Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

An Analysis of Mechanical Interactions between a Kernel and Coating Layers in a TRISO-coated Fuel Particle

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1. Introduction

The integrity of a TRISO-coated fuel particle which is being used in a HTGR (high temperature gas-cooled reactor) fuel should be assured during a reactor operation. The kernel of a TRISO particle starts to push the buffer and the coating layers of the particle outward when it swells with a neutron irradiation and contacts with the buffer. Some computer codes treated the so-called kernel and coatings mechanical interactions (KCMI) [1,2]. These KCMI analyses showed that the KCMI increased the load acting on the coating layers of a particle

This study developed a contact model for treating the KCMI. The contact model produces an explicit expression of the contact force which is simultaneously acting on the kernel surface and the coating layers. A stress distribution and pressure build-up are calculated and compared for a particle with and without a KCMI.

2. Modeling for A KCMI

Fig. 1 shows the contact states of the kernel, buffer and coating layers of a TRISO-coated fuel particle 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. In the open state of Fig. 2(a), the kernel swells without a restraint or it is separated by the buffer. The inner surface of the IPyC layer is not affected by the kernel swelling. Only the gas pressure is acting on the surface. In the closed state of Fig. 2(b), the kernel swelling causes a mechanical load to the buffer and the coating layers. If the buffer is assumed to be a spring, the spring force is simultaneously acting on the kernel surface and the inner surface of the IPyC layer. The spring force is a contact force between the kernel and the coating layers. The contact force or contact pressure is also acting on the inner surface of the IPyC layer in addition to the normal gas pressure.

In order to obtain an explicit expression of the contact force in the closed state, it is assumed that the kernel experiences an elastic deformation, a thermal expansion, and a swelling, and the buffer experiences an elastic deformation and an isotropic thermal expansion. The radial displacement at the kernel surface can be obtained through total strains, compatibility equations, and an equilibrium equation for the kernel. The radial displacement of the buffer can be obtained by using the stress analysis for a spherical shell [3]. Since the displacement at a kernel surface is equal to that of the inner surface of the buffer in a contact state, the contact force becomes

$$F = 8\pi R^2 \frac{-\eta_K - \varepsilon_K^{sw} + \eta_B}{\left(n_{1,K} + \frac{n_{1,B} w_B + n_{2,B}}{1 - w_B} - \frac{3 n_{3,B}}{1 - w_B} \frac{R^2}{r_{i,I}^2} \right)} , \qquad (1)$$

where R is a kernel radius, $r_{i,I}$ is the radius of the IPyC inner surface, η_K is a thermal strain of a kernel, η_B is a thermal strain of a buffer, ε^{sw} is a kernel swelling, $w_B = (R/r_{i,I})^3$, $n_{1,K} = 2(1\text{-}2\nu_K)/E_K$, $n_{1,B} = 2(1\text{-}2\nu_B)/E_B$, $n_{2,B} = (1+\nu_B)/E_B$, $n_{3,B} = (1\text{-}\nu_B)/E_B$, and the subscripts K, B and I mean the kernel, buffer and IPyC layer, respectively. Since the contact force is less than zero in the closed state and the denominator in Eq. (1) is always greater than zero, the contact condition is that the thermal expansion and swelling of a kernel are greater than the thermal expansion of a buffer.

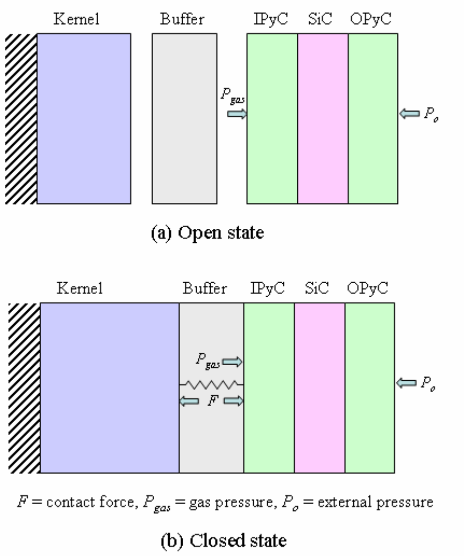

Figure 1. Contact states of the kernel and coating layers.

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 [4]. The material properties were extracted from reference [5]. A UO_2 kernel was assumed to start swelling at a burnup of 6 GWd/tU at a rate of 0.077 volume % [6]. The gas pressure was calculated to be 83.06 MPa at a final burnup [7]. 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 the burnup of 6.4 %FIMA, the tangential stress with a KCMI starts to increase considerably when compared to that without a KCMI. The burnup of 6.4 %FIMA is equivalent to 6 GWd/tU in a UO_2 kernel. The difference in the two stresses is 314 MPa at a final burnup which is very harmful to the particle's integrity. Fig. 3 presents the gas and contact pressures acting on the inner surface of the IPyC layer. The magnitude of the contact pressure starts to increase at a burnup of 6.4 %FIMA and it becomes greater than the gas pressure at a final burnup.

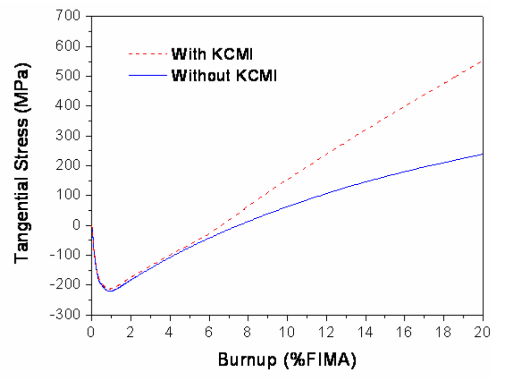

Figure 2. Tangential stress of the inner surface of the SiC layer.

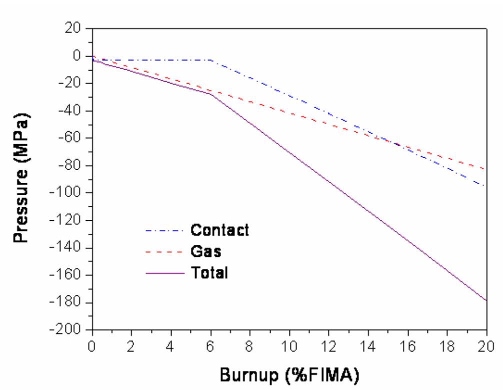

Figure 3. Gas and contact pressures.

5. Conclusions

A spring model in which the buffer layer was assumed to be a spring was devised to explicitly express the contact pressure acting on the inner surface of the IPyC layer. It was suggested from the spring model that the KCMI occurred when the thermal expansion and swelling of the kernel were greater than the thermal expansion of the buffer, and when the width between the inner surface of the IPyC and the kernel surface was less than the initial buffer thickness.

After the kernel started to swell from a specific burnup, the contact force became very large and caused a steep increase in the tensile tangential stress of the SiC inner surface. It is expected that the plasticity, creep, and densification of the kernel, and the irradiation-induced creep and dimensional change of the buffer will reduce the contact load due to a kernel swelling. A kernel swelling, however, was still judged to be one of the major factors for causing a particle failure at a higher burnup.

Acknowledgment

This work has been carried out under the Nuclear Research and Development Program supported by the Ministry of Science and Technology in the Republic of Korea.

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