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On the FCMI Concern of SFR Fuel Rod

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1. Introduction

As a sequel to the previous study of an asymptotic analysis technique for pellet cladding mechanical interaction (PCMI) problem of the pressurized water reactor (PWR) fuel rods [1,2], present work is devoted to a similar problem of the sodium cooled reactor (SFR) metal fuels which is under developing at KAERI.

Different than the PWR fuels where ceramic pellets are used, the fuel material of the SFR (called 'slugs') is a metal (currently U-10Zr) so that the fuel cladding mechanical interaction (FCMI; here, the term 'fuel' is used instead of the 'pellet' of PWR fuels) may not be as critical as the PCMI of PWR reflecting its less brittle character and thus less possibility of cracking. However, it is necessary to investigate the propensity of FCMI failure in the design stage to predict a fuel safety, which is the purpose of the present work.

The analysis procedure follows what has been presented [1,2] but a finite element analysis result particularly for the SFR fuel rods are included in this paper and thus an actual stress and the von Mises stress values are to be shown.

2. Asymptotic analysis

The geometrical description of a FCMI problem is depicted in Fig. 1. The cladding tube, slug fragments of right and left sides are designated as body 1, 2 and 3, in order. Since the stress field very close to the sharp contact edge is of primary concern, the cladding tube may be assumed as a half plane with which two semi-infinite wedges of the cracked slug are in contact.

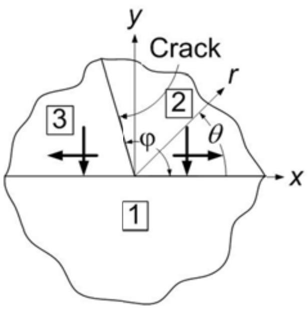


Fig. 1. Geometrical description of the FCMI contact.

Full procedure of the present asymptotic analysis can be consulted elsewhere [1,2]. Thus, only an essential step is reproduced here.

At first, an Airy stress potential is introduced such that

$$\Phi_i = r^{\lambda+1}\{a_i\cos(\lambda+1)\theta + b_i\sin(\lambda+1)\theta + c_i\cos(\lambda-1)\theta + d_i\sin(\lambda-1)\theta\} \quad (1)$$

where a_i, b_i, c_i and d_i (i designates the body number) are constants to be determined from the boundary conditions as follows.

$$\sigma^1_{r\theta}(r,0) = -\mu\cdot\sigma^1_{\theta\theta}(r,0),\ \sigma^2_{r\theta}(r,0) = -\mu\cdot\sigma^2_{\theta\theta}(r,0),$$
$$\sigma^1_{r\theta}(r,-\pi) = \mu\cdot\sigma^1_{\theta\theta}(r,-\pi),\ \sigma^3_{r\theta}(r,\pi) = \mu\cdot\sigma^3_{\theta\theta}(r,\pi),$$
$$\sigma^2_{\theta\theta}(r,\varphi) = 0,\ \sigma^3_{\theta\theta}(r,\varphi) = 0,\ \sigma^2_{r\theta}(r,\varphi) = 0,$$
$$\sigma^3_{r\theta}(r,\varphi) = 0,$$
$$\sigma^1_{\theta\theta}(r,0) = \sigma^2_{\theta\theta}(r,0),\ \sigma^1_{\theta\theta}(r,-\pi) = \sigma^3_{\theta\theta}(r,\pi),$$
$$u^1_\theta(r,0) = u^2_\theta(r,0),\ u^1_\theta(r,-\pi) = u^3_\theta(r,\pi). \quad (2)$$

where μ is the coefficient of friction on the slug and cladding interface.

Eq. (2) constitutes a simultaneous equation of twelve homogeneous equations having twelve unknowns, ai – di (i = 1,2,3), which can have non-trivial solutions only if the determinant of the coefficient matrix is null. As a result, there exists only one λ ($0 < \lambda < 1$) when $\varphi = \pi/2$ and $\mu > 0$. It is noted that a right angle crack and slipping apart of the slug fragments are assumed here.

In turn, λ and corresponding constants (a_i – d_i) yield the eigen-solutions of stress components. Then a generalized stress intensity factor, K, needs to be calculated incorporating the actual geometry and loading conditions, such as follows.

$$K = \lim_{r\to 0}\sigma_{\theta\theta}(r,\theta=0)\cdot r^{1-\lambda}. \quad (3)$$

Consequently, the stress components are to be expressed as follows.

$$\sigma_{ij}(r,\theta) = Kr^{\lambda-1}f_{ij}(\theta) + \text{non-singular bounded terms},\ (i,j = r,\theta) \quad (4)$$

where $f_{ij}(\theta)$ is the angular variation of the stress components.

3. Result

3.1 Data

Table 1 shows the material and dimension data of the present SFR fuel rod.

Table 1. Mechanical properties and dimension data for the present analysis

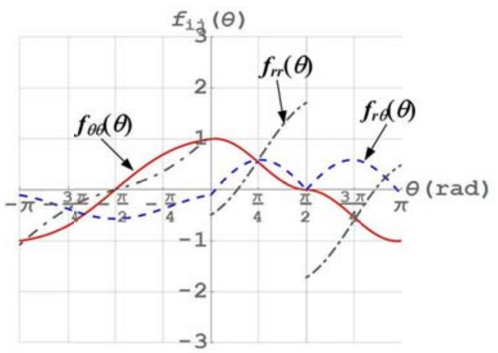
	E	v	OD	THK
HT9 clad,@400°C	173.245	0.33	7.4	0.5
U-10Zr slug, @650°C	107.266	0.35	5.54	-

E: Elastic modulus (GPa), v: Poisson ratio, OD: Outside diameter (mm, nominal), THK: Thickness (mm, nominal)

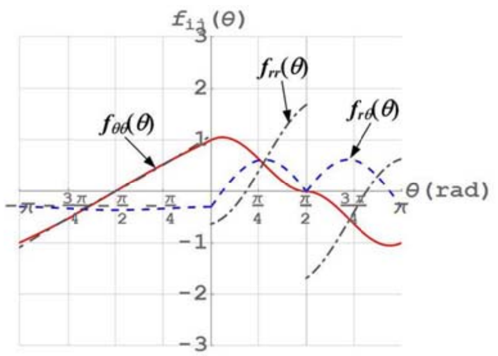
The presently designed SFR is operated under an atmospheric pressure. The fission gases released from the slug exerts pressure to the inner surface of the fuel rod. Simultaneously, a friction force takes place as well as contact forces on the contact surface of the slug and cladding as the slug expands. For the present analysis, the gas pressure and the contact pressure are set to 5.6 and 50 MPa, respectively. The friction coefficient between the slug and clad inner surface is assumed as 0.1 and 0.3.

3.2 Eige- Solutions

It was evaluated that λ = 0.769959 and 0.906783 for the friction coefficients, μ = 0.1 and 0.3, respectively. In turn, the angular variation of the stresses, $f_{ij}(\theta)$, ($i,j = r,\theta$) is obtained such as provided in Fig. 2. It shows the plots when the stress components are normalized by $f_{\theta\theta}(0)$, where θ = 0 means the fuel and cladding interface.



(a) μ = 0.1



(b) μ = 0.3

Fig. 2. Plots of $f_{ij}(\theta)$, ($i,j = r,\theta$).

3.3 Finite element analysis and generalized stress intensity factors

Fig. 3 shows the finite element model for the present FCMI problem. It is assumed that there are 10 equally spaced cracks in a slug. The plane strain condition is applied. The commercial code, ANSYS version 15, is used, and 'TARGE169' and 'CONTA172' are used for the contact elements [3].

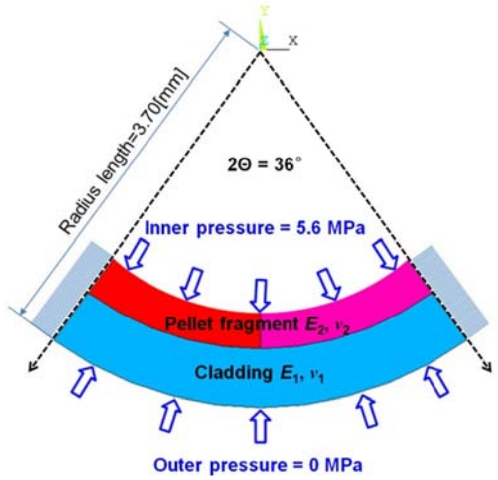
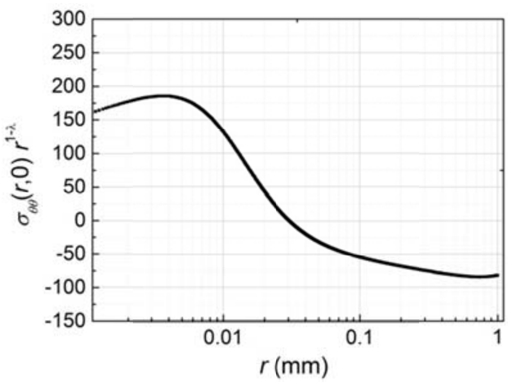
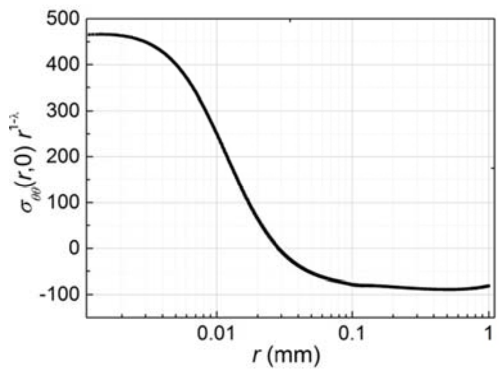


Fig. 3. Finite element model to obtain GSIF.

Fig. 4 illustrates the variation of $\sigma_{\theta\theta}(r,0)\cdot r^{1-\lambda}$ for μ = 0.1 and 0.3. Following the definition of Eq. (3), it reads that K = 190 MPa·mm$^{0.230041}$ and 470 MPa·mm$^{0.093217}$ for μ = 0.1 and 0.3, respectively.



(a) μ = 0.1



(b) μ = 0.3

Fig. 4. Behavior of $\sigma_{\theta\theta}(r,0)\cdot r^{1-\lambda}$.

3.4 Von Mises stress

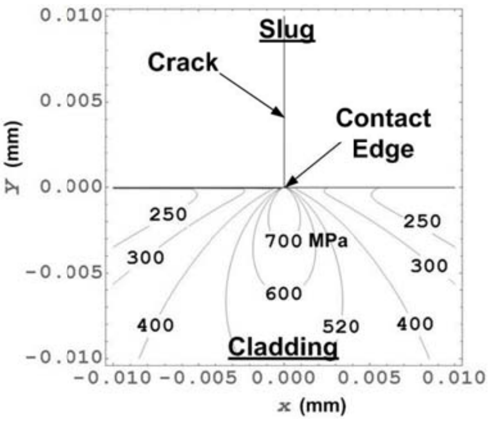
From the stress components, the von Mises stresses are calculated using the following equation.

$$\sigma_{VM} = \sqrt{3J_2} \quad (5)$$

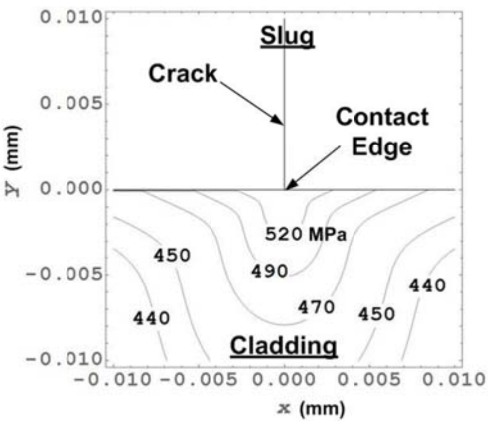
where J_2 is the 2^{nd} invariant of a deviatoric stress tensor defined as follows:

$$J_2 = \frac{1}{6}\left\{(\sigma_{rr} + \sigma_{\theta\theta})^2 + (\sigma_{rr} + \sigma_{zz})^2 + (\sigma_{zz} + \sigma_{\theta\theta})^2 \right. \\ \left. 6\left(\sigma_{r\theta}^2 + \sigma_{rz}^2 + \sigma_{\theta z}^2\right)\right\} \quad (6)$$

and $\sigma_{zz} = \nu \cdot (\sigma_{rr} + \sigma_{\theta\theta})$ with ν being the Poisson ratio of the cladding material.



(a) μ = 0.1



(b) μ = 0.3

Fig. 5. Von Mises stresses (MPa) in the cladding tube.

Fig. 5 shows the Von Mises stress values in the cladding tube in the vicinity of the contact edge formed by a slug crack. The observation area is set as ±0.01 × ±0.01 mm^2 with the center at the contact edge. Compared with the yield strength of HT9 at 400°C (521.9 MPa) [4], it is estimated that the size of the process zone, where a failure may be initiated, is around 0.01 mm and 0.003 mm in depth beneath the cladding-slug interface at μ = 0.1 and 0.3, respectively. These are regarded to be very tiny compared with the cladding thickness (0.5 mm). Therefore, it is thought that the FCMI failure will not be a critical problem in the SFR fuels.

5. Conclusions

The stress field in the vicinity of the contact edge between the cracked slugs and cladding inner surface is evaluated with using an asymptotic method to investigate a possibility of FCMI failure of the SFR fuels under developing at KAERI. The FCMI configuration is simulated as a frictional complete contact problem, and a relevant eigenvalue problem is constituted and solved. As a result, the stress components and von Mises stress field are obtained in the vicinity of the contact edge, which draws the following.

It is thought that an FCMI failure would not be a big concern for the present SFR fuels because of the following reasons. First, the stress components are bounded when a friction coefficient of the slug and cladding interface exceeds 0.3. If it is less than 0.3, a singular stress takes place. However, the process zone size is found very tiny compared with the cladding thickness even in the case of the friction coefficient being less than 0.3. Nonetheless, it may be suggested that the friction coefficient of the cracked slugs and cladding inner surface be larger than 0.3 to alleviate the FCMI failures further confidently.

ACKNOWLEDGMENT

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