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Stress Calculation of a TRISO Coated Particle Fuel by Using a Poisson's Ratio in Creep Condition

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1. Introduction

KAERI, which has been carrying out the Korean VHTR (Very High Temperature modular gas cooled Reactor) project since 2004, has been developing a performance analysis code for the TRISO coated particle fuel (figure 1) named COPA (COated Particle fuel Analysis)[1][2]. COPA predicts temperatures, stresses, a fission gas release and failure probabilities of a coated particle fuel in normal operating conditions. KAERI, on the other hand, is developing an ABAQUS based finite element(FE) model to cover the non-linear behaviors of a coated particle fuel such as cracking or debonding of the TRISO coating layers[3]. Using the ABAQUS based FE model, verification calculations were carried out for the IAEA CRP-6 benchmark problems involving creep, swelling, and pressure[4]. However, in this model the Poisson's ratio for elastic solution was used for creep strain calculation.

In this study, an improvement is made for the ABAQUS based finite element model by using the Poisson's ratio in creep condition for the calculation of the creep strain rate. As a direct input of the coefficient in a creep condition is impossible, a user subroutine for the ABAQUS solution is prepared in FORTRAN for use in the calculations of the creep strain of the coating layers in the radial and hoop directions of the spherical fuel. This paper shows the calculation results of a TRISO coated particle fuel subject to an irradiation condition assumed as in the Miller's publication[5] in comparison with the results obtained from the old FE model used in the CRP-6 benchmark calculations.

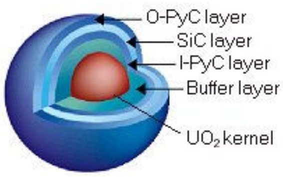

Figure 1. Structure of a TRISO-coated particle fuel

2. Methods and Results

2.1 ABAQUS Finite Element Model

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 2 by representing a quarter of a sphere.

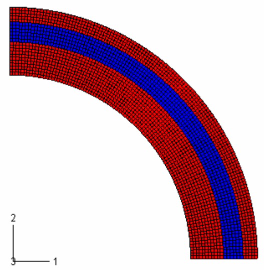

Figure 2. ABAQUS 2-D finite element model for TRISO coated particle fuel

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. 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.

In order to calculate the creep rates in the radial and the hoop directions by using the Poisson's ratio in a creep condition, a user subroutine in FORTRAN includes the following equations:

$$\dot{\varepsilon}_r = C(\sigma_r - 2\nu_c\sigma_\theta) \quad (1)$$

$$\dot{\varepsilon}_\theta = C[(1-\nu_c)\sigma_\theta - \nu_c\sigma_r] \quad (2)$$

where $\dot{\varepsilon}$ is the creep strain, C is the creep coefficient, σ_r and σ_t are the stresses in radial and tangential directions, respectively, and ν_c is the Poisson's ratio in creep condition. $\nu_c = 0.5$ is used in this calculation.

The example calculation problem selected for comparison is adopted from Miller's publication 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.

2.2 Stress Results from ν_{creep} in comparison with the results from $\nu_{elastic}$

Stress results obtained by using the improved ABAQUS based FE model are presented in table 1 in comparison with the results obtained by using the old FE model for the case adopted from Miller's publication.

Table 1. $\nu_{elastic}$ vs. ν_{creep}

Stress Components	Results for $\nu_{elastic}$ (MPa)	Results for ν_{creep} (MPa)
Without pressures applied		
σ_{rI}	20.77	20.89
σ_{rO}	-7.13	-7.15
σ_{tO}	55.80	55.97
σ_{T}	-163.00	-163.25
With pressures applied		
σ_{rI}	-8.22	-8.43
σ_{rO}	-13.99	-13.66
σ_{tO}	50.44	50.62
σ_{T}	-45.39	-46.16

Principal stresses in the radial or the tangential directions at four points in the end of the 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. The two principal stresses at four points obtained for a fluence (E>0.18 MeV) level of 1.5×10^{25} n/m^2 do not show any differences.

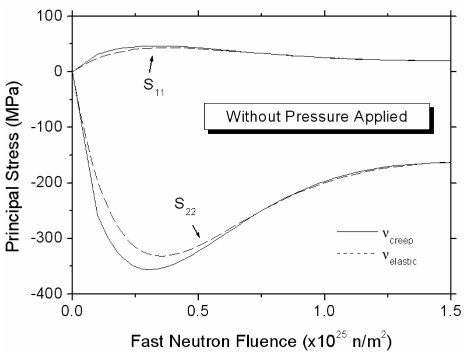

Figure 3. Principal stresses as functions of fast neutron fluences for cases without pressures applied

Figure 3 shows principal stress, S_{11} and S_{22} from ν_{creep} cases as functions of fast neutron fluences in comparison with the results from $\nu_{elastic}$ cases for a coated particle fuel with pressures applied. The effect of the application of the Poisson's ratio in a creep condition is shown in S_{22} obviously up to a fluence (E>0.18 MeV) level of 0.6×10^{25} n/m^2. The effect diminishes as the fluence increases beyond this point and finally the two stress intensities show no difference at a fluence (E>0.18 MeV) level of 1.5×10^{25} n/m^2 as is shown in Table 1. The same trend is shown for a coated particle fuel without pressures applied in Figure 4.

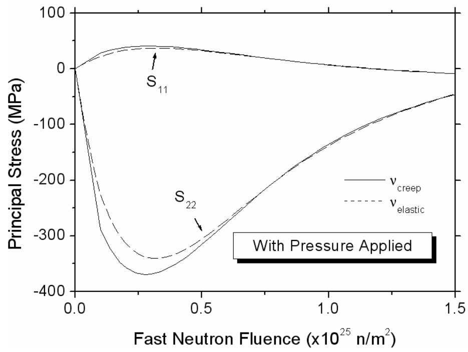

Figure 4. Principal stresses as functions of fast neutron fluences for cases with pressures applied

3. Conclusion

An improvement is made for the ABAQUS based finite element model by using the Poisson's ratio in creep condition for the calculation of the creep strain rate.

In the example problem calculations, the effect of the application of the Poisson's ratio in creep condition is clearly found in S_{22} up to a fluence (E>0.18 MeV) level of 0.6×10^{25} n/m^2. The effect diminishes as the fluence increases beyond this point and finally the two stress intensities show no difference at a fluence (E>0.18 MeV) level of 1.5×10^{25} n/m^2.

Acknowledgement

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REFERENCES

[1] K. Sawa, S. Ueta, "Research and Development on HTGR Fuel in the HTTR Project," Nuclear Engineering and Design, 233, pp.163-172, 2004.
[2] Y. M. Kim, M. S. Cho, and Y. W. Lee, "Development of a VHTR Fuel Performance Analysis Code COPA," Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, November 2-3, 2006.
[3] Hibbitt, Karlson & Sorensen, Inc., ABAQUS/Standard User's Manual, Ver. 6.2-5, 2005.
[4] M. S. Cho et al, "Calculations of the IAEA-CRP-6 Benchmark Cases by Using the ABAQUS FE Model for a Comparison with the COPA Results," Transactions of the Korean Nuclear Society Spring Meeting, Gangchon , Korea, May 25-26, 2006.
[5] G. K. Miller, R. G. Bennett, Analytical Solution for Stresses in TRISO-coated Particles, Journal of Nuclear Materials, Vol.206, pp.35-49, 1993.