechanical interaction (PCMI), sometimes leading to cladding tube failure [1-3]. Failure mechanism is believed to be stress corrosion cracking (SCC) due to the corrosive fission products from the discussion of the post irradiation examinations [4,5]. Stress or strain concentration in the cladding will assume one of the most dominant roles of SCC failure [6].

Analytic studies of the strain concentration in the cladding have been carried out by several investigators [7-11] so far, using the assumptions of a zero gap between the cladding and the pellet and axisymmetric cladding deformation. Recent post irradiation examination reveals that fuel cladding will be distorted non-axisymmetrically as a result of PCMI, and suggests that a rather large bending stress also exists as well as the membrane tensile stress in the cladding [12].

This paper presents a simplified equation for the evaluation of the strain concentration, taking the pellet-cladding gaps and non-axisymmetric deformation of the cladding into consideration. There have been few experimental studies published concerning strain distribution of actual fuel cladding, except an enlarged simulation test [13]. An experimental strain analysis is performed, using the Zircaloy-Z cladding. Experimental results comparison with calculated results, based on the derived equation, is also described.

2. Mathematical Analysis

2.1 Assumptions

Following assumptions are adopted to derive a simple equation for strain distribution in the cladding. The cladding in a reactor is assumed to deform in the same manner as the expanding mandrel method, which is conveniently used for the PCMI simulation, and for the cladding SCC sensitivity evaluation. Then, the radius of curvature for the cracked pellet is assumed not to change during deformation.

The pellet forms a number, N , of regularly spaced radial cracks. The external pressure is taken to be zero, and it is assumed that the normal pressure on the inner surface of the cladding is uniform and that the deformation is sufficiently small to be applied to an elasticity theory.

2.2 Cladding Deformation

Consider the non-axisymmetric deformation, W , as a result of pellet expansion in cladding (fig. 1,2). Deformation W_1 , due to the difference between the cracked pellet radius and the cladding, is obtained through the adoption of the sine formula to triangle OAB in fig. 2.

$$W_1 = (r_{c2} - r_{c1} + \delta) \left\{ \frac{\cos(\pi/N - \beta)}{\cos(\pi/N)} - 1 \right\} \quad (1)$$

where, r_{c1} , r_{c2} and δ are the cladding mean radii of pre- and post-deformation and the radial gap between the pellet and the cladding, respectively.

Deformation W_2 , as a result of the change in the cladding mean radius due to the

cracked pellet expansion, is similarly derived from triangle OCD.

$$W_2 = (r_{c2} - r_{c1})(1 - \cos \beta) \quad (2)$$

Now, the total deflection, W , is calculated from eqs. (1) and (2).

$$W(x) = e \left\{ \frac{1}{f} \cos(p - qx) - 1 \right\} + (e - \delta)(1 - \cos qx) \quad (3)$$

where, $e = r_{c2} - r_{d1} + \delta$, $p = \pi/N$, $f = \cos p$, $q = 1/r_{c1}$, $\beta = qx$ and x is the distance on the cladding measured from the fuel pellet cracks in the circumferential direction.

2.3 Strain Distribution

Bending strain near the position, which is half way between both ends of the pellet, due to the non-axisymmetric deformation can be obtained from the problem of uniformly loaded plates with built-in edges. From the theory of plates, bending strain, ϵ_B , bending moment, M and maximum deflection, d , become as follows.

$$\left| \epsilon_B(x) \right| = \left| M \right| \frac{h}{2D} \quad (4)$$

$$M(x) = g \left\{ -\frac{1}{2}x^2 + sx - \frac{1}{3}s^2 \right\} \quad (5)$$

$$d(x=s) = \frac{gs^4}{24D} \quad (6)$$

where $s = r_{c1} \pi/N$, h , D , g are cladding thickness, plate flexural rigidity and uniform load intensity, respectively.

Let the maximum cladding deflection be equal to that of the plates. Then, from eqs. (3) and (6):

$$g = \frac{24D}{s^4} \left\{ \frac{e}{f} \sin^2 p + \delta(f-1) \right\} \quad (7)$$

Substituting eqs. (5) and (7) into eq. (4), therefore:

$$\left| \epsilon_B(x) \right| = \frac{12h}{s^4} \left\{ \frac{e}{f} \sin^2 p + \delta(f-1) \right\} \left| \left\{ -\frac{1}{2}x^2 + sx - \frac{1}{3}s^2 \right\} \right| \quad (8)$$

Now, membrane strain, ϵ_M , and mean strain, ϵ_{mean} , can be obtained in the same way as a usual elastic analysis [11] without external pressure.

$$\epsilon_M = \epsilon_{M\text{max}} \exp(-\mu \theta) \quad (9)$$

$$\epsilon_{\text{mean}} = \int_0^p \epsilon_M d\theta \quad (10)$$

where $\epsilon_{M\text{max}}$ is the maximum membrane strain and μ is the UO_2 /cladding coefficient of friction.

For small strains, it may be possible to assume that $\epsilon_{\text{mean}} = (e - \delta)q$, $\theta = qx$. From eqs. (9) and (10) is obtained an expression for ϵ_M :

$$\epsilon_M(x) = \frac{(e - \delta)q\mu p \exp(-\mu qx)}{1 - \exp(-\mu p)} \quad (11)$$

From eqs. (8) and (11), total strain of the cladding, ϵ , can be expressed as follows:

$$\epsilon(x) = \frac{(e - \delta)q\mu p \exp(-\mu qx)}{1 - \exp(-\mu p)} \pm \frac{12h}{s^4} \left\{ \frac{e}{f} \sin^2 p + \delta(f-1) \right\} \left\{ -\frac{1}{2}x^2 + sx - \frac{1}{3}s^2 \right\} \quad (12)$$

where the plus and minus sign in the second term indicate outer and inner surfaces, respectively. When $x = 0$ and $\delta = 0$, the maximum strain concentration, $\epsilon_{\text{max}}/\epsilon_{\text{mean}}$ is,

therefore, given by:

$$\frac{\epsilon_{\max}}{\epsilon_{\text{mean}}} = \frac{\mu p}{1 - \exp(-\mu p)} \pm \frac{-4hq \sin^2 p}{p^2 \cos p} \quad (13)$$

2.4 Analysis Results

Most of the analysis presented heretofore assumed the zero gap between the pellet and the cladding and axisymmetric deformation. Recently, G. Roberts reported a method to analyze the non-axisymmetric deformation without the radial gap using polar coordinates and stress function. He obtained the hoop stress variation on the inner surface of the cladding, which has an interfacial pressure of 16 MPa and a modulus of 10^5 MPa, as shown in fig. 3, using Fourier expansions and a computer.

For comparison with the work, the results, which are computed from the proposed equation, eq. (12), with the same loading condition, are also shown in the figure. It is seen, from fig. 3, that the simplified equation, though it does not include the effect of the interfacial shear stress, agrees fairly well with the work reported by Roberts.

3. Experimental Analysis

3.1 Specimen Preparation

Fuel cladding used for the experiment is a typical Zircaloy-Z tube 16.460D, 14.70 ID and 130 mm long. Cladding diameter and thickness inspection is made with air gauge and ultrasonic technique.

The alumina (Al_2O_3), which is sintered to a thick-walled cylindrical shape, is divided circumferentially into 4 or 6 equal parts. The Al_2O_3 pellet is finished accurately to the desired diameter to substitute for the cracked fuel pellet by the centerless grinder after each part has been re-assembled with an adhesive material.

The cut Al_2O_3 pellets with a copper tube in the center hole are inserted in the Zircaloy-2 cladding to form the test specimen shown in fig. 4. The wire strain gauges of 1 mm gauge length and 2 mm pitch are plated on the outer surface of the cladding to measure the circumferential strain distribution.

3.2 Equipment Description and Strain Measurement

The local strain measurement system consists of a high pressure oil pump, electric micrometer to measure cladding deformation and a digital strain indicator, as shown in fig. 5. A test specimen is attached to the experimental assembly. The copper tube is connected to the high pressure pump, which increases an oil pressure to 1300 kg/cm^2 for 80 minutes, and is inflated by means of internal oil pressurization to expand the pellets and the cladding.

Strain distribution on an external surface on the cladding is measured at room temperature with 20 wire strain gauges intermittently. Oil pressure and the cladding diametral deformation are continuously monitored while being recorded.

The test specimen is cut diametrically after the measurements, in order to verify the angular position of the strain gauges measured from the radial cracks of the pellet.

3.3 Test Results and Discussion

One of the circumferential strain angular distribution results, which occurred on the external surface of the test specimen with four initial cracks, is shown in fig. 6. It appears, from the figure, that the strain reduction in cladding over the fuel cracks may be attributed to the bending effect which was pointed out in Section 2.3.

Friction coefficients μ between cladding i.e. Zircaloy-2 and (UO₂ or Al₂O₃) pellets at room and high temperatures, were measured preceding the present work [15]. Friction coefficient for this study appeared to be about 0.3 to 0.6 from the experiment. The curves computed with the proposed equation, eq. (12), and various friction coefficients are also presented in fig. 6.

Figure 7 shows the angular variation in circumferential strain for cladding with six equidistant radial cracks. The square and solid lines in the figure indicate the measured and calculated strain on the external surface, respectively.

A comparison between experimental results and calculated values, derived from the proposed equation, shows relatively good agreement. This reveals that there exists, on the internal surface, a large strain due to the bending component, as shown by the dotted lines in the figure, and that the bending of the cladding, due to the gap, exerts a more dominant effect than friction, unless there is a very high friction coefficient or fuel-cladding bonding.

It is seen from the figure that the strain concentration is underestimated if only the membrane strain, which is shown by the broken line, is accounted. For example, strain concentration at pellet cracks reaches up to about 1.9, while the one based on the axisymmetric deformation model, eq. (11), remains at 1.2, when the cladding/pellet friction coefficient equals 0.6.

When deformation is small, compared to the initial gap between pellet and cladding, the gap partially remained. The derived equation has a little restriction, because it is based on an assumption of uniformly distributed load. The mathematical analysis described above is based on the linear elastic theory, because SCC phenomenon under yield stress has attracted interest recently. Therefore, the derived simplified equation has to be applied for the problem which does not exceed the restriction considerably.

4. Conclusion

From theoretical and experimental analysis on strain concentration for a fuel cladding, the following conclusions are obtained.

- (1) The simplified equation, eq. (12), for calculating the cladding strain distribution which is occurred as a result of PCMI is derived, taking into consideration the pellet-cladding gaps, number of pellet cracks and friction coefficient between fuel and cladding.
- (2) Results from the proposed equation show good agreement with that based on the precise theory proposed by G. Roberts, when the pellet-cladding gap equals zero.
- (3) PCMI simulation tests, due to the expanding mandrel method, were performed using Zircaloy-2 cladding. Experimental results comparison with calculated results,

derived from the proposed equation, show relatively good agreement.

(4) The results of this study suggest that the bending of the cladding exerts a more dominant effect on the strain concentration than friction, unless there is a very high friction coefficient, or fuel-cladding bonding.

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Fig. 1 Fuel Crack Pattern Used in the Calculation

Fig. 2 Schematic Cladding Deformation Model Used in the Calculation

Fig. 4 Test Specimen

Cladding I.D.	= 10mm
Cladding Thickness	= 1mm
Cladding/Pellet Gap	= 0mm
Number of Pellet Cracks	= 10
Cladding/Pellet Friction Coefficient	= 1

Fig. 3 Angular Variation of Stress on the Inner Cladding Surface

Fig. 5 Schematic of Local Strain Measurement System

Fig. 6 Comparison between Measured and Calculated Strain Distributions for Specimen with 4 Fuel Cracks

Fig. 7 Comparison between Measured and Calculated Strain Distributions for Specimen with 6 Cracks