Development of Non-contact Deformation Measurement Method for Ballooning of Cladding in LOCA Condition

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1. Introduction

In the Loss of Coolant Accident (LOCA), the cladding is exposed to high-temperature and high-internal pressure environment. It can lead to the cladding ballooning and eventually result in burst. Since ballooned cladding can impede the core cooling capacity by blocking the flow, it is necessary that the ballooning of cladding should be defined quantitatively over time. Therefore, various studies were conducted to predict the behavior of cladding, and a linear variable differential transformer (LVDT), laser extensometer, and digital image correlation (DIC) were used to measure the deformation [1-3].

As a new experimental method, the specimen is heated using an infrared (IR) lamp system and a non-contact measurement method was adopted to avoid external influences on the specimen. However, due to the intense light of IR lamp, there is a limit to the application of laser extensometer and DIC. Thus in this study, a new non-contact measurement method is proposed. The new measurement method is accomplished by detecting the edge of the specimen through image analysis using MATLAB program. Through a window on the side of the lamp, a series of image for the cladding were taken from a DSLR camera.

2. Experimental setup

2.1 Experimental equipment and procedure

As shown in Fig. 1, a quartz tube is located inside the IR lamp to make inert environment using an argon gas. Then, the cladding tube specimen is concentrically located inside the quartz. To allow axial elongation of the cladding specimen, only upper part of the specimen was fixed while lower part was not constrained. In addition, the specimen are coated with black spray paint as shown in Fig. 2. The coated paint can reduce light reflections on the surface of the specimen and help to contrast the light from the IR lamp with the specimen, resulting in a more contrasting image.

To simulate the LOCA conditions, the specimen was heated up to 800°C at heating rate of 5°C/s. Next, a series of image for the specimen were captured from the DSLR camera located outside the IR lamp. Then, the specimen was internally pressurized up to 60 bar using an argon gas. . The heating at the 800°C was maintained until burst of cladding occurs.

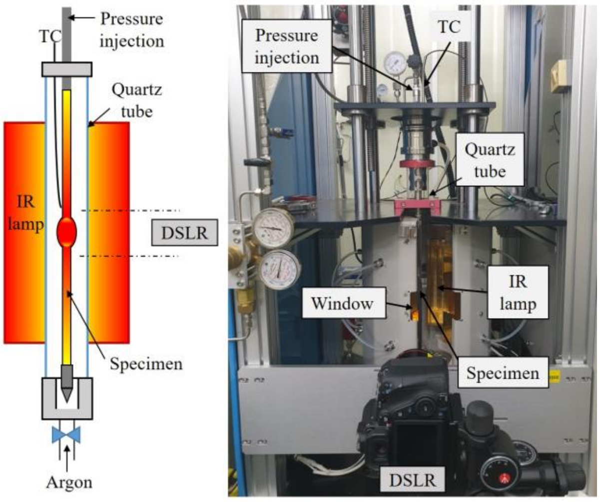

Fig. 1. Schematics and image of the experimental set up
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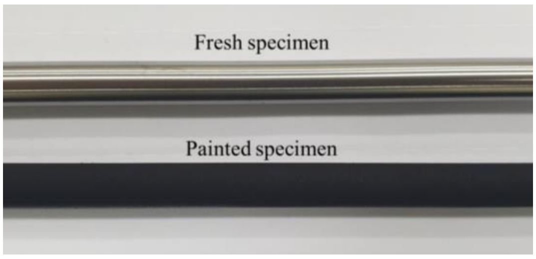

Fig. 2. Fresh and painted cladding specimen.

2.2 Image acquisition

Various methods have been attempted to photograph specimen deformations. Resolution, sharpness, and noise were selected as the main factors for obtaining high quality images, and the following settings were selected. The resolution was set to 6000x4000 at 3-frame per second (FPS) through continuous image shooting, and the CANON EOS 80D model was used. Sharpness is affected by how well the focus is achieved. High temperature endoscope was initially attempted to capture the image, however it was found to be limited in focusing. Alternatively, a CANON 100mm f/2.8L Macro IS USM lens was used, and images were taken from the outside through the window on the side of the

IR lamp, resulting in a sharper image. Lastly, to minimize noise, ISO sensitivity was set to 100 and the aperture was set to f2.8. The more the aperture is opened, the more out of focus is achieved. Out of focus gives a more concentrated effect on the edges. Therefore, the contrast between the edge and the background may be improved by adjusting the aperture.

2.3 Image analysis

As shown in Fig. 3, the deformation measurement through image analysis is performed by measuring the pixels with the detected edge of the specimen, and MATLAB R2019a (The MathWorks lnc., Natick, MA) is used to analyze the image boundary. Image processing includes the sharpness enhancement using unsharp masking (USM), the contrast adjustment, and the edge detection using Sobel operator. USM, with name imsharpen in MATLAB, can adjust the size of the region around the edge pixel and the intensity of the effect by adjusting the radius and amount value [4]. Contrast adjustment, with name imadjust in MATLAB, is used to clearly contrast the boundary. Lastly the Soble operator is used among several operators for extracting boundaries [5]. As show in Fig. 4, the USM applied image, the contrasted color image, and the black and white image before the boundary extraction are sequentially listed.

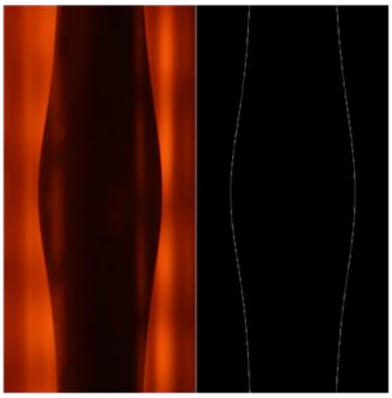

Fig. 3. (a) Captured image and (b) calculated edge image of the cladding specimen.

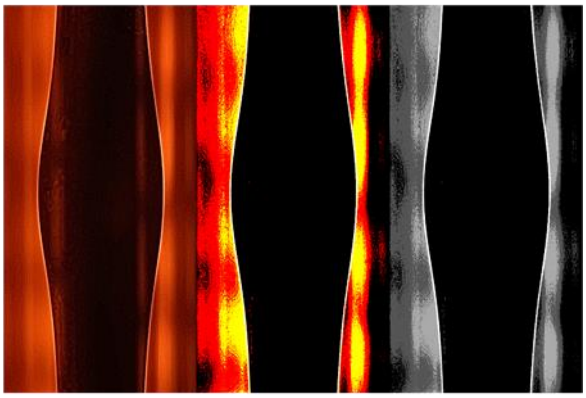

Fig. 4. (a) USM applied image, (b) contrasted color image, and (c) black and white converted image.

3. Results and Discussion

Color digital images are made of pixels, which are composed of combinations of primary colors such as red green, and blue (RGB). For the RGB colors, each image store discrete pixels with conventional brightness intensities between 0 and 255. The value of intensity can be greatly changed at the boundary of a line B between the specimen and IR ramp as shown in Fig. 5. Figure 6 shows the RGB values of pixels along a line A, which is assembly of pixels from (345, 1985) to (375, 1985). The gradient of RGB values were observed between pixel of (354, 1985) and (364, 1985), which indicates that the boundary of the cladding specimen can be defined between the pixels. Therefore, in our study, pixel of (358, 1985) was regarded as boundary pixel between the cladding specimen and IR ramp while estimated error was about 1% by each small pixel size of 0.012 mm.

Figure 7 shows hoop strain results calculated from developed image analysis technique and commercial software called as IMAGE J. The hoop strain was calculated as following Eq. (1)

$$\varepsilon_\theta = \frac{D - D_0}{D_0} \tag{1}$$

where ε_θ is hoop strain, D is the diameter of cladding, D_0 is initial diameter of cladding, respectively. As a comparison results, two results showed good agreement within the 1% of error. Also, the new image analysis technique can calculate overall diameter along an axial direction over time by continuous image processing. After the experiment, the deformed cladding were measured using vernier calipers. The difference between the measured strain and analyzed strain seems to be due to the contraction of the cooled state.

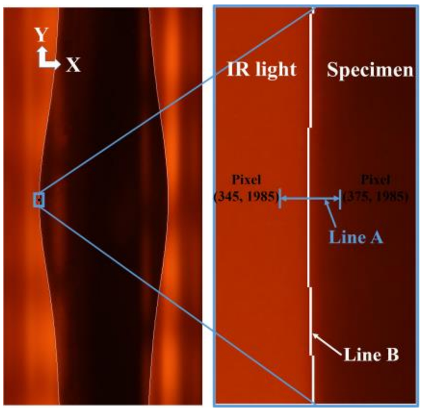

Fig. 5. Zoom-in image near the boundary.

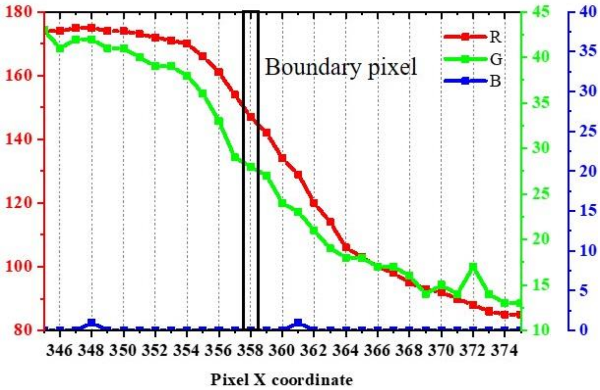

Fig. 6. The RGB values of pixels from (345,1985) to (375,1985) on line A

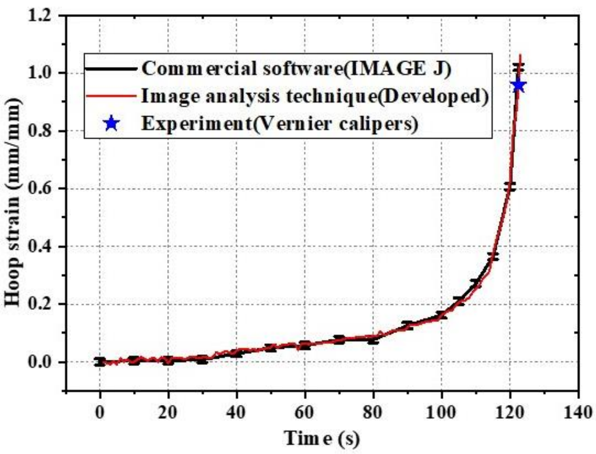

Fig. 7. Hoop strain results calculated from developed image analysis technique and commercial software IMAGE J.

4. Conclusions

The development of non-contact deformation measurement method that can be applied to the hypothetical LOCA experiment using an IR lamp was attempted through image analysis using MATLAB program. Deformation measurements were conducted through detecting the outer boundaries of the cladding. To detect the boundary, the intense light of IR lamps was contrasted with the cladding. In addition, several experimental methods and techniques have been applied to accurately measure the boundaries. As a result, it was confirmed that the boundary could be selected within the error range of 1%, and strain measurement over time could be performed.

For the future work, experiments will be conducted to produce various data to quantify the ballooning of the cladding. In addition, a finite element model will be developed for comparison with experimental results.

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