A full-field strain measurement of deformation for clad tube at high temperature using digital image correlation

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1. Introduction

In the case of a Loss of Coolant Accident (LOCA), the coolant outside the fuel is suddenly lost and the temperature of the cladding rises. When a certain condition is reached, ballooning of the cladding that is potential interference with cooling effectiveness occurs and eventually results in burst [1].

According to revised emergency core-cooling-system (ECCS) acceptance criteria, the safety analysis code system should take into account the fuel behavior models [2]. During the LOCA, since the clad tube shows multi-dimensional deformation such as ballooning and burst, various researches have been conducted to develop the clad deformation model reflecting such the multi-dimensional behaviors [3-4]. For accurate verification of the developed model, multi-dimensional deformation data of the clad should be required.

To measure the multi-dimensional deformation effectively, a digital image correlation (DIC) method can be applied. As one of the non-contact measurement method, the DIC is based on an optical method that employs pattern matching and image recognition algorithm for accurate two- and three-dimensional measurements of changes in the specimen being examined [5].

Therefore, in this study, 3D DIC method was utilized to investigate multi-dimensional deformation such as ballooning and burst of the clad. To deform the clad at high temperature, an experimental facility named 'FISRBIT' (Facility to Investigate Single Rod Behavior In Transient) was utilized by internally heating the clad tube.

2. Experimental setup

2.1 Digital Image Correlation

The digital image correlation method 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. As an input pattern for DIC measurement, natural characteristics of an unprepared sample surface or artificial color spray applied to a polished surface is used.

2.2 Specimen for DIC measurement

As shown in Fig. 1, fresh clad tube was coated using both white and black paint sprays to make artificial patterns for DIC measurement.

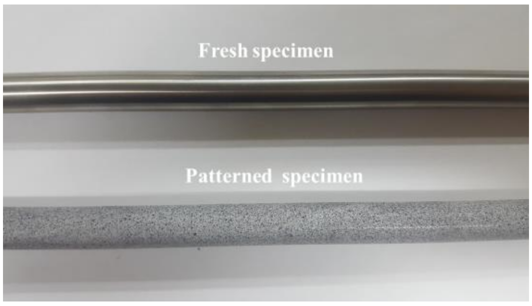


Fig. 1. Fresh and patterned clad tube specimens for DIC measurement.

For high temperature conditions of experimental facility, the spray that are resistant to high temperature above 1000 ℃ was utilized. In order to evaluate high temperature resistance of the coated pattern, preliminary test was performed. Two specimens were heated up to 800 and 1000 ℃ using a furnace, respectively. As a result, it was confirmed that the coated patterns were well maintained after heating as shown in Fig. 2.

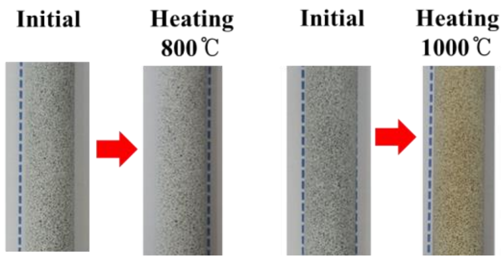


Fig. 2. Results of preliminary test for high temperature resistance of the coated pattern.

2.3 Application of digital image correlation for measurement of clad deformation at high temperature

The DIC system used in our study can be categorized as optical, hardware, software and calibration system. Table 1 shows the details of those DIC system components. 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 [7]. Calibration panel with grid size of 3 by 3 mm was employed for calibration work.

Table I : DIC system components

System	Component	Specifications
Optical	Camera	- Sensor (CMOS) - Resolution (2 MPx) - Frame speed (165 ~ 2,000 frame/s) - Field of view (20 mm ~ 1 m)
	Lens	- For low distortion - Focal length (25 mm)
	IR cut-off filter	- For high temperature
Hardware	Controller	-
	AD/DA module	- 16 bit USB - Output (2 EA) - Input (16 EA)
	Lighting	- LED Type (36W)
Software	Software	- MercuryRTv2.6 (Sorbriety s.r.o)
Calibration	Calibration panel	- Grid size (3 x 3 mm)

To simulate the clad deformation at high temperature, the DIC system was installed in an experimental set up called as 'Facility to Investigate Single Rod Behavior in Transient (FISRBIT)' as shown in Fig.3 [6]. For the 3D measurement, two cameras were used. As an experimental procedure, calibration work was performed by taking a series of exposures of a calibration grid with two cameras simultaneously for the first time. Then, the clad tube was initially heated up to 600K, and pressurized up to 7 MPa with a non-oxidizing atmosphere using the helium gas. Finally, ramp power was given to the heater to increase temperature of the clad until burst occurred. During the experiment, images of the clad were recorded, and full-field strain distribution was calculated by the DIC software system.

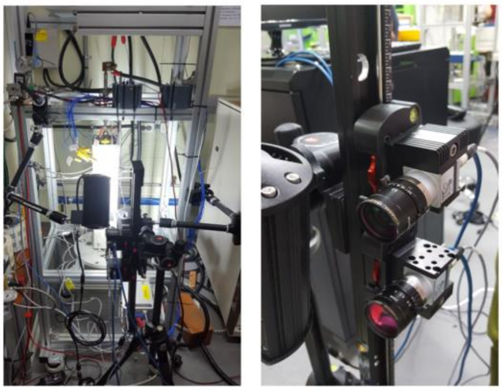
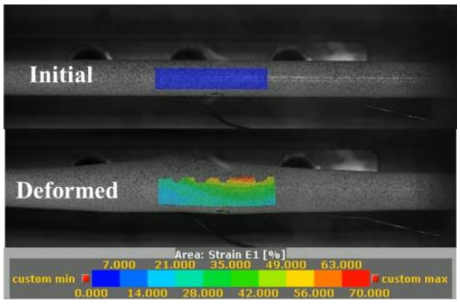


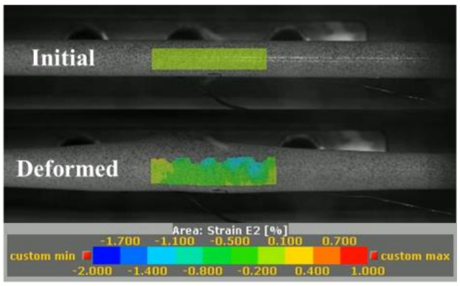
Fig. 3. Photograph of 'FISRBIT' facility equipped with components for DIC measurement.

3. Results and Discussion

Fig. 4 shows the full-field strain distribution of E1 and E2 of the clad tube at initial and ultimately deformed state. E1 and E2 represent maximum and minimum principal strains, respectively. It was confirmed that the continuous strain values could be measured within initial set region showing the ballooning at the center of the clad.



(a)



(b)

Fig. 4. DIC results of (a) maximum and (b) minimum principal strain for the clad tube before and after deformation

Based on the results of Fig.4, Fig.5 shows average and maximum principal strains of E1 and E2 within the set region. The average and maximum values of E1 were measured as 30 and 60 %, respectively while ones of the E2 were measured as almost both 0 %. It indicates that the clad tube was mainly deformed in the circumferential direction but showing non-uniform behavior.

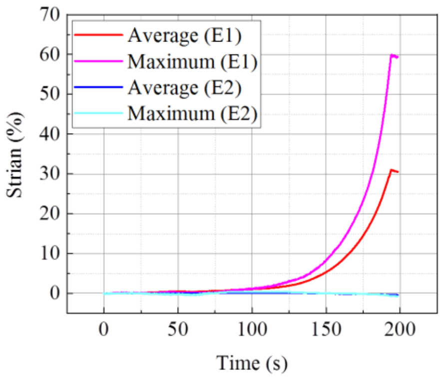


Fig. 5. Average and maximum values of E1 and E2 on the set region by the DIC

4. Conclusions

To investigate the multi-dimensional deformation of the clad tube at high temperature, single rod test was performed using FISRBIT facility with the DIC method. To evaluate high temperature resistance of the coated pattern, preliminary test was performed. As a result, the pattern could be maintained under the condition of 1000 ℃ or more. During the experiment, full-field strain distribution and principal strain components of the clad tube were analyzed using the DIC.

For the future work, after the additional calibration work of DIC, experiments under various accident conditions will be conducted to produce verification data for the clad deformation model. Also, finite element model will be developed for comparative evaluation with the DIC results.

ACKNOWLEDGEMENT

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