FEASIBILITY STUDIES FOR SPECKLE INTERFEROMETRY USED TO MEASURE DEFORMATION IN NUCLEAR FUEL CLADDING

RADIATION MEASUREMENTS AND GENERAL INSTRUMENTATION

KEYWORDS: *speckle interferometry, nuclear fuel cladding*

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Speckle interferometry is an optical technique able to measure and to image displacement of surface. An original setup is used to investigate the measurement of a deformed cylinder as a feasibility study. This shape allows us to determine the capability of this technique to measure nuclear fuel rod cladding. Indeed, in a nuclear reactor, the fuel rod undergoes different physical phenomena that induce dimensional changes in the cladding. The aim of this study is to quantify the amplitude of local ridges appearing on the outer cladding surface due to the "hourglass shape" assumed by the pellets under irradiation.

Because of the environmental constraints imposed by testing, an optical measuring device will be used to experimentally characterize mechanical strain induced by the interaction between the cladding and the fuel pellets. The aim of this paper is to examine the experimental feasibility of speckle interferometry using model samples.

An experimental setup based on the speckle interferometry technique was therefore implemented to measure local deformation in nuclear fuel cladding. Different experiments on model samples have shown that this technique is well adapted to the measuring range, shape, and condition of the surface as well as the working distance.

I. INTRODUCTION

The main component of nuclear fuel used in French pressurized water reactors (PWRs) is uranium dioxide in its ceramic state. This fuel is placed into a zirconium alloy tube that acts as the cladding.

Once in the nuclear reactor, the fuel rod undergoes different physical, mechanical, and chemical phenomena due to the extreme nuclear environment, which induces dimensional changes in the cladding. Among others, the local "ridges" formed on the outer cladding surface by the "hourglass shape" of the irradiated pellets are worthy of interest in terms of studying fuel phenomena and modeling. The size of these ridges is several tens of micrometers.[1]

This study focuses on the development of an optical method that can be used to dynamically determine the occurrence of these ridges on the outer surface of the cladding. These ridges are generated by a CEA Cadarache experimental device aimed at producing a temperature gradient in the fuel samples similar to that in fuel rods under irradiation.

To measure the induced deformation, device constraints have to be taken into account. Thus, measurements have to be performed far away from the cladding, e.g., several tens of centimeters, with a field of view close to 1 cm^2. Moreover, measurements have to be performed in real time with a high cladding temperature of almost 350°C. All these constraints can be met by using optical methods to take the measurement. Different optical techniques can be used, e.g., triangulation,[2] confocal microscopy,[3,4] and speckle interferometry.[5,6]

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However, the methods must comply with the working distance as well as provide real-time measurements, micrometer sensitivity, and a technique that can be used in industrial applications. Speckle interferometry has the capacity to meet all these requirements, which is why this paper focuses on the potential of this technique.

Speckle interferometry is well known in the optical field; numerous applications highlight the possibilities of this technique, mainly in astronomy and vibration measurement. The purpose of this paper is to determine if this technique is well adapted to nuclear research, focusing on the measurement of cladding deformation.

This paper first explains speckle interferometry, with a short section devoted to theoretical aspects. The paper then focuses on the configuration used and the experimental setup chosen for the measurement. Finally, the paper discusses the measurements taken for our application and the results.

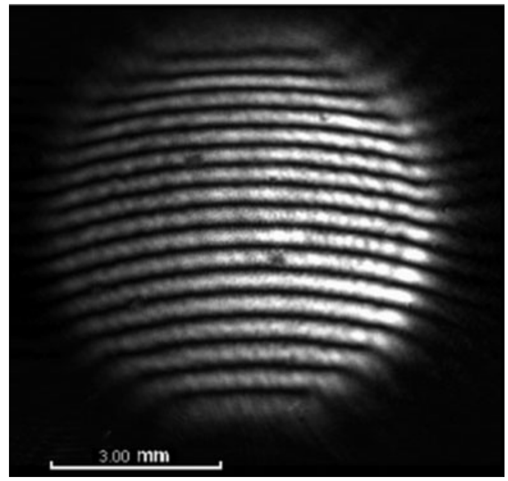

Fig. 2. Example of an interference pattern obtained with Michelson interferometer.

II. PRINCIPLE

II.A. Optical Interferometry

The concept of interference refers to the interaction of two mutually coherent waves. Interferometry is a technique of analyzing the phase property of a wave by studying the interference pattern created by its superposition on a reference wave. It is a widely used technique in the field of optical metrology[7] to measure static or dynamic displacements. Depending on the configuration, one-, two-, or three-dimensional measurements can be performed with a resolution below the nanometer.

In a typical configuration as shown in Fig. 1 (Michelson interferometer), a single incoming beam will be separated into two beams. Each beam will travel according to a different path, introducing a phase difference between them. A system is used to image the surface under examination. In this configuration, an interference pattern characteristic of the displacement between the reference surface and the examined surface can be observed (Fig. 2).

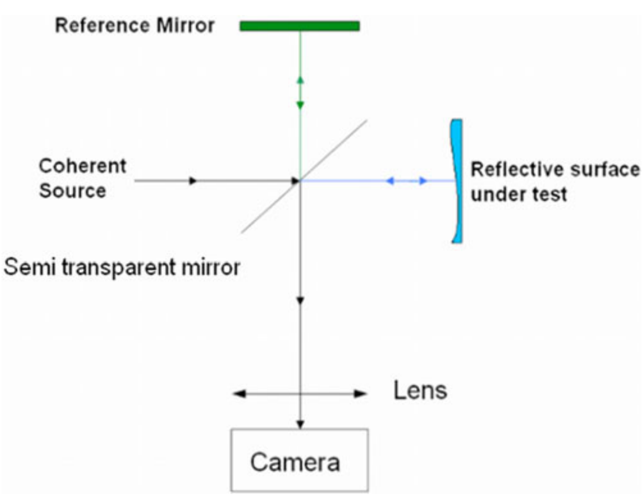

Fig. 1. Experimental configuration of an interferometer to measure the topography of a reflective surface.

This method cannot be applied directly in our application because the cladding's rough surface will create a speckle pattern.

II.B. Speckle Pattern

When a rough surface is illuminated by light, the light is scattered. In the case of coherent light, the scattered waves interfere and form a random interference pattern consisting of dark and bright spots or speckles.[8] Figure 3 shows an example of a speckle pattern. The characteristics of a granular pattern are not only directly

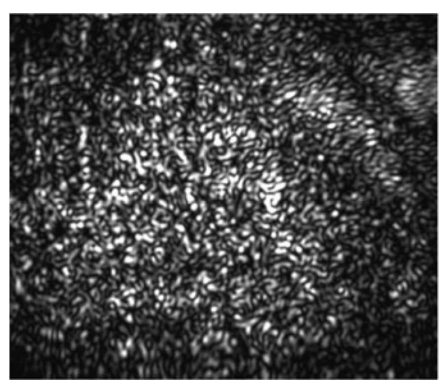

Fig. 3. Speckle pattern observed when metal fuel cladding is illuminated with a He-Ne laser.

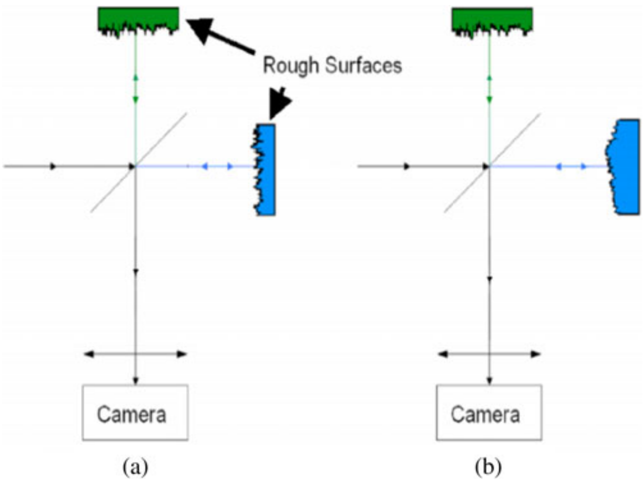

Fig. 4. Speckle interferometry (a) before deformation and (b) after deformation.

related to the setup but also to the wavelength of the source and the aperture and focal length of the imaging system.

II.C. Speckle Interferometry

Speckle interferometry is the combination of the two above-mentioned optical phenomena. In practice, the Michelson interferometer is modified: the two mirrors can be replaced by two rough surfaces. The device is shown in Fig. 4.

On the left side of Fig. 4a, a single beam is separated into two beams. Each beam travels a different path and is scattered by a rough surface. The two surfaces will form two separate speckle patterns that interfere in the camera plane. Each point on the camera plane corresponds to a point on the surface under examination and a point on the reference surface, with a certain mutual phase difference.

It is then considered that the surface under examination is deformed or displaced (Fig. 4b). The phase difference between the corresponding points will modify the speckle interference pattern accordingly.

By double exposure before and after deformation and if the displacement is less than a few orders of magnitude of the wavelength λ, it is possible to obtain a fringe pattern characteristic of the displacements. In the configuration described, each fringe corresponds to an out-of-plane deformation of $\lambda/2$ (Ref. 5).

The difference in the two pictures makes it possible to obtain fringes due to the difference in phases between the two states. If the displacement represents a few orders of magnitude of the laser wavelength, it is possible to analyze the interference pattern. An example is shown in Fig. 5a, corresponding to the speckle pattern before deformation, whereas Fig. 5b shows the speckle pattern after deformation. Figure 5c shows the result of the subtraction of the two previous figures. A flat deformable surface was used as the sample in this example. If no deformation occurred between the two pictures, the previous subtraction will give a perfect dark picture. But, it is important to avoid vibration from the interferometer in order to measure only local displacement.

III. EXPERIMENTS

III.A. Experimental Configuration

The selected speckle interferometry configuration was based on a Michelson interferometer associated with an imaging system (Fig. 6). The source was a He-Ne laser with a wavelength of 633 nm. The beam was enlarged and collimated with a telescope. A cube beam

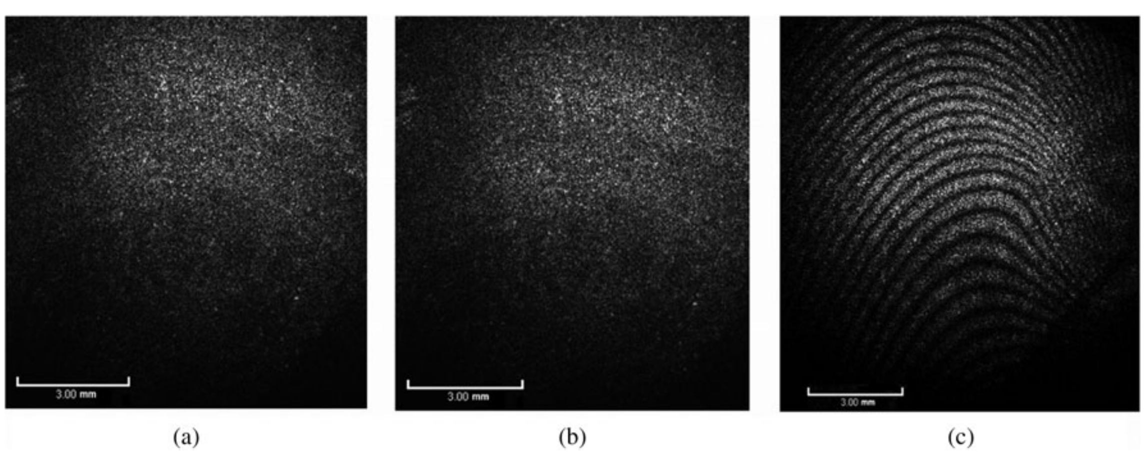

Fig. 5. (a) Speckle pattern before deformation, (b) speckle pattern after deformation, (c) fringes obtained by subtraction of the two previous pictures (b)–(a).

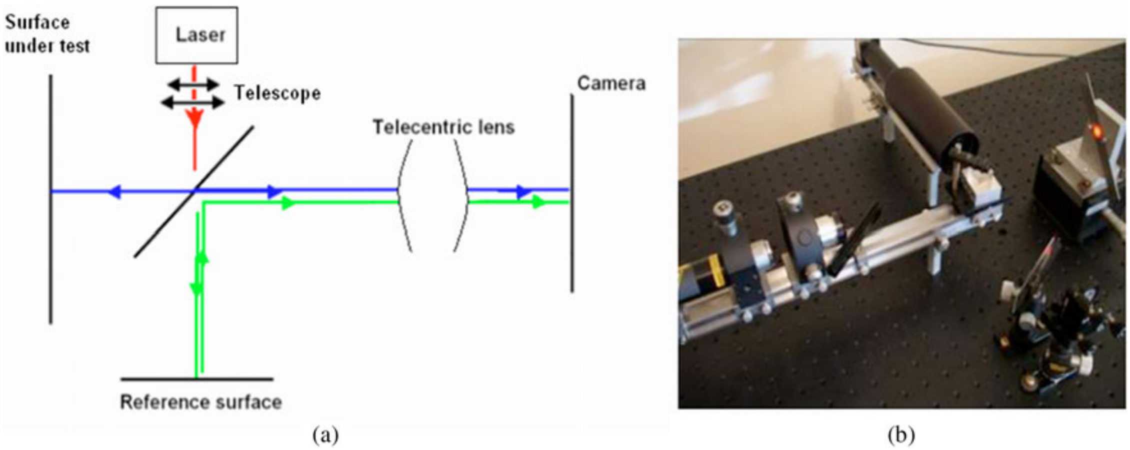

Fig. 6. (a) Out-of-plane configuration with flat-surface sample and (b) real setup.

splitter separated the single beam into two parts. Each beam illuminated two rough surfaces: a reference surface and the surface under examination. The imaging system was composed of a telecentric lens with a long working distance and a charge-coupled device camera.

The system is designed to generate a flat or convex picture of a 1-cm^2 surface located at a distance of 20 cm with a 10-μm resolution. These geometric parameters correspond to the installation constraints.

III.B. Measurement Example

To analyze and understand the results produced by this configuration, many experiments were conducted on numerous samples, ranging from simple ones to much more representative ones. A deformable sample was tested to illustrate the potential of this technique. The sample was a thin piece of metal set on the front of a mount. A screw on the back of this metal was used to apply stress to the sample (Figs. 7a, 7b, and 7c). The experiment consisted of observing deformation with the setup described above.

Figure 7d shows some of the results obtained. Circular fringes appeared for displacement of a few microns, corresponding to the contact between the screw and the sample.

IV. APPLICATION

IV.A. Deformable Cylinder

The previous experiment shows the potential of interferometry for measuring the deformation of a surface. To evaluate the adaptability of this technique to our application, a model sample representative of the expected

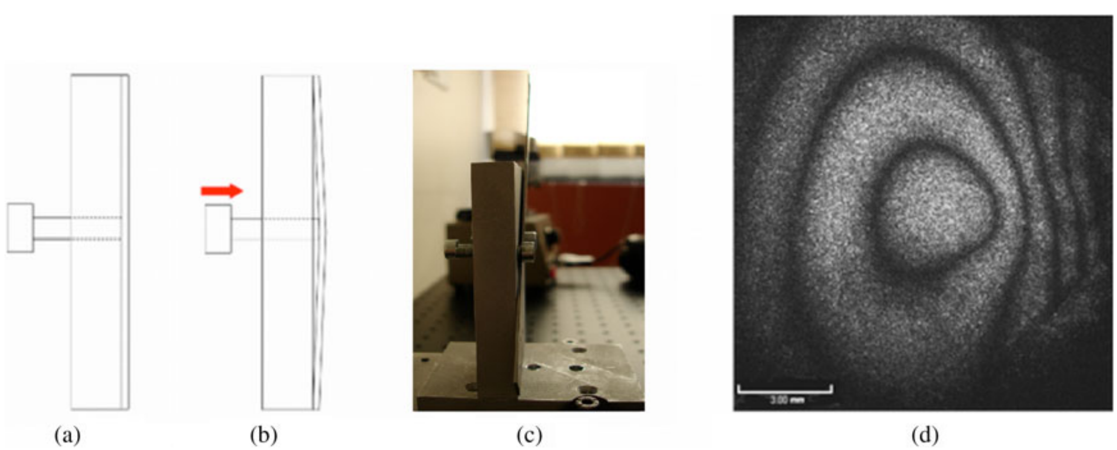

Fig. 7. (a) Flat surface in the initial state, (b) constraint is applied from the backside of the flat surface, (c) picture of the real sample, and (d) example of fringes obtained with this sample.

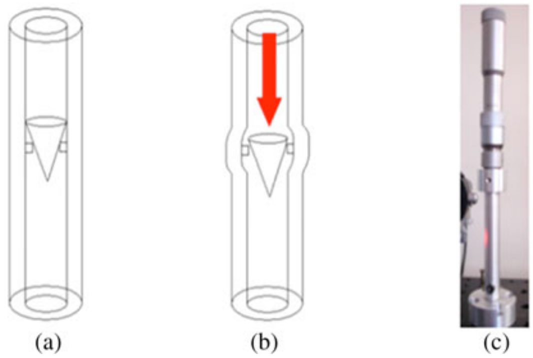

Fig. 8. (a) Cylinder in the initial state, (b) constraints are applied from the inside of the pipe by pressure on a cone, and (c) picture of the real sample.

fuel cladding deformations was developed. This sample was a deformable cylinder with the same roughness as the fuel cladding.

Figure 8 shows the way in which the sample was used: in a pipe, a cone is supported on a shoulder. The outer side of the pipe was deformed when the cone moved downward. At this point, it was assumed that deformation should be circumferential. This displacement was managed by a micrometer screw.

The sample was placed on a vertical displacement mount and on a rotation mount. Measurements were carried out either at constant stress in different parts of the cylinder or at variable stress on a fixed area of the cylinder.

The vertical displacement of the sample was used to identify the area where maximum stress was applied, whereas the rotation made it possible to check whether deformation was circumferential or local.

IV.B. Results

Once the central area of deformation had been identified, acquisitions with constant stress were performed around the tube. This experiment consisted of rotating the sample from 0 to 180 deg. Acquisitions were performed every 10 deg in order to produce fringes all around the tube. Some of the pictures are shown in Fig. 9. The comparison between all these pictures shows that the stress applied by the cone on the inside of the tube was not homogeneous. In the case of circumferential displacement, the fringe will be exactly the same in all the pictures

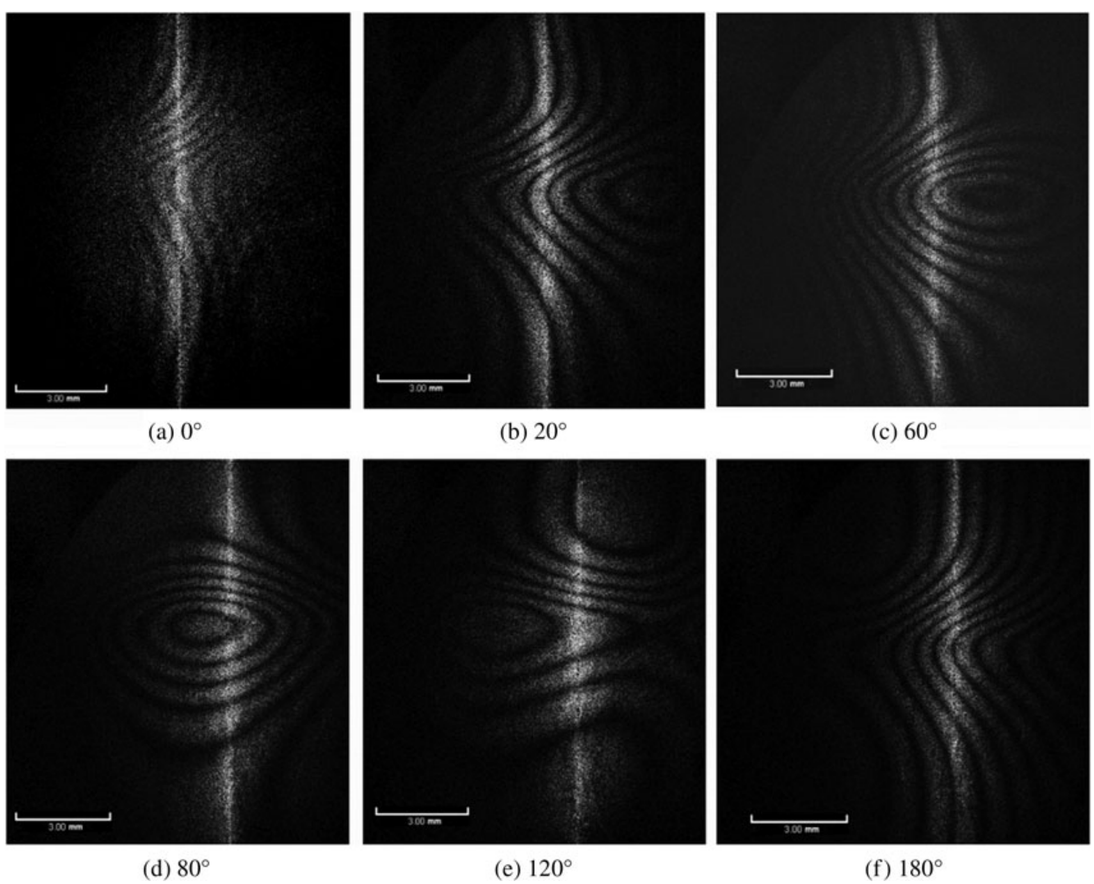

Fig. 9. Acquisitions with constant stress from 0 to 180 deg.

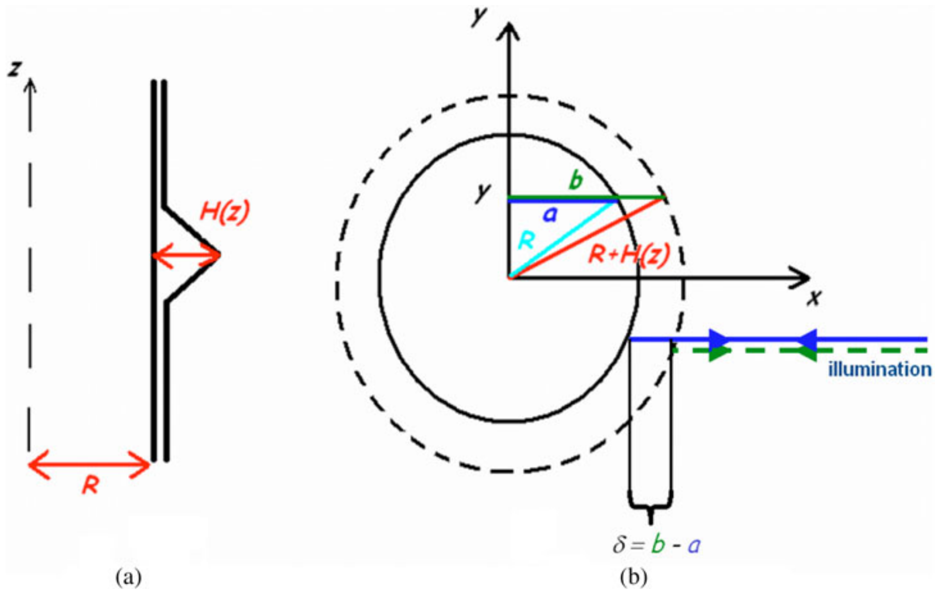

Fig. 10. (a) Fringe calculations in the case of circumferential deformation in the (x, z) plane and (b) geometrical parameters for fringe calculation in the (x, y) plane.

(or on the right in Fig. 9b) where circular fringes appear. In Fig. 9d, the circular fringes are located almost in the center of the picture, corresponding to 80 deg, before disappearing on the left of Fig. 9e at 120 deg.

A way to understand what happened with the sample is to calculate the theoretical phase difference for any given deformation. The calculation can be done using several geometrical parameters, as shown in Fig. 10. It consists of determining the path difference between the two states before and after deformation. The magnitude of displacement is named H here and corresponds to the value of the displacement of the same point between two states. In the case of circumferential displacement, H is only a function of the height z. However, in the case of a bulge for example, H is a function of both z and y. The illumination beam is parallel to the direction x.

The phase difference $\Delta\varphi$ is determined by the difference in paths, named δ, introduced by the deformation. The link between these two parameters is given by

$$\Delta\varphi = \frac{4\pi\delta}{\lambda_0} \quad (1)$$

$$\text{with } \delta = b - a \quad (2)$$

and λ_0 representing the wavelength of the laser.

According to the geometry, Eqs. (3) and (4) are

$$a = \sqrt{R^2 - y^2} \quad (3)$$

and

$$b = \sqrt{(R + H(y,z))^2 - y^2} \ . \quad (4)$$

Equations (3) and (4) can now be used to solve Eq. (1) by introducing the value of the path difference given by Eq. (2) in Eq. (1).

$$\Delta\varphi = \frac{4\pi}{\lambda_0} \times \sqrt{(R + H(y,z))^2 - y^2} - \sqrt{R^2 - y^2} \ . \quad (5)$$

To model different deformations, only the value of the function $H(y,z)$ has to be changed. For instance, Fig. 11 introduces three different cases that can be analyzed for arbitrary deformations:

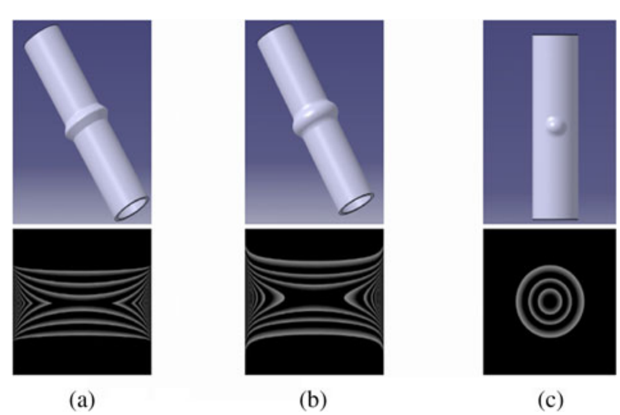

Fig. 11. Views of different calculated deformation and fringes: (a) triangular, (b) Gaussian, and (c) bulge.

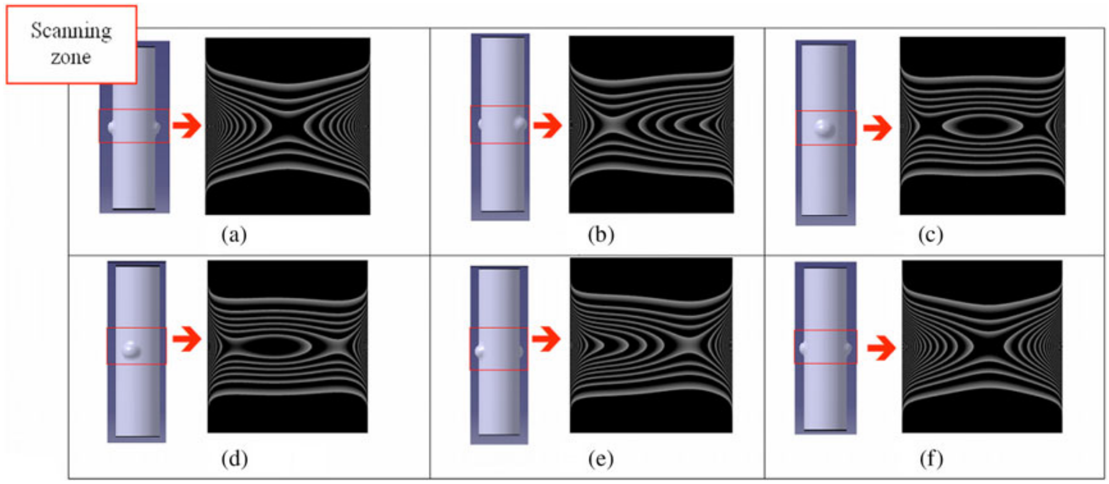

Fig. 12. Acquisitions with constant stress from 0 to 180 deg with theoretical area.

1. triangular
2. Gaussian
3. bulge (result of two orthogonal Gaussians).

Fringes were calculated for each example, but the results did not correspond to the experimental results. Other models, therefore, have to be found to obtain better representativity.

One of the best solutions consists of two wide bulges separated by the cylinder diameter. To compare with experimental data, fringes were calculated every 10 deg around the modeling tube. Figure 12 shows the results around the cylinder for different rotation angles (0, 45, 90, 110, 135, and 180 deg). In the case of calculation, the fringes were calculated for the whole diameter of the cylinder.

The aim of this study is to understand the shape of the experimental fringes. For the purpose of comparison, experimental data are compared with modeling. Simulation is done with a normalized cylinder (height equal to 1 arbitrary unit). Figure 13 shows three pictures for different rotation angles. When a cylinder is illuminated, the light is scattered, and only the normal incident beam can be imaged. This phenomenon makes it possible to image only a small part of the surface.

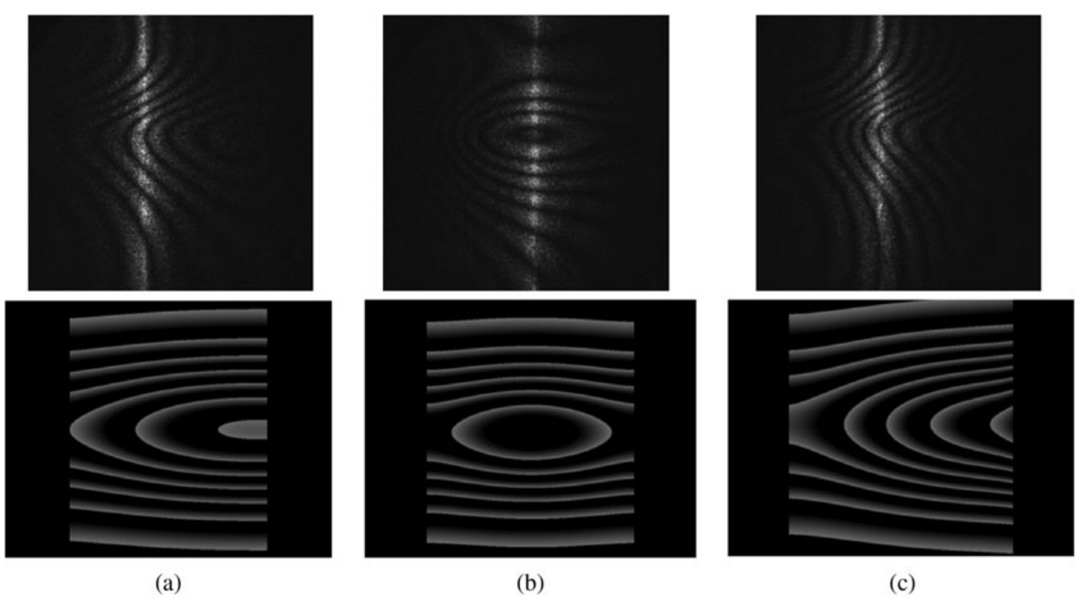

Fig. 13. Comparison between experimental results and calculation for different rotation angles: (a) 20 deg, (b) 90 deg, and (c) 180 deg.

An elliptical area evidences the presence of a bump with an out-of-plane size of ~2 μm. The shape of the fringes is similar to the first image, which indicates the existence of a bump similar to that on the other side of the tube. The cone mainly pushes on two parts of the diametrically opposed tube. But at this time of the study, exact displacement (magnitude, direction, and shape) cannot be extracted either from measurement or calculation.

V. CONCLUSIONS

An experimental setup based on the speckle interferometry technique was implemented to measure local deformation in nuclear fuel cladding. Different experiments performed on model samples have shown that this technique is well adapted to measuring the range, shape, and condition of the surface, as well as the working distance.

This research aims at studying the sensitivity of measurements to environmental conditions in the hot cells (vibration, temperature, gases flow, etc.). For an absolute calibration of the setup, the coupling with other optical techniques such as triangulation is under study. Device improvements are also being considered in order to be able to use phase shifting analysis.[9]

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