Investigation of thermal creep properties of chromium coated cladding with MERCURY

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1. Introduction

It is desirable that improvements in accident tolerance are simultaneously accompanied by improvements to normal operations in terms of compatibility with current power plants and operations, economics, and impact on fuel cycles. For this reason, accident tolerant fuels (ATFs) are being developed in several countries. "Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS)" is a program established by the IAEA to help Member States understand and address factors affecting the design, fabrication, and in-pile behavior of innovative nuclear fuels and materials for reactors currently in operation, and to increase technology readiness for candidate ATF materials.

In the ATF-TS project, a chromium coated cladding on the surface of zircaloy tubes is being studied as an ATF cladding. To predict the high temperature behavior of the coated cladding, we need not only the properties of the zircaloy, but also the properties of the coating layer. Since it is hard to find out the properties of the coating layer, we would like to derive the properties of the coating layer from the burst test results using a nuclear fuel performance code. In this paper, we derived the thermal creep parameters of the ATF cladding using a nuclear fuel performance code (MERCURY) [1] and commercial optimization software (ISIGHT) [2].

2. Thermal creep of chromium coated Opt. ZIRLO™

This section describes the process of deriving and evaluating the properties of thermal creep, which primarily affects high temperature deformation. The thermal creep can be expressed as Eq. 1. The creep equation consists of three physical parameters (A, n, Q). These parameters have different values depending on the phase of the material. To characterize the creep parameters, data from a burst experiment was used. The cladding used in the burst test is an Optimized ZIRLO™ (Opt. ZIRLO™) surface coated with chromium (Cr).

$$\dot{\varepsilon} = A\exp(-\frac{Q}{RT})\sigma^n \tag{1}$$

2.1 Burst test of coated cladding

The burst test was conducted at the Czech Technical University (CTU), where the ATF cladding was placed in a furnace and pressurized under a certain temperature to rupture, as shown in Figure 1. In the frame of IAEA ATF-TS, data from the burst tests were provided. The data include the experimental conditions, burst time, and post-rupture geometry.

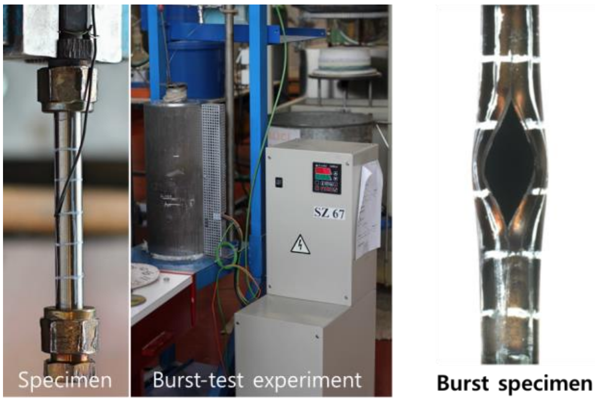

Fig. 1. Specimen and apparatus for burst test [3]

2.2 Process of deriving property parameters

In order to derive the parameters of the coated cladding, the analysis was performed by linking the optimization software, ISIGHT and the nuclear fuel performance code, MERCURY, as shown in Figure 2. Based on the physical parameters proposed in previous studies, an input matrix distributed within a certain region is constructed. Design of experiment (DOE), optimal latin hypercube is used to optimize the parameter. The input matrix values were entered into the MERCURY code to perform high temperature deformation analysis. The results were compared with the burst experimental data to analyze the sensitivity of the input parameters and find the optimal parameters. Since the thermal creep properties of the coated cladding are needed to for both the base material, Opt. ZIRLO™ and the coating layer, the high-temperature creep properties of the base material were derived from the burst test conducted with the Opt. ZIRLO™, and the thermal properties of the coating layer were derived from the ATF (Opt. ZIRLO^{TM} + Cr coating) test. In addition, since the property values are varied as function of temperature due to phase change, separate property values are derived in two temperature intervals (1080K, 1190K).

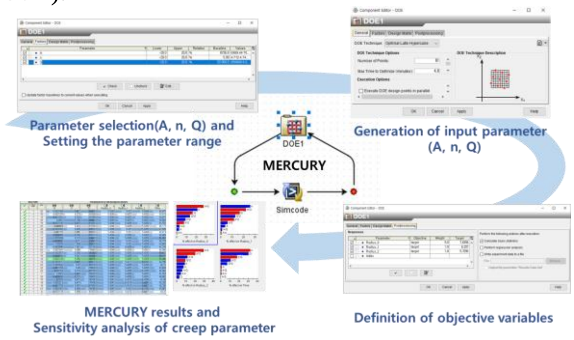

Fig. 2. Process of deriving thermal creep's parameter with MERCURY and ISIGHT.

3. Result

3.1 Analysis of thermal creep for Opt. ZIRLO^{TM}

In general, Opt. ZIRLO^{TM} is recognized as a material with similar mechanical properties to conventional zircaloy except the enhanced oxidation resistance. Therefore, the basic mechanical properties of zircaloy material defined in MATPRO [4] were applied. Erbacher [5] conducted the burst test of the zircaloy cladding to obtain the creep parameter of the zircaloy. In order to find the creep parameters of Opt. ZIRLO^{TM}, the input matrix is generated by making a few changes based on the creep parameter of zircaloy [5]. Considering the phase change, the parameters of two burst experiments (OPZ1, OPZ2) with different temperatures. The results of the analysis with the derived parameters are illustrated in Figure 3. It can be seen that the traditional zircaloy creep property predicts a later rupture time due to more deformation at high temperature. In contrast, the derived properties seem to predict the rupture time reasonably well.

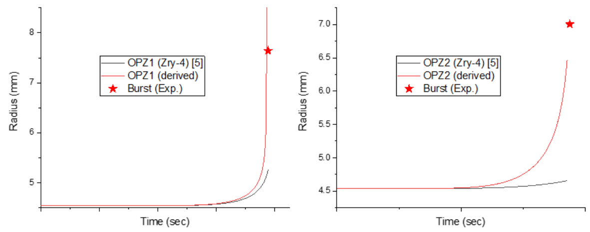

Fig. 3. High-temperature deformation analysis results and burst data of Opt. ZIRLO^{TM} (OPZ1, OPZ2).

3.2 Analysis of thermal creep for coated Cr

The previously derived Opt. ZIRLO^{TM} properties were applied to the simulation of high temperature deformation for the coated cladding. Based on the properties of Cr materials presented in the existing literature [6], an input parameter matrix within 10% was created and compared with the burst test results. OPZCR1 and OPZCR5 rupture tests were used to consider the changes in parameter values due to phase change. The results of the analysis using the derived parameters are shown in Figure 4. For each graph, the case without coating properties, the case with coating properties from the existing literature [6], and the case with the derived coating properties are shown. It can be seen that the deformation occurs quickly in the case of no coating, and the amount of deformation is reduced in the same time by coating the surface of the cladding with Cr. It can be seen that using the parameters derived through the optimization process is more predictive of the burst behavior of the experiment.

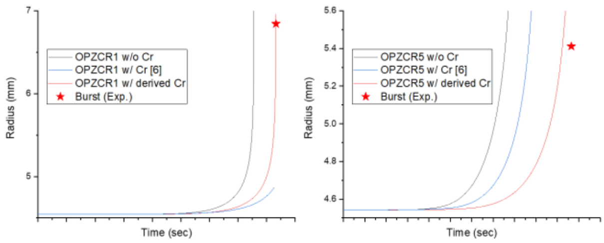

Fig. 4. High-temperature deformation analysis results and burst data of the coated cladding, (OPZCR1, OPZCR5).

3.3 Evaluation of high-temperature deformation with derived thermal creep parameter.

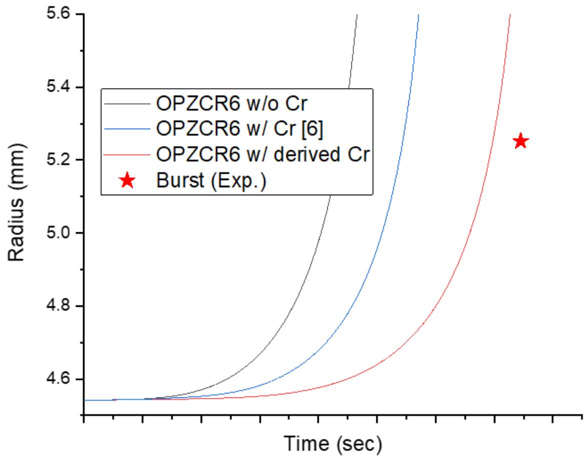

Fig. 5. High-temperature deformation analysis results and burst data of the coated cladding, (OPZCR6).

The derived thermal creep parameter of Opt. ZIRLO$^{\mathbf{TM}}$ and coating layer were applied to another rupture experiment analysis (OPZCR6) to evaluate the appropriateness of the derived parameters. Figure 5 shows the deformation behavior of simulation and experimental results. It shows the same trend in Figure 4, where the analyzed case with the derived parameters is in better agreement with the experimental results. Based on this, it can be concluded that the derived parameters are appropriate for burst analysis.

4. Conclusions

The nuclear fuel performance code (MERCURY) and optimization tool (ISIGHT) were used to derive the thermal creep properties of the coated cladding. It can be seen that the rupture time derived from the experiment is similar to the analysis result. By coating the cladding tube with chromium, the amount of deformation at high temperature was reduced.

However, total amount of creep deformation at the burst is provided in the experiment whereas amount of deformation is required for the time to obtain creep coefficient by experiment. Real-time high temperature deformation experimental data is required to understand the actual high temperature behavior. In the future, we will use the high temperature deformation history of the coated cladding to obtain the thermal deformation properties.

ACKNOWLEDGEMENTS

The preparation of this paper was supported by the Ministry of Science and ICT, Republic of Korea (RS-2022-00144002). This work was conducted in the frame of IAEA's Coordinated Research Project on Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS). Zr-based substrates for ATF fabrication within ATF-TS was provided by Westinghouse Electric Company.

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