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Numerical Investigation of Creep Behavior of Cr-coated ATF under Steady-state Condition

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1. Introduction

As one of Accident Tolerant Fuel (ATF) claddings, chromium (Cr) coated zirconium (Zr) cladding is known to reduce high temperature steam oxidation because of chromium's good resistance to oxidation [1], and to show delayed ballooning and burst during LOCA condition due to slowed creep deformation of the Cr-coated cladding [2]. In addition, the slowed creep of the Cr-coated cladding has been also reported in normal operating (steady-state) condition, resulting reduced inward creep. However, considering commercial use of the Cr-coated cladding for a long time deployment in reactor, little is known about such creep behavior under normal operating condition in detail. In this context, to understand the slowed creep behavior of the Cr-coated cladding under steady-state condition, this study investigated the mechanical behavior of the Cr-coated cladding under steady-state condition through numerical analysis.

2. Methods and Results

2.1 Numerical modeling

Numerical analysis was performed by using the 2D axisymmetric structural analysis model developed by Rho and Lee [3] with a modification. The modification includes constitutive modeling for creep behavior of metallic materials. Two numerical models representing an uncoated and a Cr-coated claddings were constructed. Each of the models have a length of 200 mm, and the Cr-coated cladding was modeled as a bi-layer model where a coating layer has a thickness of 15 μm was added onto the outer surface of the underlying base cladding (i.e., the uncoated cladding). Temperature was assumed to be 380℃ and three different inner pressures which are 10 MPa, 12.5 MPa, and 15 MPa were considered. To model creep behavior of the uncoated cladding, the thermal creep model described in FRAPCON [4] was employed. The model expresses the thermal creep strain $\bar{\varepsilon}^{cr}$ as follows:

$$\bar{\varepsilon}^{cr} = \varepsilon_s^p\left(1-\exp\left(-C\sqrt{\dot{\bar{\varepsilon}}_s^{cr}t}\right)\right)+\dot{\bar{\varepsilon}}_s^{cr}t \tag{1}$$

$$\dot{\bar{\varepsilon}}_s^{cr} = A\frac{E}{T}\sinh^n\left(\frac{B\bar{\sigma}}{E}\right)\exp\left(-Q/RT\right) \tag{2}$$

$$\varepsilon_s^p = D\left(\dot{\bar{\varepsilon}}_s^{cr}\right)^F \tag{3}$$

where *A*, *B*, *C*, *D*, *F*, and *n* are material constants for the creep model. These constants for the creep behavior of the uncoated cladding were taken from FRAPCON [4]. In addition, the Cr coating layer's creep behavior was modeled using a power-law creep model and its constants were taken from Wagih et al [5].

2.2 Results

Figure 1 shows radial displacement histories at the outer surface of the uncoated and the Cr-coated claddings obtained from the present study and Abaqus that is commercial FEA software, which verifies the structural analysis model used in the present study. Also, Fig. 2, which shows hoop strain distributions of the Cr-coated cladding when the inner pressure is 10 MPa, confirms the good agreement between the analysis model and FEA.

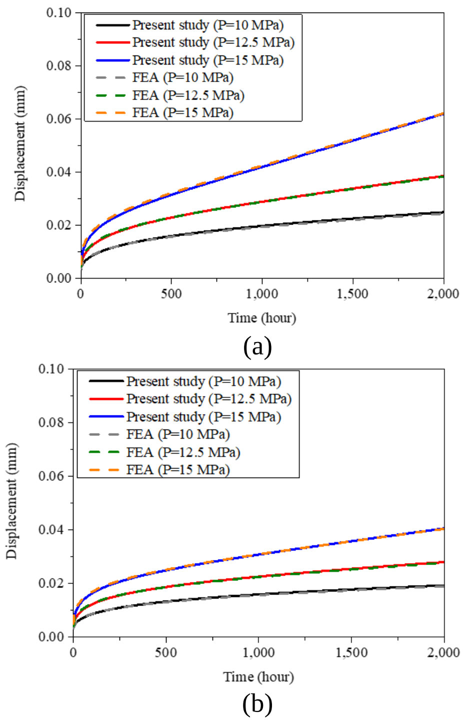

Fig. 1. Radial displacement histories of the uncoated and the Cr-coated claddings with different inner pressures obtained from the present study and FEA. (a) uncoated cladding, (b) Cr-coated cladding.

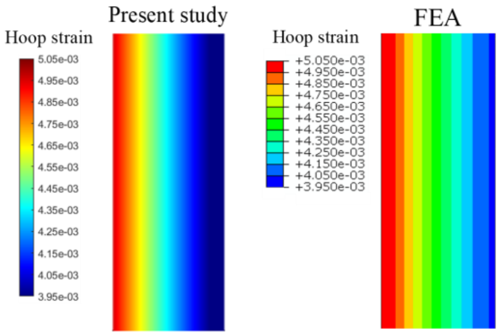

Fig. 2. Hoop strain distribution of the uncoated and the Cr-coated claddings when the inner pressure is 10 MPa obtained from the present study and FEA.

In order to investigate the reduced creep deformation, hoop strain histories at the outer surface for both claddings which were obtained from the present analysis model are depicted in Fig. 3. It can be noted that the Cr-coated claddings show markedly reduced deformation compared to the uncoated cladding. This behavior would also indicate that the Cr-coated cladding will be able to satisfy the current safety criterion (hoop strain limit by 1%) which is for the uncoated Zr based cladding under normal operating condition.

In addition, hoop stress histories at the middle of the underlying base cladding for the uncoated and Cr-coated claddings were also compared and are shown in Fig. 4. It can be found that the hoop stress for the Cr-coated cladding continues to decrease while it increases for the uncoated cladding. This reduction in the magnitude of the stress in the coated cladding would be due to the coating layer's high resistance to deformation which offsets the stress applied to the base cladding by inner pressure, which leads to the reduced creep deformation of the coated cladding in the normal operating condition.

3. Conclusions

In this study, the slowed creep behavior of the Cr-coated cladding under steady-state condition was investigated through numerical analysis. It was found that the employed structural analysis model with the modification showed good agreements with the finite element analysis results, and also found that the steady-state deformation of the Cr-coated cladding is markedly reduced compared to the uncoated cladding. From the stress analysis, the reduction would come from that the magnitude of the stress applied to the base cladding is significantly reduced by the coating layer. Hence, it is expected that this study will further improve the understanding of the mechanical behavior of the Cr-coated cladding in the steady-state condition and be able to give design guidelines of the coated cladding to prevent accidents that can occur under normal operating condition such as PCMI by creep down of the cladding.

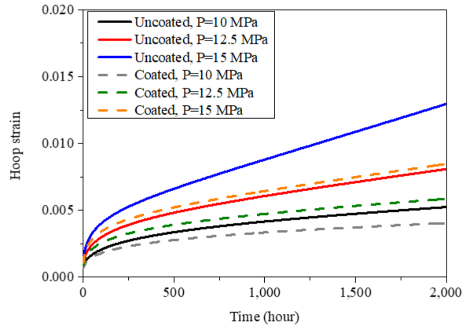

Fig. 3. Hoop strain histories of the uncoated and the Cr-coated claddings with different pressures under steady-state condition.

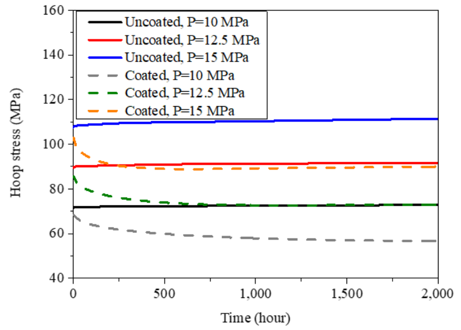

Fig. 4. Hoop stress histories of the uncoated and the Cr-coated claddings with different pressures under steady-state condition.

Acknowledgement

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