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An Analysis of Kernel-Coatings Mechanical Interactions in a TRISO-Coated Fuel Particle using a Finite Element Method

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1. Introduction

The kernel-coatings mechanical interactions (KCMI) in a TRISO-coated fuel particle damage the integrity of the particle by creating an excessive load to coating layers during the fuel lifetime in a very high temperature reactor (VHTR). The kernel of a TRISO particle starts to push the buffer and the coating layers of the particle outward when it swells and contacts with the buffer under a neutron irradiation. It is necessary to quantify how much of a contact pressure is exerted on the coating layers.

This study developed a contact model for treating the KCMI using a finite element method. The contact model produces the contact pressures which are simultaneously acting on the surfaces between the layers in the TRISO particle. A stress distribution is calculated and compared for a particle with and without a KCMI.

2. Stress Analyses for a TRISO Particle using a Finite Element Modeling

The TRISO-coated fuel particle is a sphere which consists of a fuel kernel, a buffer layer, an inner pyrocarbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer pyrocarbon (OPyC) layer. There might be a gap between kernel and buffer or between buffer and IPyC. Total radial and tangential strains, a set of compatibility equation, and an equilibrium equation are given in a literature [1]. The following second-order differential equation can be obtained by mathematically manipulating the above-mentioned equations.

$$\begin{aligned}
&\frac{\partial^2 u}{\partial r^2}+\frac{g_{12}+2g_{11}-2g_{21}}{g_{11}}\frac{1}{r}\frac{\partial u}{\partial r}+\frac{g_{12}-2g_{22}}{g_{11}}\frac{u}{r^2}\\
&=\frac{\partial}{\partial r}\left(\varepsilon_r^{(n-1)}+\Delta\varepsilon_r^{th,(n)}+\Delta\varepsilon_r^{sw,(n)}\right)+\frac{g_{12}}{g_{11}}\frac{\partial}{\partial r}\left(\varepsilon_\theta^{(n-1)}+\Delta\varepsilon_\theta^{th,(n)}+\Delta\varepsilon_\theta^{sw,(n)}\right)-\frac{b_{11}}{g_{11}}\frac{\partial\sigma_r^{(n-1)}}{\partial r}-\frac{b_{12}}{g_{11}}\frac{\partial\sigma_\theta^{(n-1)}}{\partial r}\\
&+\frac{2}{r}\left(\frac{g_{11}-g_{21}}{g_{11}}\left(\varepsilon_r^{(n-1)}+\Delta\varepsilon_r^{th,(n)}+\Delta\varepsilon_r^{sw,(n)}\right)+\frac{g_{12}-g_{22}}{g_{11}}\left(\varepsilon_\theta^{(n-1)}+\Delta\varepsilon_\theta^{th,(n)}+\Delta\varepsilon_\theta^{sw,(n)}\right)\right)\\
&-\frac{2}{r}\left(\frac{b_{11}-b_{21}}{g_{11}}\sigma_r^{(n-1)}+\frac{b_{12}-b_{22}}{g_{11}}\sigma_\theta^{(n-1)}\right)
\end{aligned} \tag{1}$$

where r = radial coordinate (m), u = radial displacement (m), ε = strain, σ = stress (MPa), g_{ij} = element of a matrix $[G]$, b_{ij} = element of matrix $[B]$, i = 1, 2, j = 1, 2, $\Delta\varepsilon^{(n)} = \varepsilon^{(n)}-\varepsilon^{(n-1)}$, the superscripts ($n$), th and sw mean n-th time step, thermal and swelling, and the subscripts r and θ mean radial and tangential directions. The matrices $[G]$ and $[B]$ are as follows.

$$[G]^{(n)}=\left(\frac{1}{E^{(n)}}\begin{bmatrix}1 & -2\nu\\ -\nu & 1-\nu\end{bmatrix}^{(n)}+\omega\Delta\phi^{(n)}K^{(n)}\begin{bmatrix}1 & -2\mu\\ -\mu & 1-\mu\end{bmatrix}^{(n)}\right)^{-1}. \tag{2}$$

$$[B]^{(n)}=[G]^{(n)}\left(\frac{1}{E^{(n-1)}}\begin{bmatrix}1 & -2\nu\\ -\nu & 1-\nu\end{bmatrix}^{(n-1)}-(1-\omega)\,\Delta\phi^{(n)}K^{(n)}\begin{bmatrix}1 & -2\mu\\ -\mu & 1-\mu\end{bmatrix}^{(n-1)}\right). \tag{3}$$

where E = Young's modulus (MPa), ν = Poisson's ratio, K = irradiation creep coefficient (MPa 10^{25} $m^{-2})^{-1}$, μ = Poisson's ratio in creep, ω = relaxation factor, ϕ = fast neutron fluence (10^{25} m^{-2}, E > 0.18 MeV$)^{-1}$.

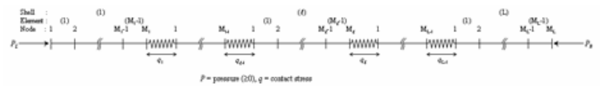

Fig. 1 Finite element divisions in multiple spherical layers

Fig. 1 shows a geometric finite element model for multiple layers under loads at both ends. Integrating Eq. (1) over the intervals in the finite elements in Fig. 1 by using the Galerkin method [2] and assembling the result equations gives the system of finite element equations.

$$\begin{bmatrix}[A_G] & [Y]\\ [X] & [0]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{q\}\end{Bmatrix}=\begin{Bmatrix}\{F_G\}\\ \{0\}\end{Bmatrix}+\begin{Bmatrix}\{F''_G\}\\ \{0\}\end{Bmatrix}+\begin{Bmatrix}\{F'_G\}\\ \{0\}\end{Bmatrix}, \tag{4}$$

where $\{u\}$ = displacement vector, $\{q\}$ = radial contact pressure vector, $[A_G]$ = stiffness matrix, $[X]$ = boundary- condition matrix, $[Y]$ = contact-condition vector, $\{F\}$ = load vector. The matrices $[A_G]$, $[X]$, and $[Y]$ and the vector $\{F\}$ are very lengthy, so their descriptions are omitted here. But they can be obtained easily. Eq. (4) calculates the displacements of the nodes in layers and the contact pressures exerting on the layer surfaces. Through the information about the displacements and contact pressures, the stresses and strains at every node of Fig. 1 are calculated.

3. Characteristics of a TRISO-Coated Fuel Particle for a KCMI Analysis

The dimensional data, material properties, and irradiation conditions of a TRISO-coated fuel particle chosen in this study are described in the IAEA CRP-6 normal operation benchmark case 13 [3]. The material properties were extracted from reference [4]. A UO_2 kernel was assumed to start swelling at a burnup of 6 GWd/tU at a rate of 0.077 volume % [5]. The gas pressure was calculated to be 83.06 MPa at a final burnup [6]. The gas pressure was assumed to increase linearly with a burnup.

4. Calculation and the Results

Fig. 2 shows the tangential stress of the inner surface of the SiC layer with and without a KCMI. At Fig. 2, the reason why the stress is very large in the case of a KCMI is that the buffer is assumed to be firmly adhered to the kernel and IPyC and to not be de-bonded during irradiation. Thus the buffer and IPyC layers simultaneously pull the SiC layer inward. Actually the buffer is de-bonded from the kernel or the IPyC layer at the early stage of an irradiation. The buffer layer just shrinks without pulling the IPyC and SiC layers. The de-bonding effect of the buffer layer should be included in the finite element model. At a fluence of 4.8×10^{21} nvt, the tangential stress with a KCMI starts to increase considerably when compared to that without a KCMI. The difference in the two stresses is about 300 MPa at a final fluence which is very harmful to a particle's integrity.

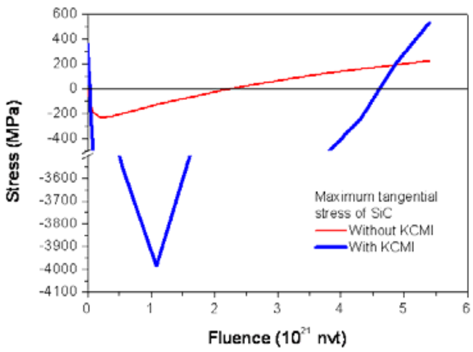

Fig. 2. Tangential stress of the inner surface of the SiC layer with and without a KCMI.

5. Conclusions

The KCMI was analyzed by utilizing a finite element model using the Galerkin method. A set of finite element equations, which were obtained through the method, explicitly calculates the layer displacements and the radial contact stresses between layers. In the model, the buffer layer was assumed to be firmly adhered to kernel and IPyC. The model has calculated the increase in the maximum SiC tangential stress due to a KCMI very well. The stress is, however, considerably large over the intermediate range of a fluence because a de-bonding of the buffer layer is not considered in the model. It will be included soon.

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