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FEA stress analysis considering cavity formation of metallic fuel pin under transient state

Hyun-Woo Jung [a],Young-Ryun Oh[a], Yun-Jae Kim [a]*
[a]*Korea University, 5ga Anam-dong, Sungbuk-gu, Seoul, Korea*
[*]*Corresponding author: kimy0308@korea.ac.kr*

1. Introduction

There is a great deal of research into SFR, which is one of GEN IV reactors. When it comes to the accidents of SFR, there are two cases of accident process. One of them is In-pin process that molten fuel is discharged into upper plenum. The other is Ex-pin process that the molten fuel is discharged into coolant because of breakage of cladding.[1] To expect the processes under transient state, it is essential to assess stress state of the fuel pin. The aim of this research is to study the stress state of the fuel and the cladding under transient state using the commercial finite element analysis software, ABAQUS v6.13.[2]

2. Methods and Results

2.1 Condition of FE model

To conduct mechanical analysis of the fuel pin, EBR-II benchmark is used for a reference. The configuration of the fuel pin is descried in Fig.1. [3]

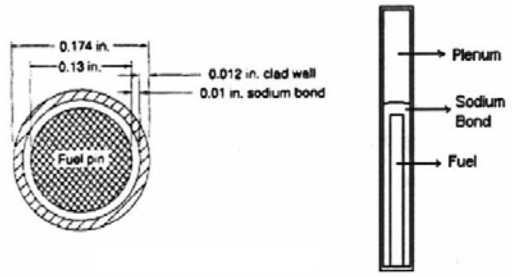

Fig.1 Description of the metallic fuel

The fuel pin is made of CAX4 elements, which is 4 node, axi-symmetric element. When it comes to the material property, mechanical properties of metallic fuel are assigned to fuel part, which are provided below equations (1), (2). [3]

$$\begin{aligned}
&E = 56 - 0.1158\times(T - T_3) \qquad T < T_3\\
&E = 20 - 0.1273\times(T - T_3) \qquad T_3 \le T < T_6\\
&E = 31 - 0.08\times(T - T_6) \qquad T \ge T_6\\
&E: \text{Modulus of Elasticity (GPa)}\\
&T: \text{Temperature (°C)}\\
&T_3 : \alpha+\delta \rightarrow \beta+\gamma \text{ phase transition temperature}\\
&T_6 : \beta+\gamma \rightarrow \gamma \text{ phase transition temperature}
\end{aligned} \tag{1}$$

$$\sigma_y = \begin{Bmatrix} 0.04\times(T_6 - T) + 10 & T \ge T_6 \\ 0.08\times(T_6 - T) + 10 & T < T_6 \end{Bmatrix} MPa \tag{2}$$

Those of HT9 are assigned to cladding part, which are provided below equations (3). [3]

$$\begin{aligned}
E &= 2.137\times10^5 - 102.74T \ (MPa)\\
G &= 8.964\times10^4 - 53.78T \ (MPa)
\end{aligned} \tag{3}$$

The temperature profile of fuel pin is extracted from the EBR-II benchmark. With reference to the previous experiment results, it is assumed that the maximum swelling strain is 10%.[1],[3]

2.2 Fuel-Cladding gap effect

In the manufacturing process of the fuel pin, the slight gap between the fuel and the cladding is intended. At the low-burnup stage, the gap is closed because of thermal and swelling deformation of the fuel. As a reference, overall physical phenomena of the fuel pin is presented on the Table.1. [3]

Burnup (%)	Relevant phenomena
0.0	Irradiation begins
0.5 ~ 1.0	1. Grain boundary tearing and cracking because of swelling and become axially at the high-temperature axial section 2. Resulting axial friction force is enough to stop the axial growth of the fuel by compressing the existing open gas pores. Furthermore, swelling rate reduces due to axial frictional force. 3. The radial contact pressure between fuel and clad is low due to extrusion of the inner zone fuel into the cracks. 4. Fission gas release into the plenum begins.
1.0 ~ 2.0	1. Cracks are closed and fuel becomes both axially and radially restrained at the hot axial location. 2. Radial contact pressure between fuel and clad rises to a level somewhat higher than plenum pressure. Open gas pores start to be compressed to accommodate for solid/liquid fission product swelling. 3. Fission gas release fraction rises rapidly to 50 %.
2.0 ~ 13.0	Contact pressure holds at a level somewhat higher than the plenum pressure as the open pores are further compressed to

	accommodate accumulation of solid products.
13.0 ~ 20.0	Fuel does not have enough open pores to accommodate solid fission product accumulation. The resulting fuel-clad contact pressure rises significantly. When open pores are less than 5 %, the contact pressure rises rapidly and breach may result.

Table.1 Overall physical phenomena of the fuel pin

The gap distance is a major factor determining Fuel cladding mechanical interaction (FCMI). Fig. 2 is stress contours varying with the gap distance.

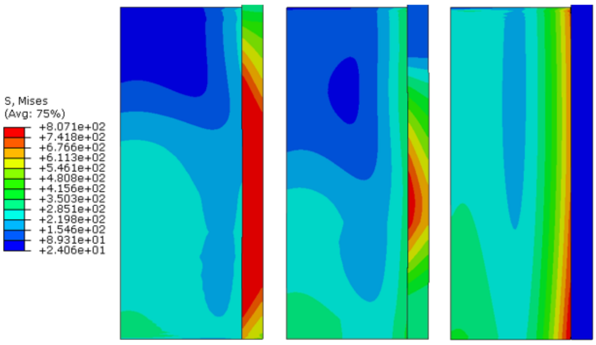

Fig.2 Mises stress contours of fuel and cladding varying with the gap distance

In case that the initial gap distance is 0.13 mm, the maximum Mises stress becomes 807.1 MPa, in case of 0.14 mm, the maximum Mises stress becomes 518.7 MPa, and in case of 0.15 mm, the maximum Mises stress becomes 6.2 MPa. This result implies that the initial gap distance is an important factor determining FCMI. However, the stress of actual pin caused by FCMI is insignificant. To solve this problem, various models such as Fuel cracked model and Fuel anisotropic model are suggested.[4]

2.3 Cavity simulation

New model simulating cavity formation is developed. USDFLD and DLOAD, which are a Fortran-coded subroutine programs supported by ABAQUS, are used for this model.[2] USDFLD is used to reflect the loss of stiffness of elements and DLOAD is used to make internal pressure when the fuel is molten. Fig.3 is Mises stress contours of the fuel pin when the cavity is formed under transient state. It is confirmed that the Mises stress decreases on the section where the cavity forms in this model and it is similar to cavity-region-removed model.

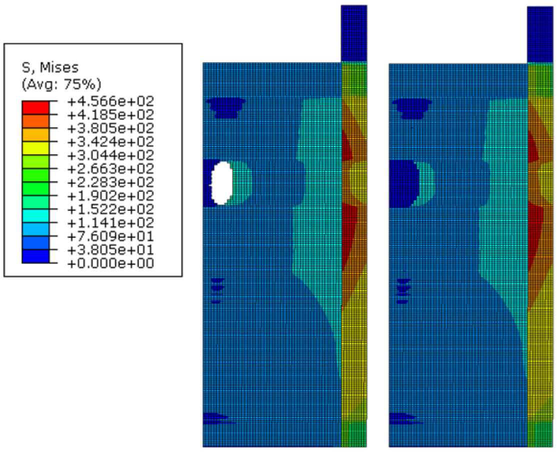

Fig.3 Mises stress contours of cavity-formed fuel and cladding analyzed by using cavity-region-removed model and new cavity simulation model

3. Conclusions

It is checked out that the gap distance between the fuel and the cladding is a major factor determining FCMI stress. In this regard, initial boundary condition of the fuel pin such as the initial gap distance should be set carefully when the stress analysis of the fuel pin under transient state is conducted. In case of simulating cavity formation, it is confirmed that the new cavity simulation model that elements in cavity region lose their stiffness is valid.

REFERENCES

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