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A Stress Analysis using ABAQUS on a TRISO with its Inner Pyrocarbon Cracked

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1. Introduction

A tri-structural isotropic particle (TRISO) is a coated fuel particle of a high temperature reactor (HTR) fuel which consists of a kernel, a low-density pyrocarbon layer called a buffer, an inner high-density pyrocarbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon (OPyC) layer. The particle integrity must be maintained during irradiation in order to contain hazardous fission products within the particle.

Most HTR fuel performance models analyzing the TRISO integrity are one-dimensional in order to reduce the long calculation time involved in a failure analysis on a large number of TRISOs. However, multi-dimensional phenomena such as crack, de-bonding, and asphericity intensify the failure of TRISOs. It is necessary to include the multi-dimensional effects on the particle integrity into the one-dimensional models. Miller et al. [1] addressed a statistical approach in which the stress in a cracked particle is statistically related to the stress in an uncracked particle and parameter variations. The stress in a cracked particle is calculated using a finite element method, and stress in an uncracked particle is calculated using an HTR fuel performance code.

This study treats a stress analysis on the coating layers of a TRISO using a finite element software, ABAQUS [2]. The maximum tangential stresses of the SiC layers of an intact TRISO and a TRISO with its IPyC cracked are compared.

2. ABAQUS modeling

2.1. An Intact TRISO

The geometry and material properties of a TRISO are given in Ref. [3]. The modeling and analysis of a TRISO mechanical behaviors are performed using ABAQUS/CAE. Three axisymmetric, deformable, shell-shape parts named IPyC, SiC, and OPyC are created in the Part module of the ABAQUS/CAE. Each part is a half spherical shell.

Three material property files named IPyC, SiC, and OPyC are made in the Property module of the ABAQUS/CAE. The material behaviors of IPyC and OPyC are creep with user-defined law, depvar with three solution-dependent state variables, elastic with Young's modulus and Poisson's ratio, expansion, user-defined field, and swelling with suboptions of ratios. The material behaviors of SiC are elastic with Young's modulus and Poisson's ratio, and expansion. Three sections named IPyC, SiC, and OPyC are created and connected to the materials IPyC, SiC, and OPyC, respectively. The sections are assigned to the respective parts. In the Assembly module, three instances are created from the previously made three parts with a dependent instance type. In the Step module, the visco procedure type is selected.

In the Interaction module, the tie constraint is applied to the interfaces between IPyC and SiC and between OPyC and SiC where the SiC surface is a master. In the Load module, a time-dependent pressure is applied to the inner surface of IPyC, and a constant pressure is applied to the outer surface of OPyC. The boundary condition of zero U1 and UR3 is set at the sections of half spherical shells. In the Mesh module, eighty elements are assigned along every arc of the spherical shells, and 6, 4, and 3 elements are assigned to the sections of half IPyC, SiC, and OPyC shells, respectively. The element type is CAX8 that is quad-dominated and free in mesh controls. In the Job module, a location of a user FORTRAN file is specified which describes three ABAQUS FORTRAN subroutines USDFLD, CREEP, DLOAD.

2.2. A TRISO with IPyC cracked

For an IPyC part, two quarter spherical shells are created instead of one half spherical shell. The region between the two quarter spherical shells means the IPyC crack that extends around the full circumference of the IPyC. It is assumed that the crack exists from the beginning. The rest of the ABAQUS modeling is the same as for an intact particle.

3. Stress results

3.1. Layer stress in an intact TRISO

Table 1 lists the stresses acting on the coating layer surfaces of an intact TRISO at a fluence of 1.5×10^{25} n/m^2 that are calculated using ABAQUS. The stresses are calculated at integration points. The stresses of this work agree very well with Miller and Bennett's results [3].

Table 1. Stresses acting on the coating layer surfaces of an intact TRISO at a fluence of 1.5×10^{25} n/m^2.

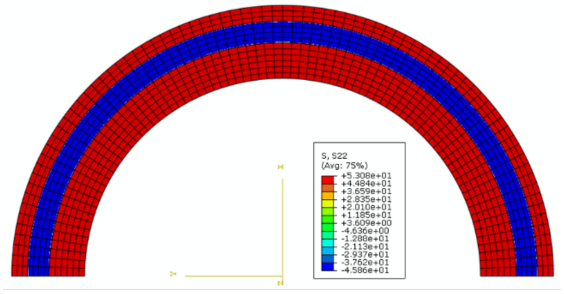
Stress components	This work	Ref. [3]
Without pressures applied		
$\sigma_{r,IPyC,OUT}$	21.46	20.67

$\sigma_{\theta,\mathrm{SiC,IN}}$	-163.76	-164.3
$\sigma_{\mathrm{r,OPyC,IN}}$	-6.80	-7.25
$\sigma_{\theta,\mathrm{OPyC,IN}}$	57.83	56.69
With pressures applied		
$\sigma_{\mathrm{r,IPyC,OUT}}$	-8.00	-8.68
$\sigma_{\theta,\mathrm{SiC,IN}}$	-45.72	-47.51
$\sigma_{\mathrm{r,OPyC,IN}}$	-13.30	-13.76
$\sigma_{\theta,\mathrm{OPyC,IN}}$	52.51	51.35

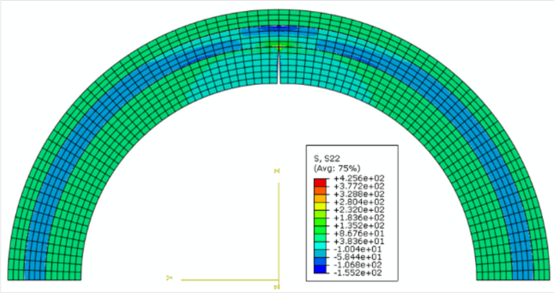
Note. The subscripts r and θ mean radial and tangential directions, respectively. The subscripts IN and OUT mean innermost and outermost integration points.

3.2. Layer stresses in a TRISO with IPyC cracked

Fig. 1 shows tangential stresses at the coating layers of an intact TRISO and a TRISO having a cracked IPyC at a fluence of 1.5×10^{25} n/m^2 when pressures are applied to the inner surface of IPyC and the outer surface of OPyC. The tangential stress is compressive at the SiC layers of an intact TRISO, which means that the inner SiC layer does not crack. On the other hand, the tangential stress at the inner SiC layer of an IPyC-failed is tensile.



(a) Intact TRISO



(b) TRISO with IPyC cracked

Fig. 1. Tangential stresses at a fluence of 1.5×10^{25} n/m^2.

Fig. 2 shows the variation of the SiC tangential stresses at a location of crack tip. The SiC tangential stress of a cracked TRISO is tensile all over the entire fluence level, and it becomes the highest near 0.34×10^{25} n/m^2. That means that the SiC layer may crack at the early stage of irradiation. Fig. 3 shows the radial and tangential stresses of an IPyC along the IPyC crack path at a fluence of 1.5×10^{25} n/m^2. The two stresses of a cracked TRISO increases sharply toward the crack tip. These increased tensile IPyC stresses cause the tensile and very large tangential stress of the SiC inner surface. Accordingly, the IPyC inner surface of a cracked TRISO is more inward displaced that that of an intact TRISO because it is not bound along the crack path of the IPyC layer.

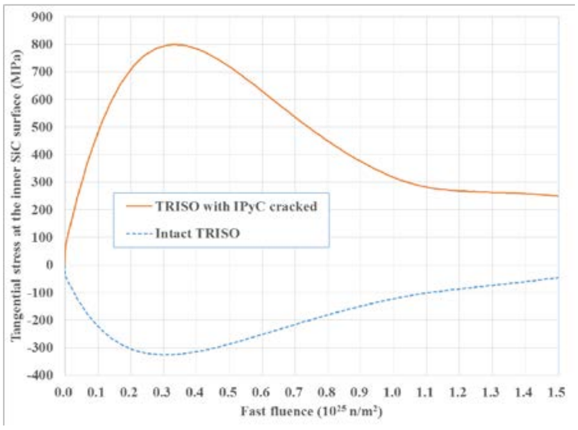


Fig. 2. Variation of SiC tangential stresses at a crack tip.

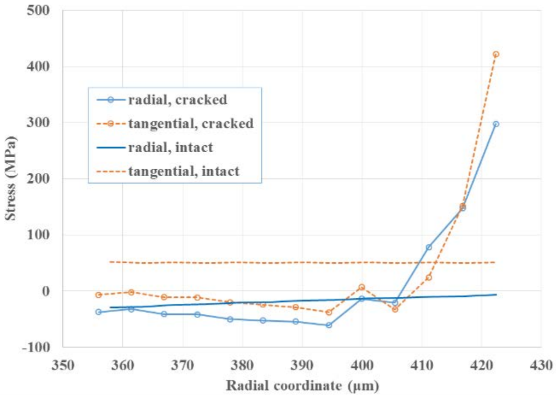


Fig. 3. IPyC stresses along an IPyC crack path.

4. Summary

The SiC tangential stress of a TRISO with its IPyC cracked becomes tensile and rises to its highest value at the early stage of irradiation. The IPyC crack greatly increases the possibility of the SiC failure. This three-dimensional effect on a TRISO failure must be included into a one-dimensional particle failure modeling.

ACKNOWLEDGEMENTS

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