*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 29-30, 2014*

# Simulation and Analysis on Hoop Strength Test of Multilayered SiC Composite Fuel Cladding

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## 1. Introduction

Silicon carbide-based ceramics and their composites have been studied for fusion and advanced fission energy systems. SiC composite have excellent high temperature properties, irradiation tolerance, inherent low activation, and superior mechanical properties[1,2]. For fission reactors, $SiC_f$/SiC composites can be applied to core structural materials[3,4]. Multi-layered SiC composite fuel cladding, which consists of monolith inner/outer layer and intermediate SiCf/SiC composite layer is one of candidates for a replacement for the zirconium alloy cladding, owing to the superior high temperature strength and low hydrogen generation under severe accident conditions. The SiC composite cladding has to retain the mechanical properties and its structure from the inner pressure caused by fission products to apply a cladding of fission reactor. The inner pressure caused by fission products induces hoop stress in a circumferential direction. Hoop strength test using expandable polyurethane plug is designed for evaluating the mechanical properties of fuel cladding. However, the stress caused by the plug is distributed nonuniformly because of the properties of plug and the deformation tendency is different from the results pressure vessel test. In this paper, hoop strength test of the multilayered cladding was simulated in order to evaluate hoop stress and shear stress at the cladding and the fracture of the cladding was analyzed.

## 2. Methods and Results

In this study, finite element analysis was used to analyze hoop strength test for examining mechanical properties in fuel cladding.

### *2.1 FEA of Hoop Strength Test*

A simplified 3D FEM model of the hoop strength testing system was shown in Fig. 1. In the model, polyurethane was used as an expansion plug at the room temperature. Considering the hyper-elastic properties of polyurethane, the hyper-elastic material model (Yeoh's model) in ABAQUS was used. Coefficients of hyper-elastic material properties were used from Wang's paper[6]. The ring specimen was multilayered SiC composite, which consists of inner monolith SiC layer, intermediate $SiC_f$/SiC composite, and outer monolith SiC layer. The ram was high strength steel. The bottom of the plug and the ring specimen were constrained in six degrees of freedom (DOF). The ring specimen length was 30 mm, outer diameter and inner diameter was 8.5 mm and 7.8 mm, respectively. Force was applied to the upper of the ram. The friction coefficient between the plug and the cladding was assumed as 0.1.

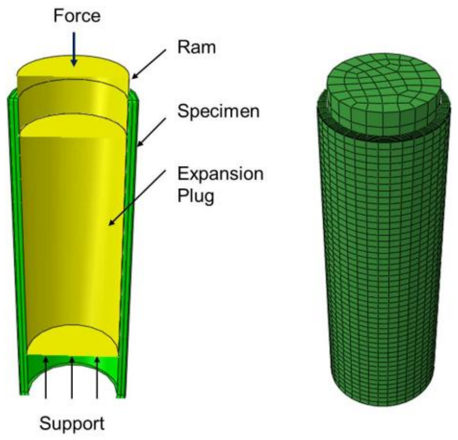


Fig. 1 simplified 3D FEM model of the hoop strength test system of multilayered SiC composite fuel cladding.

Fig. 2 shows von mises stress distribution of the SiC composite fuel cladding in the hoop strength testing system when the pressure load was 20 MPa. It was observed that the stress was mostly induced in upper part of the cladding. The nonuniform stress distribution is caused by the friction between the pug and the cladding. The friction disturbs the plug to uniformly pass the pressure on to the bottom of the cladding. It is confirmed that the stress was distributed uniformly assuming frictionless between the plug and the cladding.

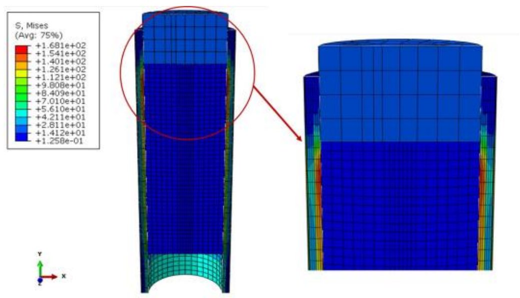


Fig. 2 Stress distribution of the cladding in hoop strength testing system.

In the FEA results of the cladding, most stress caused by the pressure load was applied to the inner SiC layer. It was observed that the intermediate $SiC_f$/SiC composite layer was less stressed than inner SiC layer. The maximum von mises stress of the intermediate layer and the inner layer was 43.5 MPa and 160.6 MPa, respectively.

In the load-displacement curve of tri-layered SiC composite cladding during the hoop strength test, small drop of the load was observed in low load region. After that the fracture at the composite layer was occurred in high load region. Considering the FEA results, it is concluded that the crack is initiated at the inside surface of the inner SiC layer in relatively low load and the propagating crack is blocked at interface between the inner SiC layer and the intermediate composite layer. As the pressure load increases, $SiC_f/SiC$ composite layer would be fractured when concentrated stress of crack tip overcomes the strength of $SiC_f/SiC$ composite layer. The FEA results explain the tendency of the test results very well. It suggests that the 3D FEM model in Fig. 1 with hyper-elastic material model of polyurethane plug can be used to represent the hoop strength testing system.

*2.2 Fracture Analysis of SiC composite Cladding*

Through FEA results, fracture analysis of multilayered SiC composite cladding was performed. Fig. 3 shows complex stress fields existing in the cladding at highest von mises stress region of the cladding during hoop strength test. Von Mises stress, axial stress $\sigma_{ZZ}$, circumferential stress (hoop stress) $\sigma_{TT}$, and radial stress $\sigma_{RR}$ show gradient through a cross section of the specimen. These stress distribution indicate that the hoop strength test of multilayered SiC composite cladding is more complicated than thin-walled cylinder. In the result of axial stress of the cladding, significant axial compressive stress was observed. This is caused by clad bending due to the clad bulging effect (a barreling effect) of the tested clad and friction between the plug and the cladding. The maximum axial compressive stress was -62.2 MPa, and the axial compressive stress at mid-section (highest mises stress region) of the cladding was -34.9 MPa.

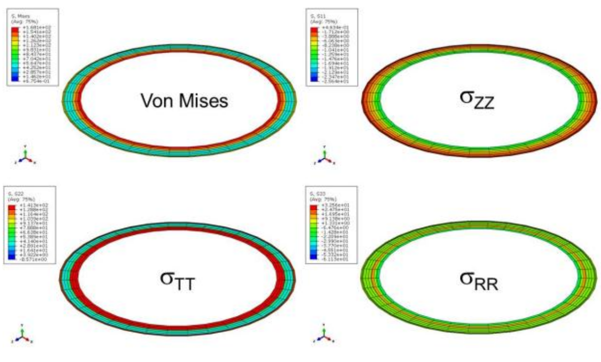


Fig. 3 Stress distribution at the mid-section of the cladding, which shows highest von mises stress.

Table 1 shows the stress range in multilayered SiC cladding from the FEA results. The large axial compressive stress caused localized shear stress in the inner SiC layer. Max shear stress of inner SiC layer at mid-section of cladding = $(\sigma_{TT} - \sigma_{ZZ})/2$ = 88.7 MPa. This will increase the possibility of shear failure at the inner SiC layer.

Table 1. True stress range in multilayered SiC cladding form FEA results

| $\sigma_{RR}$ (MPa) | $\sigma_{TT}$ (MPa) | $\sigma_{ZZ}$ (MPa) | Von Mises (MPa) |
|---|---|---|---|
| –16.1 ~ –0.4 | ~ 142.5 | -62.2(-34.9*) ~ 26.2 | ~ 160.6 |

* The stress of the cladding at mid-section

Based on FEA results about the axial compressive stress and shear stress, the hoop strength test of multilayered SiC composite cladding can result in a shear failure. The fracture of tri-layered SiC composite cladding was shown in Fig. 4. From the fracture of inner SiC layer, the crack caused by shear failure mode was mainly observed. Therefore, the significant compressive axial stress and shear stress in a hoop strength testing system have to be considered importantly to evaluate the mechanical properties of SiCf/SiC composite layer using a hoop strength test.

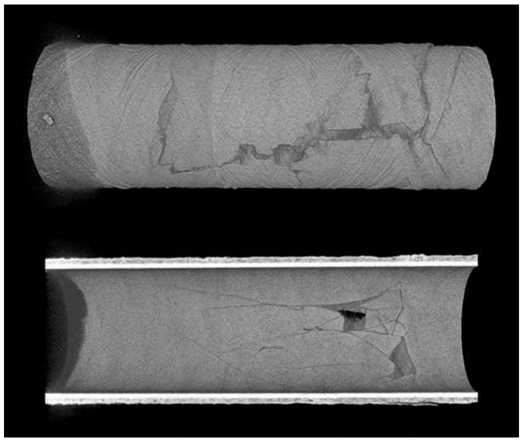

Fig. 4 Fractured tri-layered SiC composite cladding specimen.

## 3. Summary

Finite element analysis was conducted to simulate hoop strength test of a multilayered SiC composite fuel cladding. The hyper-elastic material model of a polyurethane plug was used in ABAQUS to calculate stresses of the fuel cladding during the hoop strength testing.

In the FEA results of the multilayered cladding, it was observed that the highest stress is induced in the inner SiC layer. The von Mises stress of the intermediate $SiC_f/SiC$ composite layer was about three times smaller than that of the inner SiC layer. Therefore, cracks would be firstly initiated at the inside surface of the inner SiC layer. The creation of cracks at a low pressure was observed in the hoop strength test of tri-layered SiC composite cladding. SiC composite layer would be fractured when the concentrated stress of the crack tip overcomes the strength of $SiC_f$/SiC composite.

In order to investigate the fracture of the cladding, the stress of the inner SiC layer was analyzed. Highly nonuniform stress and significant compressive stresses were observed in the axial stress, which were induced by clad bending due to the clad bulging effect and friction between the plug and the inner surface of the cladding. The compressive stress caused a large localized shear stress in the inner SiC surface, which might lead to shear failure of material. The microstructure of the fractured cladding suggested the shear failure in the inner SiC and consecutive failure throughout the cladding.

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