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Preliminary study of mechanical behavior for Cr coated Zr-4 Fuel Cladding

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1. Introduction

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2-zirconium alloy system, can tolerate loss of active cooling in the reactor core during design-basis and beyond design-basis events for a considerably longer time period (depending on the LWR system and accident scenario) while maintaining or enhancing fuel performance during normal operations and operational transients.

To decrease the oxidation rate of Zr-based alloy components, many concepts of accident tolerant fuel (ATF) such as Mo-Zr cladding, SiC/SiCf cladding and iron-based alloy cladding are under development. One of the promised concept is the coated cladding which can remarkably increase the corrosion and wear resistance.

Recently, KAERI is developing the Cr coated Zircaloy cladding as accident tolerance cladding [1, 2]. To coat the Cr powder on the Zircaloy, 3D laser coating technology has been employed because it is possible to make a coated layer on the tubular cladding surface by controlling the 3-diminational axis. Therefore, for this work, the mechanical integrity of Cr coated Zircaloy should be evaluated to predict the safety of fuel cladding during the operating or accident of nuclear reactor.

In this work, the mechanical behavior of the Cr coated Zircaloy cladding has been studied by using finite element analysis (FEA). The ring compression test (RCT) of fuel cladding was simulated to evaluate the validity of mechanical properties of Zr-4 and Cr, which were referred from the literatures and experimental reports [3-7]. The pellet-clad mechanical interaction (PCMI) behavior of the Cr coated Zr-4 cladding were investigated by thermo-mechanical FEA simulation.

2. Simulation of ring compression test (RCT) for Cr coated fuel cladding

2.1 FEA model

The geometric properties and boundary conditions of FEA model were determined based on the RCT condition of Kim et al [1] to compare the simulation and the experimental results. As shown in Fig. 1, the base Zr-4 cladding tube has 9.5mm outer diameter with 0.57mm of thickness and Cr coating was composed on the Zr-4 surface with 80μm thickness. Additionally, it was modeled that the thickness of Zr-4 tube was reduced to have the same total thickness compare with the conventional Zr-4 cladding (570μm). All of simulations were performed by using ABAQUS 6.12 (Dassault Systemes, USA) with about 4000 of reduced 8-node 3D stress elements (C3D8R).

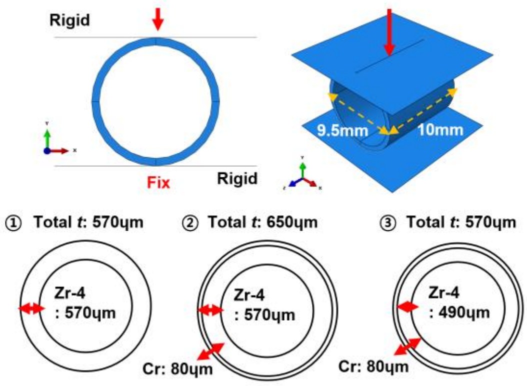

Fig. 1 Analysis model for ring compression test of coated fuel cladding and cladding model variation.

2.2 Simulation results

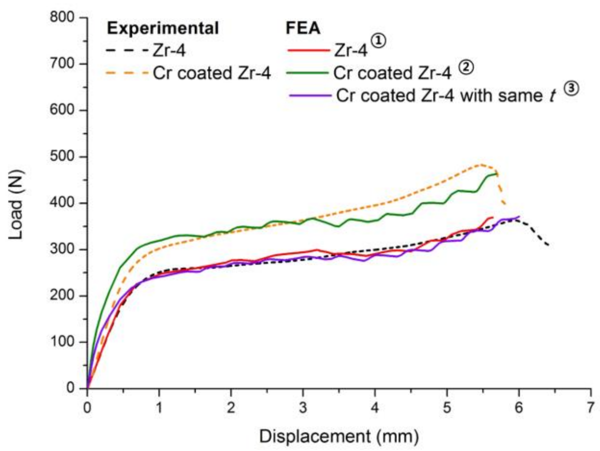

Fig. 2 Load-displacement results of RCT obtained from experiment and FEA simulation.

The load-displacement results obtained from the RCT simulation were depicted with referred experimental results [1] as shown in Fig. 2. It was found that the both of simulation results of base Zr-4 cladding and Cr coated cladding showed good agreement with the experimental results, respectively. In the both case of experiment and simulation, the compressive stiffness and strength of Zr-4 cladding were increased by Cr coating because of higher elastic modulus of Cr and increased total thickness of cladding tube (650μm). In the case of Cr coated Zr-4 cladding with 570μm thickness, the compression stiffness was somewhat increased and the similar compression strength was obtained compared to the conventional Zr-4 cladding. This is important result because it implies that the mechanical performances of Cr coated Zr-4 cladding can be maintained or increased although the thickness of Zr-4 was reduced.

3. Simulation of Pellet-Clad mechanical interaction (PCMI) for Cr coated fuel cladding

3.1 Pellet-clad mechanical interaction (PCMI) model

The upper section of fuel rod was simplified and modeled using 2D axisymmetric elements with symmetric boundary condition. The assumed geometry, materials and boundary conditions are shown in Fig. 3. The FEA model is composed of two individual UO_2 pellets, cladding, 20μm initial pellet-clad gap and open region of upper plenum. Also, the convective boundary condition was conducted to simulate the heat transfer from the coolant. Then, 800mW/mm^3 of heat generation was applied in UO_2 pellets similar to the real operating condition of nuclear fuel system. The right figure in Fig.3 shows the result of temperature distribution and the expanded UO_2 pellets with the assumed conditions.

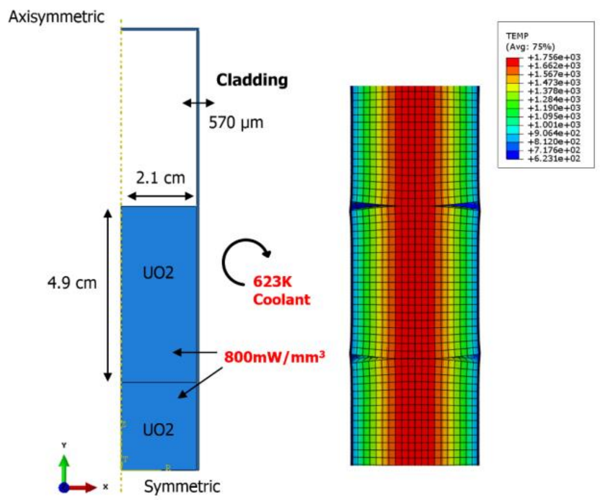

Fig. 3 Simply assumed PCMI simulation model and result of temperature distribution.

3.2 Simulation results

Fig. 4 shows the radial displacement and equivalent plastic strain of conventional and Cr coated Zr-4 fuel cladding with respect to the axial position. It can be seen that the local displacement peak was generated at the interface between two pellets due to the thermal expansion. Also, almost same amounts of displacement were generated between the conventional and Cr coated Zr-4 cladding, similar to the results of RCT (Fig. 2). However, in the case of Cr coated Zr-4, the equivalent strain of cladding outer wall showed much higher value compare to the conventional Zr-4 cladding. It can be though that some of plastic deformation of Zr-4 layer was transferred to the thin Cr coating layer based on the lower equivalent strain at inner wall, compared to the conventional cladding.

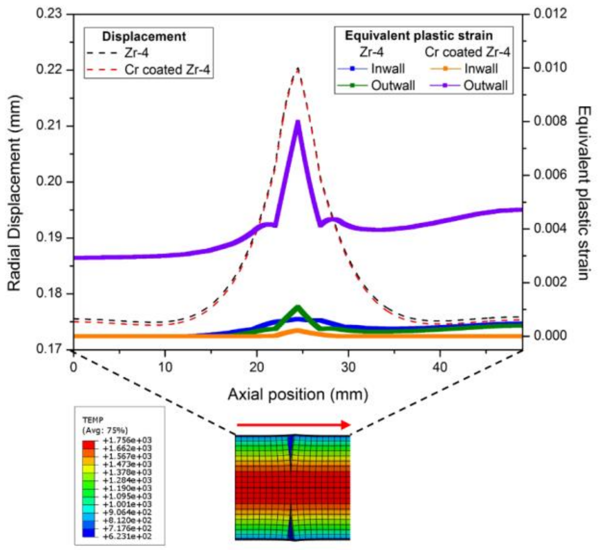

Fig. 4 Displacement and equivalent plastic strain of fuel cladding along the axial direction.

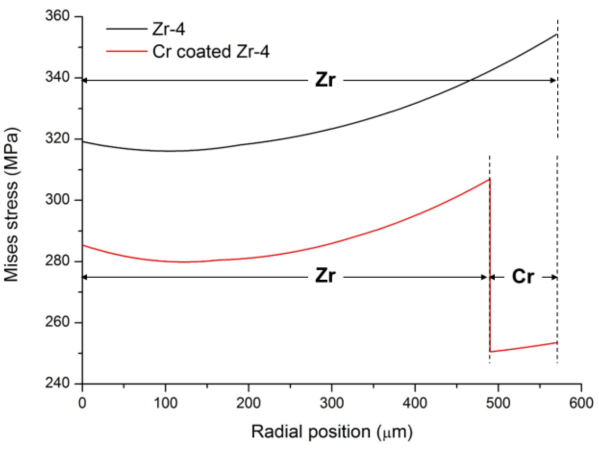

Fig. 5 Mises stress of fuel cladding along the radial direction.

At the maximum displacement position, the Mises stress was plotted with respect to the radial position as shown in Fig. 5. It could be found that the Cr coated Zr-4 layer received lower stress compared to the conventional Zr-4 cladding. It was come from the fact that the Cr layer could reduce the stress in Zr-4 layer by plastic deformation of itself (Fig. 4). Also, because the Cr has much higher elastic modulus compared with Zr-4 (279 and 87.175GPa, respectively), much more stress is generated in Cr layer although the lower stress was shown in Fig. 5 due to the lower yield strength of Cr compared with the Zr-4. Based on these results, it can be concluded that the mechanical durability of Zr-4 could be improved when the Cr layer was coated because some of stress could be absorbed in Cr coating layer due to its much higher elastic modulus.

4. Conclusions

In this work, the mechanical behavior of the Cr coated Zircaloy cladding has been studied by using finite element analysis (FEA). The ring compression test (RCT) of fuel cladding was simulated to evaluate the validity of mechanical properties of Zr-4 and Cr. The pellet-clad mechanical interaction (PCMI) properties of Cr coated Zr-4 cladding were investigated by thermo-mechanical finite element analysis (FEA) simulation. The mechanical properties of Zr-4 and Cr was validated by simulation of ring compression test (RCT) of fuel cladding. Based on the results, it can be concluded that the mechanical durability of Zr-4 could be improved when the Cr layer was coated because some of stress could be absorbed in Cr coating layer due to its much higher elastic modulus.

Acknowledgement

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