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# Experiment for cladding large deformation at high temperature with multi-dimensional strain measurement using digital image correlation

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## 1. Introduction

The economic concerns compelling utilities to consider the increase of average burnup for fuel assemblies and to adopt new type of cladding materials to enhance thermal and safety margins. To sustain such aggressive conditions by fuel and reactor core requires new investigations for fuel rod behavior under reference accidental conditions to meet current safety criteria and to provide new technical bases for modelling. As per revised emergency core-cooling-system (ECCS) acceptance criteria [1], the safety analysis code system should take into account fuel behavior models. In LOCA scenario, fuel cladding experiences ballooning/burst at high temperature because internal pressure results in large deformation outward. The cladding behavior affects safety analysis results due to flow blockage and oxidation at high temperature.

Fuel rod behavior under transient conditions has been investigated by several researchers for many decades. Chung and Kassner (1979) studied the effect of the internal pressure, heating rate and temperature on the ballooning deformation of Zircalloy-4 cladding [2]. Chapman et al. (1979) reported that clad deformation is extremely sensitive to small temperature variation at the surface [3]. The irradiating low burn-up clad tubes were used to investigate thermo-mechanical behavior cladding under LOCA conditions. Karb et al. (1982) investigated the influence of nuclear environment on the cladding failure behavior [4]. Erbacher and Leistikow (1987) noted that ATD has great influence on the circumferential strain in α-phase and (α+β)-phase domain of Zircaloy-4 cladding [5]. Kim et al. (2004) reported that phase transformation from α to β phase plays an important role in the deformation of Zircaloy-4 [6]. The clad tube was directly heated using resistive heating and burst investigation was done under isothermal/transient heating conditions. Nagase et al. (2009) analyzed clad behavior of new materials under high burn-up ranging from 66 to 76 MWd/kg by Infra-red heating technique [7].

Previous works have focused on obtaining burst hoop strain and its temperature in the view of burst criteria. As high fidelity fuel modelling, multi-D fuel codes such as BISON and ALCYONE, DRACCAR have been developed. However, multi-D code systems are still validated with those 1D measurements. To validate multi-D codes against experimental results, multi-D measurement should be acquired during deformation.

In this study, experimental setup for cladding large deformation with multi-D strain measurement using DIC (digital image correlation) was carried out, which is named as ‘FISRBIT’ (Facility to Investigate Single Rod Behavior In Transient). Multi-D strain of cladding to be measured are studied while the cladding large deformation occurs. Test specimens were examined in terms of oxidation and geometry after the experiments.

## 2. Experimental setup

### *2.1 FISRBIT*

An experimental facility named ‘FISRBIT’ has been designed to study cladding large deformation at high temperature by internally heating the Zircaloy-4 clad tube. The Fig. 1 shows details of the test section. The clad tube of length 340 mm (outer diameter of 9.5 mm) was placed concentrically inside an enclosure of length 500 mm and the assembly was placed in vertical position. The clad tube was fixed at the top flange of enclosure and connected to a highly flexible copper clamp at the bottom end to minimize the bowing of clad tube at elevated temperatures. The clad tube was internally heated using a tungsten heater of 100 mm length. The tungsten heater was placed concentrically inside clad tube. The window of enclosure is extended to measure multi-D strain by DIC.

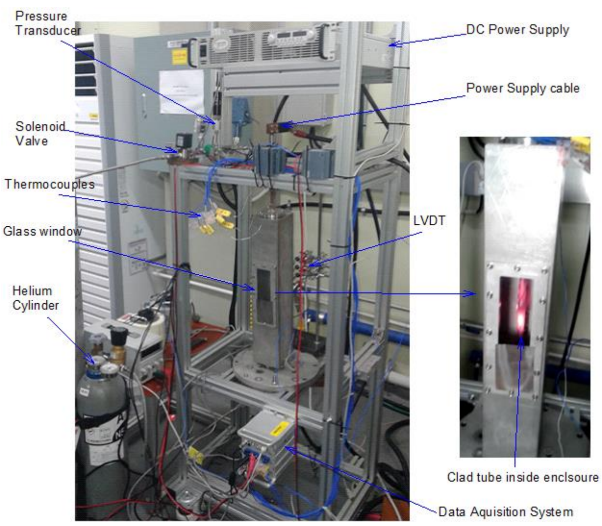


Fig. 1. Experimental setup of ‘FISRBIT’ without DIC equipment

### *2.2 Multi-D strain measurement*

To measure multi-D strain of cladding during experiment, DIC technology was employed, which is one of the non-contact full-field strain measurement techniques with a broad range of applications. The DIC technique is based on tracking system for geometrical change in the gray scale distribution of surface patterns in small neighborhoods called subsets during deformation. Using two cameras system, three-dimensional surface coordinates can be obtained by acquiring digital stereo pair images of the specimen as well as two-dimensional ones. For optical system, high speed camera with frame speed from 165 to 2,000 frame per second was used. The camera is based on CMOS sensor with resolution of 2 MPx and field of view (FOV) from 20 mm to 1 m. Additionally, lens with focal length of 25 mm and infrared (IR) cut-off filter were applied for low distortion and high temperature measurement. For hardware system, controller and AD/DA module were employed for data control and acquisition. For software system, mercury RT version 2.6 (Sorbriety s.r.o) was used [8]. During the experiment, images of the clad were recorded, and full-field strain distribution was calculated by the DIC software system.

### *2.3 Experimental procedure*

The clad tube was pressurized with helium up-to the desired pressure by energizing the solenoid valve in the pressure line. The helium gas was supplied to the enclosure through bottom end flange to create non-oxidizing atmosphere around the clad tube. The vent valve provided at the top end was kept open for some duration for purging out existing air inside the enclosure. The clad tube was initially heated up-to the operating temperature i.e. 500-573 K and then ramp power was given to the heater. The transient temperature, pressure, deformation and power was recorded using the data acquisition system. Since DIC software is linked with data acquisition system, multi-D strain data to be measured are synchronized with measurement of rod internal pressure, temperature and so on.

## 3. Results and Discussion

The cladding experiences large deformation (ballooning) and burst at 1769 s. As shown in figure 2, rod internal pressure was set as 70 bar at the beginning of test. Internal pressure was measured as 66 bar when burst occurs. Cladding surface temperatures were measured at top, middle and bottom location by thermocouples. As well as, cladding temperature at plenum location was measured because plenum temperature strongly governs rod internal pressure. For this case, burst location is close to bottom region. Therefore, surface temperature at bottom is higher than middle. LVDTs also are equipped with cladding to measure radial displacement of cladding by contact method.

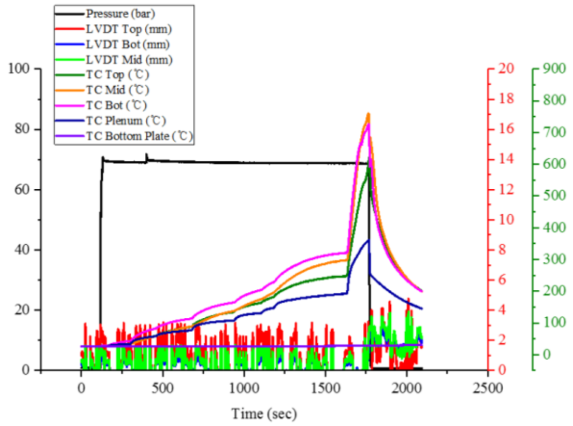


Fig. 2. Experiment results of FISRBIT

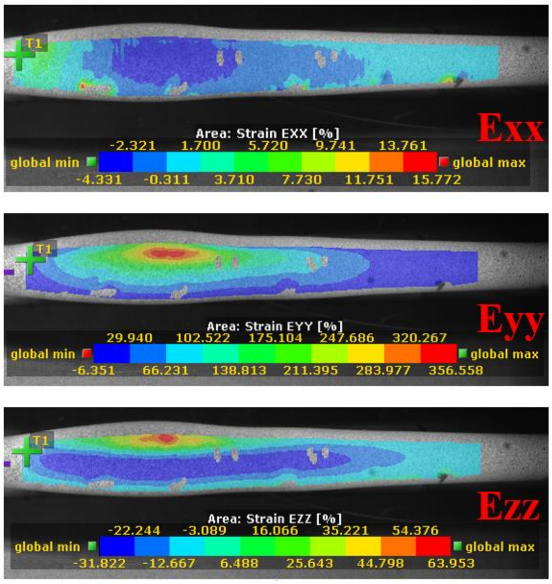


Fig.3. Measured multi-D strains (Exx, Eyy and Ezz) by DIC technology

In figure 3, results of multi-D strains are shown just before the clad burst. All data during experiment are stored in system and it can be analyzed. In Cartesian coordinate, principal strain at each axis is shown. Two camera measure displacement of all speckle pattern on the specimen. DIC software converts the measured displacement to strain. Eyy result demonstrates that the localized strain distribution at highly deformed region is shown as red color. At localized region, Ezz also represent highlighted but trend is quite different.

To analyze permanent strain at 3D, test specimen was scanned as shown in figure 4. Laser scanning machine (Laser Desing Inc.(USA)) which can scan the object with 2.4 um accuracy and automatic 6 axis motion was employed. It is obvious that the measured data is highly consistent with test specimen. In addition, oxidation of cladding was investigated by examination of oxygen profile of deformed cladding.

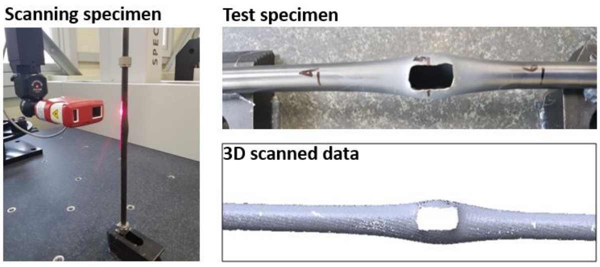


Fig.4. 3D scanning results of burst cladding tube by FISRBIT experiment

## 4. Conclusions

To acquire the multi-D validation data for multi-D fuel code, experiment for cladding large deformation with DIC was performed named as FISRBIT. The FISRBIT acquires cladding surface temperature at several locations and rod internal pressure. The measurement system is linked with DIC. All data to be measured can be stored during experiment. Test specimen were examined in terms of oxidation and deformed shape. In particular, 3D scanned data of specimen can be applied into calculation of burst area to research fuel dispersion through burst zone.

For the future, test matrix of experiment for cladding large deformation will be determined. Measured data including cladding temperature, rod internal pressure and multi-D strain by DIC will be provided by FISRBIT. Those data can be applied into validation of multi-D fuel code system.

## ACKNOWLEDGEMENT

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