Stress Analysis of a TRISO Coated Particle Fuel by Using ABAQUS Finite Element Visco-Elastoplastic Solutions

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1. Introduction

The fundamental design for a gas-cooled reactor relies on an understanding of the behavior of a coated particle fuel. KAERI, which has been carrying out the Korean VHTR (Very High Temperature modular gas cooled Reactor) Project since 2004, is developing a fuel performance analysis code for a VHTR named COPA (COated Particle fuel Analysis). A validation of COPA was attempted by comparing its benchmark results with the visco-elastic solutions obtained from the ABAQUS [1] code calculations for the IAEA-CRP-6 TRISO coated particle benchmark problems involving a creep, swelling, and pressure[2].

However, the ABAQUS finite element model used for the above-mentioned analysis did not consider the material nonlinearity of the SiC coating layer that showed stress levels higher than the assumed yield point of the material. In this study, a consideration of the material nonlinearity is included in the ABAQUS model to obtain the visco-elastoplastic solutions and the results are compared with the visco-elastic solutions obtained from the previous ABAQUS model[2].

2. Methods and Results

2.1 ABAQUS Finite Element Model for Visco-Elastoplastic Analysis

The finite element(FE) model deals with the stresses in three load-bearing layers of the TRISO coated particle: the inner pyrocarbon (IPyC) layer, the SiC barrier layer, and the outer pyrocarbon (OPyC) layer. The two- dimensional finite element model is shown in Figure 1 by representing a quarter of a sphere. The elements are four-noded axisymmetric quadrilaterals (CAX4 in ABAQUS). The nodes along the bottom surface extend along the equator of the sphere. To enforce a spherical symmetry of the model, the nodes along the horizontal and the vertical surface of the model are constrained to move only in the radial direction. Elements are grouped together in logical sets to allow for a specification of the material properties for the PyC and the SiC. The yield stress of the SiC layer was assumed to be 350 MPa and was also assumed to strain harden to the ultimate tensile strength of 400 MPa[4]. Because of the anisotropic nature of the PyC irradiation induced dimensional changes, the material properties are evaluated at the integration points in a spherical coordinate system: The first component direction is aligned along the radial direction, and the second and the third are aligned in the hoop direction. The stresses reported below are taken from this intrinsic spherical coordinate system. Fission gas pressure is applied to the inner surface of the IPyC layer and the external ambient pressure is applied to the outer surface of the OPyC layer.

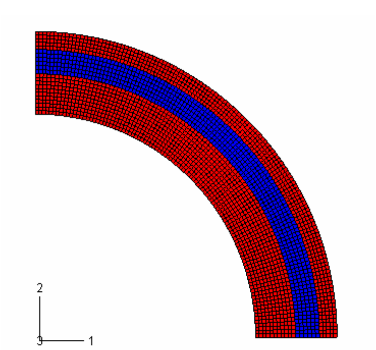

Figure 1. ABAQUS 2-D Finite Element Model for TRISO Coated Particle Fuel

2.2 Comparison between the ABAQUS Visco-Elastic Solutions and the Visco-Elastoplastic Solutions of Miller's Case

The problem selected for a comparison is adopted from Miller's publication[3] which provides the dimensions, applied pressures, an irradiation temperature, creep coefficients, and swelling rates of a nominal target particle. The particle is irradiated to a fluence (E>0.18 MeV) level of 1.5×10^{25} n/m^2 in the problem. In order to get the visco-elastoplastic solutions of the TRISO coated particle fuel the material nonlinearity of the SiC layer is considered. Consideration of the material nonlinearity of the SiC layer has its basis in the previous results from the CRP-6 calculation by using the ABAQUS finite element visco-elastic analysis model[2].

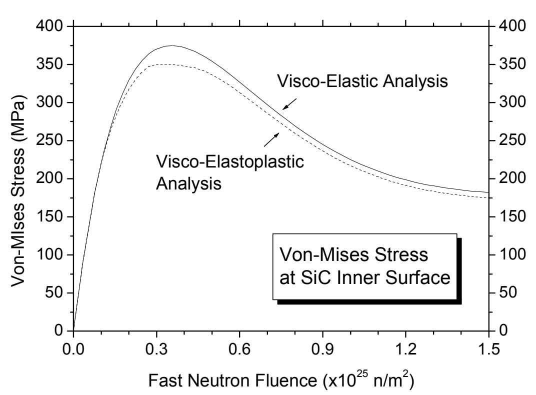

Figure 2. Von-Mises Stress of the SiC Layer Resulted from the ABAQUS Visco-Elastic and the Visco-Elastoplastic Analysis at SiC Inner Surface

As is seen in Figure 2, the maximum stress reached about 375 MPa around the neutron fluence of 0.3×10^{25} n/m^2 in the visco-elastic solution. That is, the stress intensity exceeds the yield stress of the SiC coating layer and it means that material nonlinearity could be considered in this case.

Comparison of the ABAQUS results from the visco-elastic solutions and visco-elastoplastic solutions is presented in table 1, where the values calculated for four stress components at the end of an irradiation are listed. The stress σ_T is the tangential stress at the inner surface of the SiC layer. This value is crucial because it determines the failure of a particle. Subscripts r and t represent the radial and the tangential directions and subscripts I and O represent the interfaces between the IPYC and the SiC layers and the OPYC and the SiC layers, respectively. In the first case considered in table 1, no internal or external pressures are applied. In the second case of table 1, an internal gas pressure and an external ambient pressure are applied. In both cases, ABAQUS visco-elastic solutions show a quite good agreement in results with Miller's solutions. However the ABAQUS visco-elastoplastic calculations of the σ_T, the tangential stresses at the inner surface of the SiC layer show a comparatively large difference from those of ABAQUS visco-elastic or Miller's solutions regardless of the application of the pressures.

Table 1. ABAQUS results vs. Miller's derivation

Stress Components	ABAQUS Results (MPa) elastoplastic	elastic	Miller's Derivation (MPa)
Without pressures			
σ_{rI}	20.73	20.77	21.36
σ_{rO}	-7.13	-7.13	-7.59
σ_{tO}	55.8	55.8	56.68
σ_T	-155.3	-163.0	-165.3
With pressures			
σ_{rI}	-8.58	-8.22	-7.94
σ_{rO}	-13.64	-13.99	-14.11
σ_{tO}	50.45	50.44	51.34
σ_T	-35.22	-45.39	-47.69

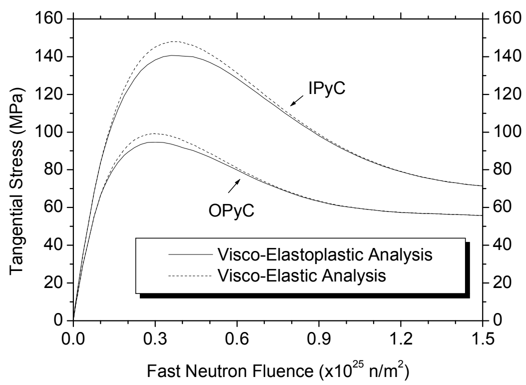

Figure 3. Von-Mises Stress of the PyC Layers from the ABAQUS Visco-Elastic and the Visco-Elastoplastic Solutions

Figure 3 presents the Von-Mises stress of the PyC layers, as a function of the fast neutron fluence, resulting from the ABAQUS Visco-Elastic and the Visco-Elastoplastic Solutions. The stress levels of PyC layers from the visco-elastoplastic analysis is 4% to 5% lower that that of visco-elastic analysis. That is, the material nonlinearity assumed in the SiC layer affects the static behavior of the adjacent PyC layers.

3. Conclusion

Visco-elastoplastic analysis that considered the material nonlinearity of the SiC layer of a TRISO coated particle fuel was performed. The results were compared to that of the visco-elastic analysis.

As for the SiC layers, the visco-elastoplastic analysis presented 6% lower stress levels than the visco-elastic analysis did.

The stress levels of the PyC layers from the visco-elastoplastic analysis are 4% to 5% lower that that of visco-elastic analysis. That is, the material nonlinearity assumed in the SiC layer affects the static behavior of the adjacent PyC layers.

Acknowledgement

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