Thermo-mechanical analysis of multi-layered accident-tolerant fuel (ATF) claddings

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1. Introduction

Zirconium-based alloys such as Zircaloy, Zirlo, and M5 are used in all pressurized light water reactors (LWR). If the cooling capacity is lost due to a power loss accident like the Fukushima nuclear power plant, hydrogen generation and hydrogen explosion may occur through the oxidation reaction with steam evaporated at high temperatures. Therefore, extensive research has been conducted to solve this problem through the surface coating of Zr-alloy cladding, which is called accidenttolerant fuel (ATF) cladding [1,2].

Currently, various coating methods are being developed for the outer surface coating on the Zircaloy cladding matrix to develop ATF cladding. However, the outer coating method has a fatal disadvantage in that it is difficult to protect the inner surface of the cladding in the cladding ballooning and burst conditions [3,4]. Therefore, coating the inner surface of the cladding has been studied and has shown a significant reduction of secondary hydriding even under breakaway conditions, such as the cladding burst [5].

In this study, a finite element analysis (FEA) system was established for modeling that reflects the multiphysics behavior of a triple-layered cladding with inner and outer surfaces coated using the ABAQUS™ framework. User-subroutines were utilized to implement complex nuclear fuel thermo-mechanical phenomena such as fission gas release and gap conductance in ABAQUS™. Through the developed finite element analysis system, multiphysics thermo-mechanical analysis, such as creep down and pellet-cladding mechanical interaction (PCMI), of multiple-layered cladding was performed under the various operating conditions, including steady state, power ramp, and load following cyclic load.

2. Methods and Results

2.1 Simulation conditions

The schematic of the triple-layered cladding used in this study is presented in Fig. 1, and detailed specifications are provided in Table 1. For UO_2 and Zr-4 properties, detailed material thermo-mechanical models of elasticity, plasticity, fission gas release, creep, swelling, thermal conductivity, and thermal expansion were inputted through user-subroutines utilizing FRAPCON-4.0 and MATPRO property databases [6,7]. In this study, pure Chromium (Cr) was chosen as a coating material. As in the case of Cr coating, various property models including thermal conductivity, creep, and plasticity was applied [8]. For the pellet-cladding gap conductance, the gas mixture conductivity due to initial gap gas and fission gas release was considered, and the contribution of radiation and contact to the gap conductance was also modeled through user-subroutine GAPCON [9].

Table I: Multi-layered ATF cladding design

Design Factor	*Design Value*
Fuel pellet diameter (mm)	*8.192*
Fuel pellet height (mm)	*10.15*
Fuel-cladding radial gap(mm)	*0.08*
Cladding matrix material	*Zr-4*
Cladding matrix thickness (mm)	*0.575*
Coating material (mm)	*Cr*
Inner coating thickness(mm)	*0.1*
Outer coating thickness	*0.1*
Total thickness of multi-layered cladding (mm)	*0.775*
Rod fill gas	*He*
Initial fill gas pressure	*2*

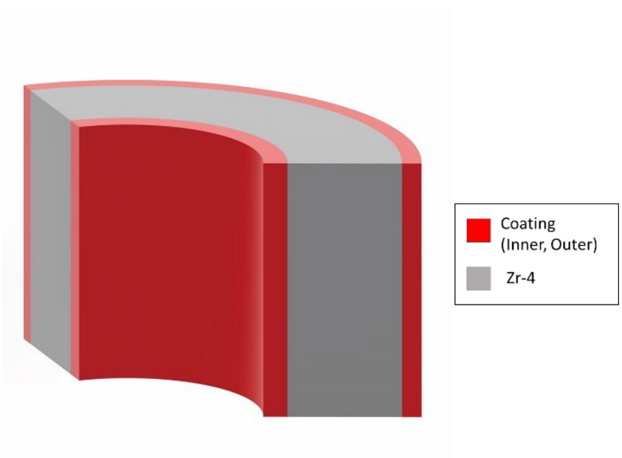

Fig. 1. Schematic of the triple-layered cladding

The multi-layered cladding geometry, mesh, and boundary conditions are illustrated in Fig. 2 and Fig. 3, respectively. The CAX4T element (4-node axisymmetric thermally coupled quadrilateral, bilinear displacement, bilinear displacement, and temperature) is chosen for the meshing scheme and the element type. Axial direction symmetry boundary conditions and pressure boundaries were applied. Additionally, the constant heat transfer coefficient condition was assumed.

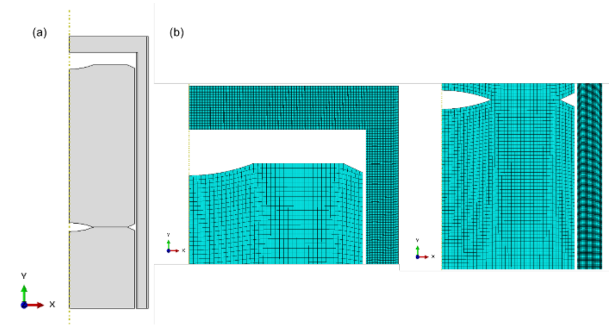

Fig. 2. The geometry and the mesh of the ATF cladding

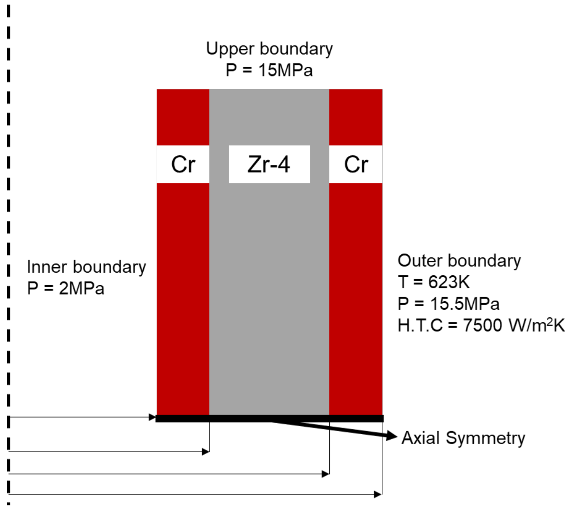

Fig. 3. Boundary conditions of the benchmark case

2.2 Thermo-mechanical behavior of the ATF cladding

As a preliminary study, the fuel performance calculations were performed assuming that the reactor is operated at a fixed power of 20 kW/m, resulting a discharged burnup of approximately 52 GWd/tU. The results of the temperature analysis are presented in Fig. 4 and Fig 5. As seen in Fig. 5. (b), the temperature gradient varied due to the difference in thermal conductivity between the base metal and coating layers of the multilayer cladding.

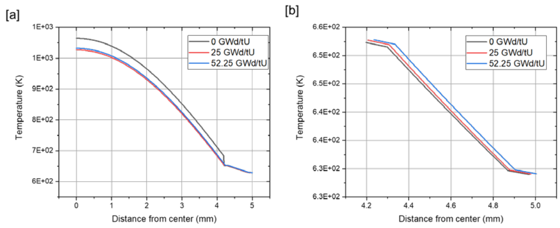

Fig. 5. Radial temperature profile of [a] fuel rod and [b] multi-layered cladding

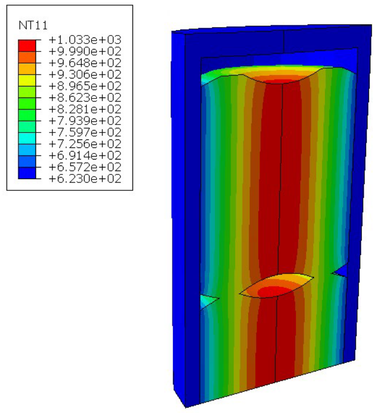

Fig. 4. Fuel rod temperature profile of multi-layered cladding

PCMI analysis, based on gap size evolution and contact, was performed. Fig. 6 depicts the variation in pelletcladding radial gap size with burnup. It is calculated that the gap increases slightly at the beginning of the operation due to the densification of the pellets and then gradually decreases. This was attributed to fuel swelling and contact was observed at approximately 18 GWd/tU. The contact stress analysis of the burnup of a nuclear fuel rod containing multiple cladding tubes, shown in Fig. 7, shows that the stress distribution inside the cladding was almost uniform in the beginning when no contact occurred, but the stress gradient between the cladding and the base metal changed as contact was initiated. Due to the small thickness of the coating layer and the difference in modulus, the contact stress propagates and concentrates in the coating layer.

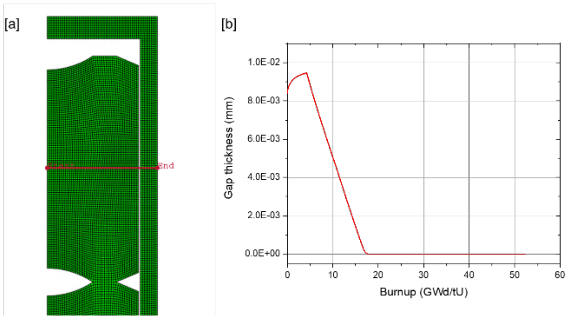

Fig. 6. Radial gap [a] thickness measurement path and [b] calculation results

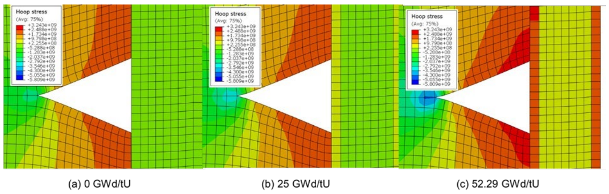

Fig. 7. Hoop stress calculation results as function of burnup

3.Conclusion

In this study, the development of the axisymmetric FEA model of ATF fuel rod containing multi-layered cladding using ABAQUS^{TM} was conducted. By using this model, it is expected that the mechanical behavior of the ATF cladding can be evaluated under steady-state operation and transient power conditions such as the load-follow operation. Furthermore, this model may be utilized for design studies to optimize multi-layer cladding, including sensitivity analysis and optimization of coating layer thickness for multi-layer cladding. In addition, this FEM analysis system will be able to calculate all types of normal operation (base irradiation, load follow, frequency control, ERPO) to evaluate whether the fuel rod of the proposed reactor can prevent PCI failure.

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