Mechanical Analysis of TRISO Particles in a Stiff Matrix

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1. Introduction

Fully ceramics microencapsulated (FCM) fuels consist of coated fuel particles embedded in silicon carbide matrix. [1] SiC matrix in the FCM is formed by NITE progress which results in a high density (above 90% TD of β-SiC) one. This dense matrix is considered as additional barrier against release of radioactivity to the coolant system. SiC is resistance to air, steam oxidation up to very high temperature. [2] High chemical resistance and high thermal conductivity of SiC matrix provide higher safety measure than low density graphite matrix of conventional HTGR fuel.

Silicon carbide coating layer in a TRISO particle provides barrier to the fission products generated during nuclear power generation by uranium fuel kernel. Integrity of SiC layer is critical for the safety performance of FCM fuel. Mechanical stress analysis is essential as well as irradiation test to understand failure mechanism of TRISO fuel particle. Most of TRISO fuel performance code deployed the one dimensional spherical method developed by Prados and Scott. [3] In a FCM, NITE SiC matrix is strongly interact with TRISO particles. We are presenting a realistic 3D method for FCM performance analysis.

2. Stress Analysis

2.1. Description of mechanical system

Field equation of motion in a solid structure under free body force is written in tensor notation as follows;

$$\sigma^{ji}_{,j} = 0 \quad \text{and}$$

$$\varepsilon_{ij} = u_{i,j} \ .$$

where σ , ε , and u are stress tensor, strain tensor, and displacement vector, respectively. Stress and strain tensors should be symmetric to be a physical quantity. For FCM fuel where all composing materials are ceramics, the rheological model is adopted. [4]

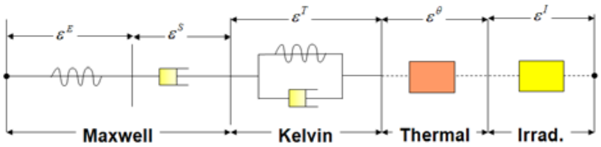

Figure 1. Rheological strain model

The strain tensor, ε, is sum of 5 components; elastic strain ε^E, transient creep strain ε^T, steady state creep strain ε^S, thermal strain ε^θ, and irradiation strain ε^I as shown in Figure 1.

Equation correlating the strain and stress is expressed as follows with further approximation on transient creep strain as suggested by CEGA [5];

$$\varepsilon = \varepsilon^E + \varepsilon^T + \varepsilon^S + \varepsilon^\theta + \varepsilon^I \ ,$$

$$\sigma = C^E \varepsilon^E \ ,$$

$$\varepsilon^T = M^T \sigma \ ,$$

$$\varepsilon^S = M^S \sigma \ ,$$

$$\varepsilon^\theta = \alpha\left(T - T_0\right) \ ,$$

$$\varepsilon^I = \varepsilon^I\left(\Phi\right) \ ,$$

where C is the elastic modulus tensor, M is the compliance tensor, α is the thermal expansion coefficient of material, and Φ is the fast neutron fluence. All coefficients are either isotropic or transverse isotropic. In this instance, we will have at most 5 independent values for each coefficient. T_0 is the reference temperature. For TRISO particle which is coated at elevated temperature, it is reasonable to set the coating temperature as the reference temperature. For FCM matrix, NITE melting temperature is set as the reference temperature.

Above relations between stress and strain can be arranged as following form.

$$\sigma^{ij} = C^{ijkl}\left(\varepsilon_{kl} - \varepsilon^0_{kl}\right) \ .$$

The rank 4 effective elastic modulus tensor C^{ijkl} should satisfy the major and minor symmetry condition to satisfy symmetry conditions required for σ^{ij} and ε_{kl} (ε^0_{kl}).

Spherical TRISO particles embedded in a matrix can be effectively modeled as a periodic lattice of body centered crystal. This system can be solved by a two scale asymptotic expansion method. [6] Two scale asymptotic expansion method were revisited recently and applied to stress-strain analysis using finite element method. [7]

Two step asymptotic expansion method was successfully applied to find temperature distribution in a TRISO compact and a prismatic block fuel by author. [8] In TRISO thermal diffusion problems, the slowly varying solution is of little interest since thermal conductivity in matrix zone is very high. More interest is on kernel part due to high heat generation.

A compact is usually inserted in a graphite block or a clad tube with sufficient gap. Matrix material such as graphite and silicon carbide has very small thermal expansion coefficient. In this regards, we can approximate external boundary condition of a compact as free boundary. Considering that the largest driving force for stress is the IIDC of pyrolytic graphite, we can also approximate free boundary at the BCC lattice.

2.2. One dimensional method

A BCC lattice may be further approximated as an isotropic sphere. In this situation, we can utilize existing fuel performance code developed for TRISO fuel with slight modification. [9] In case of conventional HTGR fuel, TRISO is surrounded by over-coating layer and low density graphite. Most TRISO performance code assumes free stress condition after outer pyrolytic (oPyC) coating. For FCM, additional layer to consider the matrix is necessary since refractory NITE SiC matrix limits displacement of oPyC.

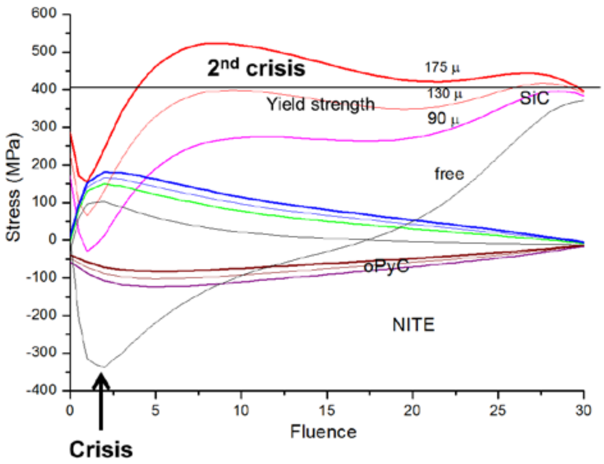

Figure 2. Stress variation according to fluence

Figure 2 shows variation of tangential stress as depletion according to "effective thickness" of NITE matrix. For conventional TRISO where free boundary condition is imposed at oPyC, expansive stress at SiC coating layer in early stage due to irradiation induced compression of PyC layers is important. After first crisis, mechanical stress of TRISO particle is lessened until high fluence where oPyC expansion results compressive stress on the SiC coating layer. Depending on the effective thickness of NITE SiC, maximum stress of SiC can be higher than the yield strength. So, it is critical to find "effective thickness" of NITE SiC matrix appropriate for one-dimensional analysis.

2.3. Three dimensional model

TRISO in a compact can be modeled as a periodic body centered cubic lattice (BCC). Periodic boundary condition is imposed at cubic faces. Considering that the boundary condition of a fuel compact is free, the boundary condition at cubic faces can be approximated as free stress.

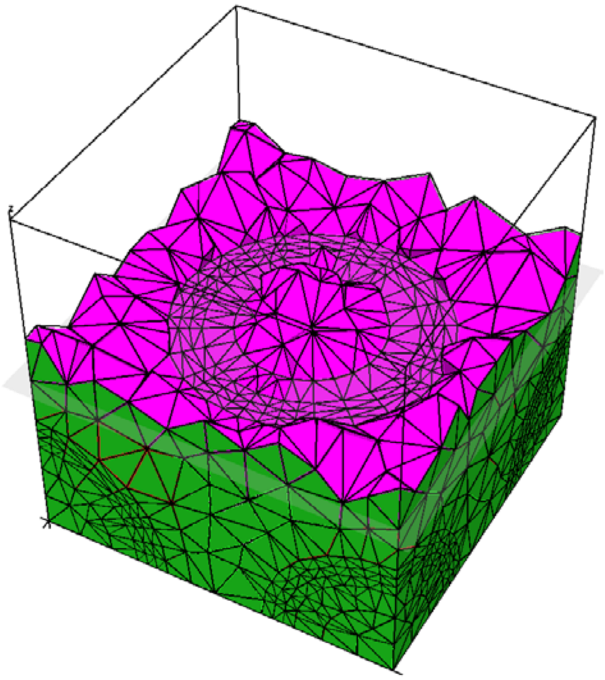

Figure 3. Three dimensional nodalization

Figure 3 shows an example of tetrahedron finite element nodalization.

Material such as fuel kernel, SiC coating layer, NITE SiC matrix is considered as an isotropic material. However, the pyrolytic carbon coating layer has strong anisotropy depending on the manufacturing process. Due to floating bed CVD coating process, the transverse isotropy along the parallel plane to the surface of TRISO appears. It is simple problem to handle such transverse isotropy in 1D spherical model where transverse axe coincide with radial direction. However in 3D Cartesian model, we need to rotate the 4th rank elasticity tensor properly along radial axis from center of the TRISO.

$$C^{ijrs} = \mathbf{g}_m^i \mathbf{g}_n^j \mathbf{g}_p^r \mathbf{g}_q^s C^{mnpq}$$

where, $\mathbf{g}_m^i = \cos(i,m)$, the angle cosine between two axis i and m. With weak formulation, FEM matrix coefficient can be obtained by an integral over tetrahedron elements, where the stiffness matrix is evaluated at the center of the tetrahedron. Standard sparse matrix solver can be used to find the displacement vector.

3. Conclusion and Further Study

Existing 1D TRISO stress analysis code is extended to handle NITE SiC matrix as an additional layer. It was found that there are strong dependence on the "effective thickness" of NITE SiC matrix.

A 3D finite element model to handle TRISO particle which has transverse isotropy in spherical coordinate system is developed in this study. We presented the developed formula in this submission. The calculation result will be presented at the conference.

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