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Comparison of Measurement and Analysis of High Temperature Steady-state Creep Experiment for Equipment Verification

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1. Introduction

The creep strain rate of Zircaloy-4, which is generally described based on the Arrhenius equation [1], is one of the basic property parameters for a nuclear fuel code that numerically predict the deformation behavior of fuel cladding during a loss of coolant accident (LOCA). The nuclear fuel code predicts the real-time deformation of the fuel cladding, and in-situ experimental data is needed to verify this predicted result. Therefore, a non-contact measurement method was developed through the previous study to obtain in-situ deformation data [2].

In this study, for verification of established experimental equipment, comparison work with experimental results of previously known studies was performed [1]. Comparison work was conducted through creep test on the β-phase, and the results were evaluated through a commercial tool ABAQUS [3] analysis based on the creep equation suggested by Rosinger et al. [1]. In the ABAQUS analysis, the creep equation was applied using user defined subroutines.

2. Experimental setup

2.1 Experimental equipment and procedure

The experimental equipment is basically the same as that of the previous study [2], and a modified quartz tube was applied to reduce light formation affecting the specimen image. As shown in Fig. 1, apparatus consists of an Infrared (IR) furnace controlled by thermocouple (TC) measurement regulation loop to control the temperature of the specimen, a pressurization section, and optical equipment to capture the deformation. Argon gas was continuously supplied inside the quartz tube to maintain an inert atmosphere during the entire procedure.

The steady-state creep test was performed twice with internal pressure of 3 and 6 bar at a temperature of 1373K, and controlled by the procedure shown in Fig. 2. The temperature was raised to a target temperature of 1373 K with 5 K/s heating rate and the temperature is stabilized for 300 seconds. After temperature stabilization, the cladding tube was pressurized to an experimental pressure condition(3 or 6 bar) using argon gas and then maintained at the constant pressure. Steady-state creep tests were conducted to rupture to evaluate creep model over the entire strain and to produce verification data for separate effect test (SET) of nuclear fuel codes.

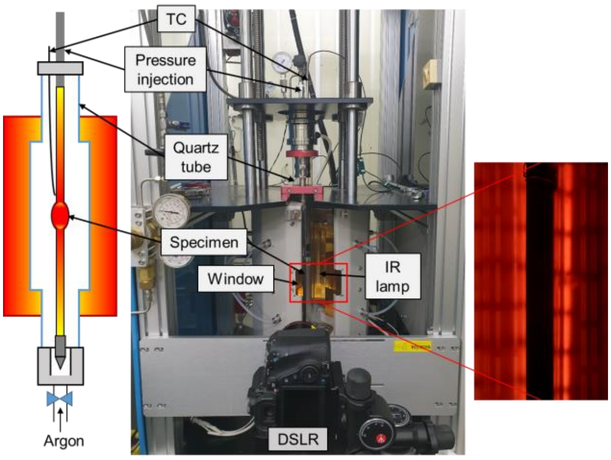

Fig. 1. Schematics and image of the experimental set up

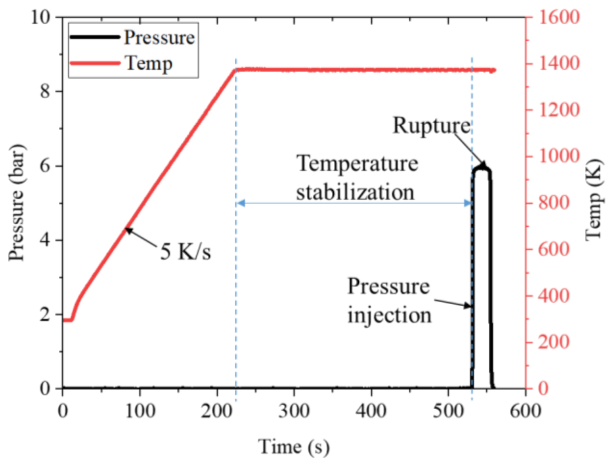

Fig. 2. Temperature and pressure histories during a 6 bar test of 1373 K

2.2 FE analysis model and boundary conditions

As shown in Fig. 3, the ABAQUS finite element (FE) model was designed as the axisymmetric model of a 100 mm long. The boundary conditions were freed only in the axial direction at the bottom, as in the experiment, and the temperature and pressure conditions were also inputted, as in the experiment. The material properties of Zircaloy-4 are based on the MATPRO [4], and the creep rate on the β-phase is defined by Rosinger as Eq. (1) [1], and applied through user defined subroutine.

$$\dot{\varepsilon} = 7.9 \cdot \sigma^{3.78} \cdot \exp\left(-\frac{17079}{T}\right) \tag{1}$$

Additionally, the burst criterion was defined as the burst model, which is a function of strain over time applied to FRAPTRAN-2.0 [5].

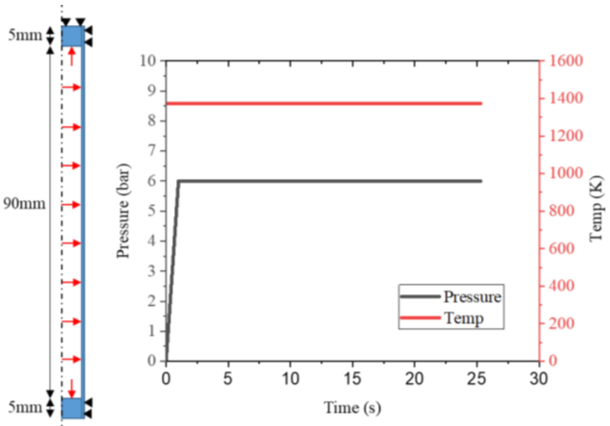

Fig. 3. FE model, boundary conditions, and input value of 6 bar test at 1373 K for ABAQUS analysis

3. Results and Discussion

According to the material properties [4], thermal expansion in axial direction by high temperature experimental condition can be neglected since it does not exceed 1%. Both strains measured through image analysis and calculated through ABAQUS analysis are shown in Fig. 4. The strain of experiment in Fig. 4 were measured during the time the pressure was injected in the same way as the FE analysis. Because burst criterion used in analysis was derived from several types of transient tube burst tests, it could be different to the steady-state burst results. So, the ABAQUS analysis was terminated later than experiment. But it can be seen that the strain of the experiment is similar those of the analysis using Rosinger's creep equation. It means that the established equipment can perform similar to the referenced studies [1].

The initial steady-state creep strain rate of the experiment was measured higher than the analysis, and a slight difference was found in the strain rate of 6 bar experiment. It is the reason that the creep equation is defined as a value representing the strain rate measured under various stress and temperature conditions, as shown in Fig.5

As a result, considering the difference of the experimental method and the instability of the material experiment, the strain over time shows good agreement.

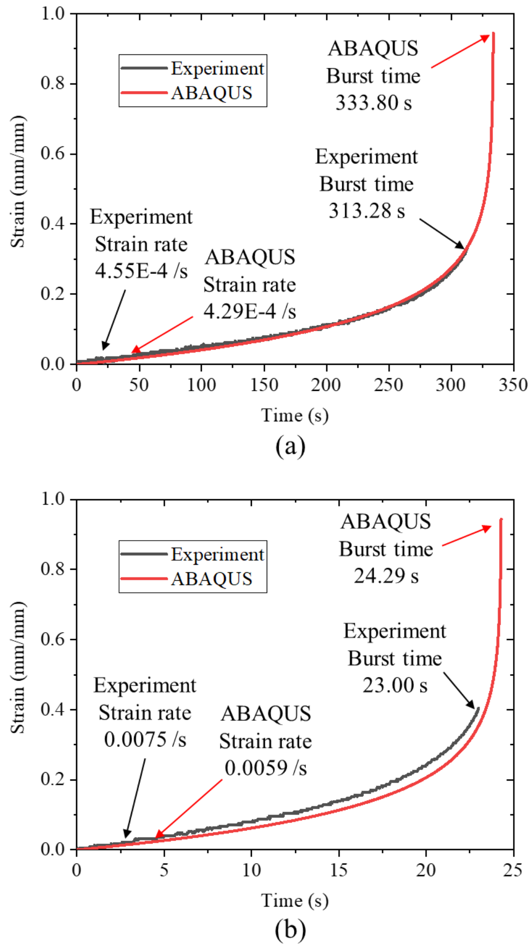

Fig. 4. Comparison of the hoop strains over time: (a) 3 bar, and (b) 6 bar results at 1373K

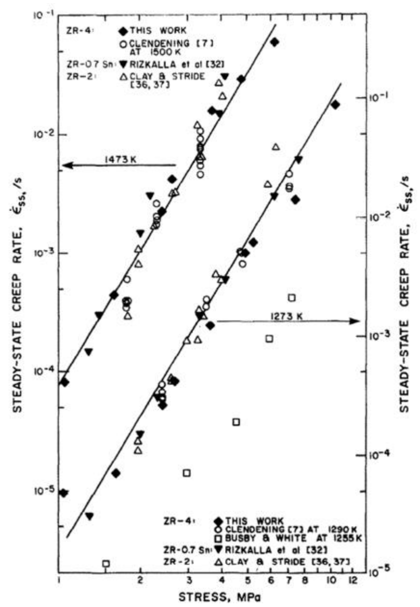

Fig. 5. Steady-state creep rate versus applied stress for tests conducted in the β-phase range at 1273 and 1474 K [1]

4. Conclusions

In order to verify the established experimental apparatus, the creep experiment was performed on the β-phase with Zircaloy-4 cladding. The experimental results were evaluated using an FE model designed based on previously known studies. The experiments and analysis were performed under the similar temperature and pressure conditions. As a result, except for the difference according to the burst criterion, the strain data showed good agreement over the entire time. Therefore, it was confirmed that the established equipment can perform experiments similar to the referenced studies and can additionally measure in-situ deformation data.

For the future work, the established equipment will perform burst test under various transient heating conditions to confirm the heating rate effects and will be used to produce verification data for SET.

ACKNOWLEDGEMENT

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