An Attempt to Evaluate Mechanical Deformation of ATF Cladding

JaeYong Kim [a*], SungUk Lee [a], YongSik Yang [a], JuYeop Park [b], SeungKyun Kang [c]
[a] *LWR Fuel Technology Research Division, Korea Atomic Energy Research Institute, Daejeon, 34057, ROK*
[b] *Korea Institute of Nuclear Safety, Daejeon, 34142, ROK*
[c] *Seoul National University, Seoul, 08826, ROK*
[*] *Corresponding author: kjykjy@kaeri.re.kr*

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1. Introduction

Whereas conventional nuclear fuel cladding consists of a single layer of Zirconium alloy, accident tolerant fuel (ATF) cladding consists of a Cr or CrAl coating layer with a thickness of about 10-15 um on top of the Zirconium alloy tube. Our previous study developed a model to evaluate the mechanical deformation and damage of claddings composed of these different materials when subjected to various loads under in-reactor conditions [1]. The developed standalone FDM model, 'multilayer' model, will integrate with FRAPCON [2], a steady-state nuclear fuel performance code developed by the NRC. This paper describes model improvement, localized property measurement for each layer and the module design.

2. Model improvement and V&V study

2.1. Fuel radial temperature distribution

Although Cr or CrAl coatings are thin, they have different thermal conductivities than Zirconium alloys, which can result in different radial temperature gradients for different layers of the cladding, as shown in Figure 1. This can cause different radial temperature gradients of the pellet. 'Multilayer' model divides the ATF cladding into several nodes for the thermal stress analysis. Therefore, it is planned to add a model to obtain the radial temperature gradients of the coating layer, Zirconium alloy layer, and pellet from the coolant.

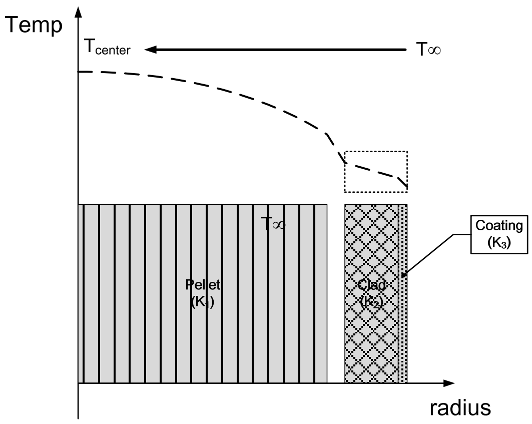

Fig. 1. Virtual radial temperature distribution of ATF cladding

2.2. Pellet and cladding contact

'Multilayer' model relocates the outermost point of the pellet and the innermost point of the cladding to the position that averages the radial displacement of the pellet and the cladding when the pellet and the cladding are in contact. We plan to improve the current simple methodology to deal with pellet and cladding contact by finding out the range of location where the pellet and cladding can meet under various temperature and pressure conditions.

2.3. More realistic plastic property

'Multilayer' model uses bi-linear properties with a fixed slope in the plastic region to perform elastic-plastic analysis. Since the plasticity of metallic materials has a non-fixed slope in the form of a power law, we plan to improve 'multilayer' with a more realistic power-law plastic properties. Since the slope is not fixed, it is expected to be highly dependent on the loading-step, and further research is needed on how to calculate the yield stress and how to handle the loading step.

2.4. Verification and validation study

The improved model will be verified by comparing with ABAQUS [3] results under temperature and pressure conditions. The validation will be performed by using the deformation equipment of a cladding such as DIMAT (Deformation In-situ Measurement Apparatus by image-analysis Technique) [4]. The accuracy of the improved model prediction would be presented by comparing the measured deformation of the cladding at a certain temperature and pressure with the numerical analysis results.

3. Local property measurement of each layer

3.1. Local property of coating layer

Direct measurement of the properties of thin coating layers is very difficult, so new precise measurement techniques are being developed. In general, it is known how to measure localized properties of thin coating layers by Nano indentation, micro pillar compression test, etc. However, these measurement methods vary greatly depending on the experimental apparatus, test section configuration, and data processing algorithm, so a combination of techniques optimized for ATF cladding is needed. We will conduct research as shown in Figure 2 for improving local property measurement technologies to the commercial level, and optimizing ATF local property measurement method and data processing algorithm using by Nano indentation.

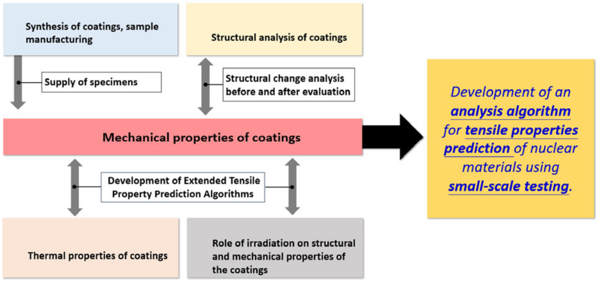

Fig. 2 Research flow chart for localized property measurement

3.2. Irradiation effect on ATF cladding property

Microstructure changes caused by neutron irradiation can lead to irradiation damage such as changes in the properties of the coating layer, voids and dislocations, especially at the coating layer interface. However, neutron irradiation takes a very long time and is very expensive, so ion irradiation is often used for preliminary evaluation. However, due to the small depth of penetration of ion irradiation, measurement techniques such as Nano indentation are essential. The ion irradiation test of the ATF cladding will be conducted by the Polish Nuclear Research Institute (NCBJ) and the mechanical properties will be measured at room and high temperature using by Nano indentation tests. Microstructure analysis will also be performed.

4. Module design to integrate with FRAPCON

FRAPCON calculates the nuclear fuel deformation using the FRACAS subroutine in the 'Mechanical-Deform' module after the nuclear fuel temperature is calculated as shown in Figure 3. The current 'Mechan' variable is used for using the FEA model in the case of 1 and the FRACAS-I model in the case of 2 to calculate the nuclear fuel deformation. A new branch point will be created and integrated with FRAPCON to use the 'ATF' module in the case of 3. It consists of 'preprocess_TM' which links the variables used in FRAPCON with the variables used in 'multilayer' model, 'multilayer' model which calculates stress, strain, and displacement at each node, and 'postprocess_TM' which links the calculated values with the variables used in FRAPCON.

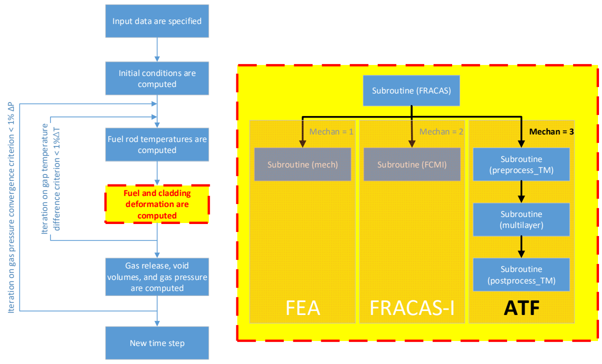

Fig. 3. Schematic drawing of ATF module

5. Conclusion

In order to accurately evaluate the mechanical deformation and fracture of ATF cladding, we are trying to improve model, V&V the improved model, and measure the local properties of each layer. We are measuring effective physical properties through multiple axial/ring tensile tests and local mechanical properties of each layer through small scaling tests. Research-Academy-Industry collaborations are underway to develop technologies to reduce the uncertainty of local property measurement methods. And irradiation and high temperature effects are being gathered through international collaborative research using by Nano indentation. These efforts are expected to significantly increase the understanding of ATF coating cladding performance.

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