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The Development of Finite Element Model for Pellet-Cladding Mechanical Interaction

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1. Introduction

This paper studies a FEA(Finite Element Analysis) model to describe PCMI under a power ramp and pressure loading conditions. From this PCMI model, the stress fields of pellet and cladding are evaluated. In order to compute the stress and strain fields in the cladding which were failed under the power ramp, this model might be extended to include the missing chip shape which occurred in the process of assembling or manufacturing of fuel rod. This missing chip of pellet has an affects on the temperature and the stress of the cladding in the vicinity of the chip edge so that the possibility of fuel failure is increased during the power ramp. The pellet fragmentation (see Figure 1) can be also accounted because the fuel cracking occurs immediately after reactor start-up and plays an important role in relaxing stresses in pellet but escalating the stress in cladding [1].

In order to develop the PCMI FEA model and verify the stress results with cladding creep property, the geometry of perfect pellet and cladding are used. Then the verified model and methodology will be applied to the stress and strain predictions for the fuel failure through PCMI. The FEA consists of heat transfer analysis and thermal stress analysis including the creep effect of the cladding. The gap between pellet and cladding was modeled using the contact element so that the phenomenon of gap closing and opening is considered. Therefore the heat generation of the pellet can be transferred to the cladding by heat conduction or convection.

In the stress analysis, the friction coefficient between cladding and pellet is assumed to equal 1.0 for the pellet-cladding bonding state. ANSYS creep library was applied to simulate the creep property of the cladding. The ZIRLO^{TM} cladding creep equations were fitted into the "modified time hardening" equation.

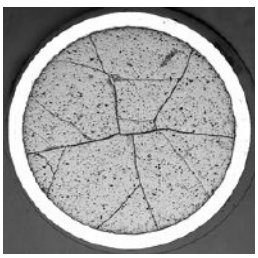


Figure 1. Macrography of a fuel rod irradiated

2. Analysis Model

A general purpose FE program ANSYS [2] has been used in the analysis. A section of a fuel rod is modeled with 3D volume elements (see Figure 2). ANSYS enables to import thermal calculations into stress calculation. Therefore the same topology is utilized for both thermal and mechanical analyses. The 3D 20-node isoparametric brick element SOLID90 is used for the thermal analysis and the compatible 3D SOLID95 element used for the stress analysis.

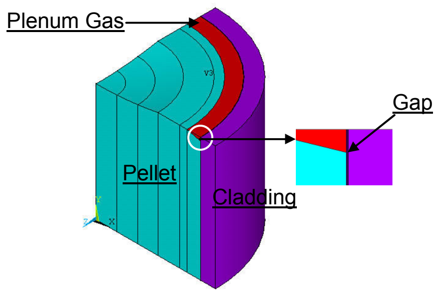


Figure 2. 1/8 Model of a perfect fuel rod

Heat transfer between the pellet and cladding is simulated by using contact element TARGE170 and CONTA174 which represent the 3-D surface-to-surface contact. The pellet and cladding may be in contact or in a more or less distant positions relatively each other. Therefore, the heat transfer mechanism is divided in conduction and convection also. The gap heat transfer factor is provided by the gas conductivity and heat transfer gap.

$$\lambda = \alpha \times \delta \qquad (1)$$

Where, λ = Thermal conductivity
α = Heat transfer factor
δ = Heat transfer gap

The contact stress between the pellet and cladding is calculated in the structure analysis which imports the temperature distributions from the heat transfer analysis. In the stress analysis, the friction coefficient between cladding and pellet is assumed to equal 1.0 for the pellet-cladding bonding state.

Material properties and geometry used for UO_2 pellet, cladding and helium gas are mainly taken from the 17x17 OFA fuel rod. The modified time hardening equation from ANSYS creep library option 6 is selected to simulate the high stress creep of the ZIRLO^{TM} cladding.

$$\varepsilon_{cr} = C_1 \sigma^{C_2} t^{C_3+1} e^{-C_4/T} \big/ \left(C_3 + 1\right) \qquad (2)$$

Where, ε_{cr} : Equivalent creep strain
σ : Equivalent stress
C1~C4: Coefficients

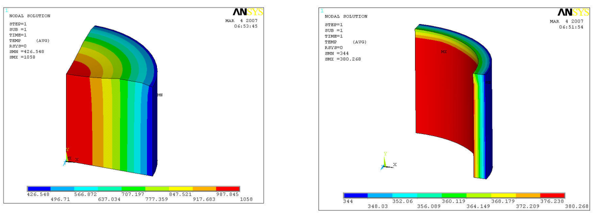
3. Analysis & Results

In the thermal stress analysis, the sequential method is implemented to calculate the thermal stress rather than the direct method which solves the heat transfer and structure analysis at once because the direct method is limited to use only the same geometry of both thermal and stress analyses. When the missing chip of pellet is taken into account, the heat transfer and stress analysis might be different from each other.

In heat transfer analysis, heat generation in the pellet is set as a starting parameter together with cold gap and coolant temperature. The calculated temperatures are summarized at Table 1 which indicates the FEA results are in agreement with the heat equation. As we expected the temperature around cladding inside adjacent to pellet chamfer is approximately 12℃ lower than that of the other cladding inside as shown in Figure 3. This lower temperature results from the helium gas with relatively low conductivity filled in the pellet chamfer void.

Table 1. Temperature results of heat transfer analysis

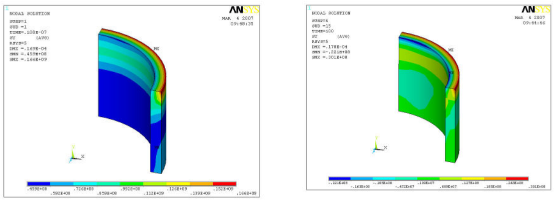
Pellet & Cladding	FEA, ℃	Theory, ℃	Diff. %
Pellet Center	1058	1069	-1.0
Pellet Surface	426	432	-1.4
Cladding Inside	380	377	+0.8
Cladding Outside	344	344	-



(a) Pellet (b) Cladding

Figure 3. Pellet and Cladding Temperature (℃)

The stress induced by thermal gradient and coolant pressure is simultaneously calculated and the stress results are provided to the modified time hardening creep equation. Figure 4 represents the cladding hoop stress results without and with cladding creep property, respectively. The maximum hoop stress occurs at cladding outside around pellet chamfer in both cases. When cladding creep is considered, the maximum hoop stress is reduced to about 20%. Also It is shown in Figure 5 that the total strain tends to decrease with time.



(a) without creep (b) with creep (after 100 hrs)

Figure 4. Cladding hoop stress distribution (Pa)

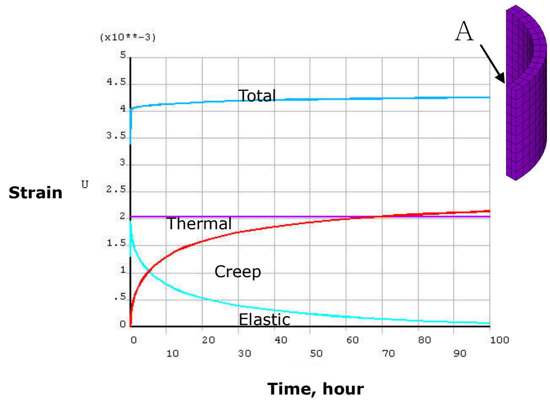


Figure 5. Strain History at the cladding inside "A" point

4. Conclusion

The FEA model to simulate PCMI under a power ramp and pressure loading conditions were developed to compute the stress and strain fields in the cladding. It is confirmed that ANSYS creep library is applied to take account of the creep property of the cladding. Therefore this PCMI model and methodology might be extended to include the missing chip, pellet cracks and cladding defects. In addition, this model may be used for design studies to optimize pellet geometry such as length and chamfer.

5. Acknowledgement

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[2] ANSYS, User's Manual, Version 10.0, Swanson Analysis Systems, Inc.