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On-line deformation measurements of nuclear fuel rod cladding using speckle interferometry

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ABSTRACT

This paper reports an experimental setup developed to detect and quantify the deformations of the cladding surface of nuclear fuel pellets submitted to analytical transient conditions. It consists of an optical instrument based on the speckle interferometry technique, able to provide non-destructive measurements on scattering surfaces such as nuclear fuel rod claddings. Here are presented first results performed on-line and *in situ*, with micrometric resolution. Then, limitations of the system as well as further developments are discussed.

1. Introduction

In nuclear power reactors, different physical phenomena occur during normal or incidental operations, creating strains on the outer part of the fuel cladding (primary or secondary local ridges). In this work, in order to study the kinetics of this effect, the aim is to perform on-line deformation measurements of the outer cladding surface. Representative temperature gradients in fuel samples are produced by an original setup developed by the CEA Cadarache (*i.e.* DURANCE equipment). This device consists of an induction furnace setting central fuel temperature and a cooling system monitoring cladding temperature. Under conditions representative of a power transient, outer cladding diameter changes have been observed in the range of a few tens of micrometres. Optical techniques offer a good potential for *in situ* inspection in nuclear environments (Tozer, 1983). In a previous work (Vauselle et al., 2012), speckle interferometry has been identified as well suited to perform local ridges measurements with micron resolution. Speckle interferometry is an optical technique able to image and to measure displacements of rough surfaces. In this paper is presented the setup which has been implemented in the DURANCE experimental device and results of *in situ* and on-line measurements in conditions representative of analytical transient conditions.

2. Material and methods

2.1. DURANCE equipment

This device has been developed and patented (Pontillon et al.,) by the CEA Cadarache to simulate the thermal gradient seen by the fuel pellets in Pressurized Water Reactors (PWR). Thanks to this induction furnace (Fig. 1), deformation on cladding can be generated in the lab; and an improvement of the system will consist in performing *in situ* measurement of the cladding deformation. The environment of this measurement is affected by many constraints. First, the measurements are ultimately expected to be performed into high activity cells since the sample will be irradiated fuel. This technique must also face the presence of electromagnetic fields (used for heating) and vibrations due to cooling system of the DURANCE device. These measurements are also expected to be realized through a quartz tube (2.5 mm-thick) containing an argon flow and through a transparent thermal insulator (3.5 mm-thick) surrounding the fuel rod. Other elements as the working distance (at least 11 cm) and the roughness of the surface have to be considered. According to all these specifications, it has been decided to setup an optical device based on speckle interferometry (Vauselle et al., 2012), whose principle is described in the next section.

2.2. Speckle interferometry

First, interferometry is a measurement technology based on interferences between two beams (at least). For example, on Fig. 2,

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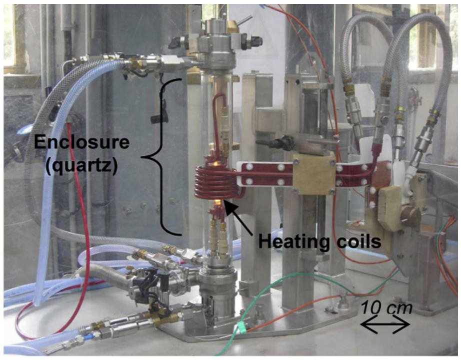

Fig. 1. Photograph of the DURANCE device.

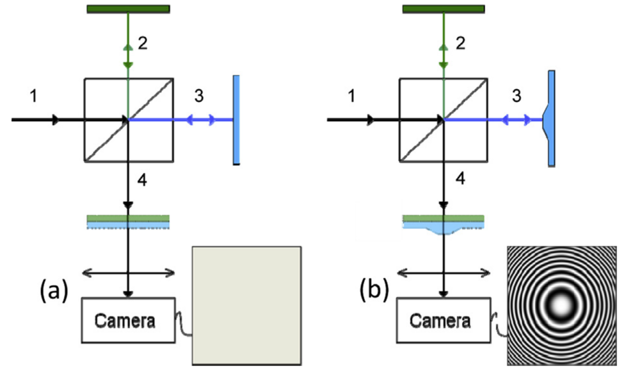

Fig. 2. Interferometer method scheme.

the original optical beam (1) is separated in two other beams (2 and 3). Then after reflection on two surfaces (in green and blue too), these two beams are superimposed to form again a single beam towards the camera (4).

If the two surfaces are similar, no structure appears on the camera (Fig. 2a). However, by moving or deforming one or the other surface, a fringe pattern representative of the difference between the two shapes appears (Fig. 2b). Unfortunately, this classical technique cannot be applied to this work because the surface of the fuel cladding is seen as a scattering surface, *i.e.* a light beam illuminating this surface is randomly reflected in space. Then, all these individual reflections interfere together, leading to the formation of a so-called "speckle" (Françon, 1978). Speckle interferometry has to be used if at least one of the two beams in Fig. 2 is a speckle field (Jacquot, 2004).

Since the information coming from a speckle cannot be interpreted directly, two recordings are needed; one for the initial shape of the surface and another one after deformation of this surface (Jacquot, 2004). By subtracting these two pictures, a fringe pattern representative of the difference between the two recordings appears (Fig. 3), describing the surface shape evolution that occurred between the recordings (Vest, 1979; Leendertz, 1970).

To sum up, speckle interferometry consists in recording interferences from two fields (at least one is a speckle) and in subtracting the interference patterns observed before (Fig. 3a) and after (Fig. 3b) deformation or displacement of the tested surface.

2.3. Experimental setup

Fig. 4 details the components and the overall dimensions of the optical setup placed on DURANCE. The beam coming from the laser source (He–Ne) is directed towards both a reference and the device under test (DUT) thanks to the beam splitter (BS). After reflection on this two surfaces, the beams interfere together in the direction of a CCD camera which is used to record the interference patterns. Other optical elements are inserted in order to adjust the size or the intensity of the light beams (O, P, L, $\lambda/4$).

Finally, a piezo translation is added to the reference holder in order to perform phase-shifting which is a classical technique employed in interferometry to access the signal phase (Burke, 2000; Picart, 2007). Indeed, a fringe pattern contains intensity information but no phase information, which is essential to access the sign of the displacement or of the deformation to be measured. The phase-shifting technique employed here is detailed in the next section.

For these first experiments, a model has been designed, which is able to produce repeatable and automated deformations of few micrometres on a cladding rod (Fig. 5). This device has been placed on DURANCE as indicated on Fig. 4 (DUT).

3. Calculation

As mentioned above, the absolute phase is determined thanks to the phase-shifting technique (Burke, 2000). Here a temporal phase shifting is applied by moving the reference longitudinally. Indeed, the intensity signal detected at a point of x and y coordinates in the interference pattern can be basically written as:

$$I(x,y) = A + B\cos(\Delta\varphi(x,y)) \quad (1)$$

where I is in watts, A and B are constants values depending on the intensities of the two interfering beams and $\Delta\varphi$ is the phase of the signal at the point of coordinates x and y.

Because A, B and $\Delta\varphi$ are unknown values in Equation (1), three recordings (at least) are needed to retrieve $\Delta\varphi$, which is essential to determine the sign of the deformation. In this way, the reference surface is moved in order to provide a known additional phase-shift between the two interfering beams. For example for three recordings, the phase-shift between the interference patterns must be $2\pi/3$, leading to a displacement of $\lambda/3$ (λ is the laser source wavelength). In this case, the system can be written as:

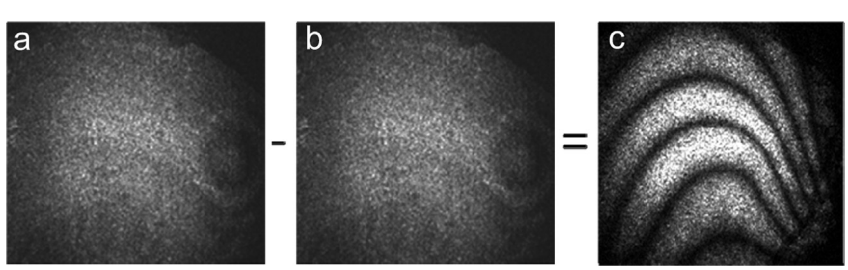

Fig. 3. Examples of speckle of a metallic plate for (a) initial shape and (b) final shape, (c) subtraction of (a) and (b).