

Report of High Temperature Measurements with a Fabry-Perot Extensometer

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Abstract— Fabry-Perot (FP) sensors like other Fiber Optic (FO) sensors may be of particular interest for in pile experiments in MTR with little room available thanks to their compact size. Light weight also reduces gamma heating hence limiting the thermal effect. Different physical parameters such as temperature, strain, displacement, vibration, pressure, or refractive index may be sensed through the measurement of the optical path length difference in the cavity. We have developed a Fabry-Perot extensometer able to operate at high temperature (up to 400°C), under a high level of radiation (neutron and gamma flux). The measurement based on interferometry is largely insensitive to radiation induced attenuation (RIA) thanks to the wavelength encoding of the useful signal, but for such high fluence as encountered in a reactor core, a special rad-hard fiber is needed. Operating in the wavelength domain around 1µm remains preferable to minimize the impact of irradiation. Moreover, fast neutron radiation is expected to change the structure of the fiber and possibly others materials in the transducer. Then, we revised the basic scheme of Extrinsic Fabry-Perot Interferometer (EFPI) so that the effects of compaction remain limited. Tests under mixed neutron and gamma irradiation permitted to verify the general behavior and particularly the low drift with radiation induced compaction (RIC). Also, two types of tests have been conducted to verify the accuracy at high temperature. The first ones are “measurements” of thermal dilatation of materials: the sensor is fixed on a sample and knowing its thermal expansion, it is possible to predict the measurement expected from the optical sensor when the temperature is increased from low to high temperature. The comparison between the predicted and experimental outputs informs on how the sensor is accurate. The second types are tests on a tensile test bench operating at high temperature. The Fabry-Perot measurements are compared, in the elastic domain, with the expected strain given by the Young modulus of the material, and also on a larger strain domain, with the measurements of a high temperature axial extensometer. Both types of tests are presented and commented.

Index Terms— Extensometer, Fabry Perot sensor, Material testing reactor, Optical fiber sensor, White light interferometry

I. INTRODUCTION

VARIOUS R&D programs are implemented in order to improve the performance and the safety of existing and

future plants as well as to assess and develop new reactor concepts. Among them, irradiation experiments in Material Testing Reactors (MTR) allow to optimize designs for improved technologies and to qualify innovative fuels and materials. In particular, the Jules Horowitz Reactor (JHR) [1], a new Material Testing Reactor under construction in Cadarache (France) is expected to feature highly instrumented experiments. As well, next generations of power reactor could benefit enhanced in-core online monitoring.

Optical Fiber Sensors (OFS) display some interesting features in order to equip irradiation rigs in MTR. In order to make measurement of elongation, we have developed a Fabry-Perot Sensor (FPS) able to work under high temperature and large neutron fluence [2,3]. This development has first been carried out jointly with SCK•CEN in the framework of the Joint Instrumentation Laboratory (JIL), then CEA has continued the development to improve the operation at high temperature.

In this article, we will first present the principle of the sensor; next, we will focus on two sets of different experiments conducted to evaluate the accuracy of the FPS when operating at high temperatures. They are based on the study of the thermal dilatation of the support and on the tests on a tensile testing machine.

II. THE FABRY PEROT SENSOR

Our Fabry-Perot sensor developed for applications in MTR is based on a classical scheme (Fig. 1). In the selected design each face of the cavity is connected to a localized area of the sample separated by the gage length. Any variation of the gage length produces a similar variation of the Fabry-Perot cavity length.

The input beam reflects on both faces of the cavity and the state of interference generated by the two reflected beams depends on the ratio: $\frac{Lc}{\lambda}$, where Lc is the cavity length and λ is the wavelength. White light interferometry takes advantage of the channeled spectrum - obtained thanks to the broad spectrum of the SLED and to the spectrometer with enough resolution - to retrieve the cavity length Lc [3].

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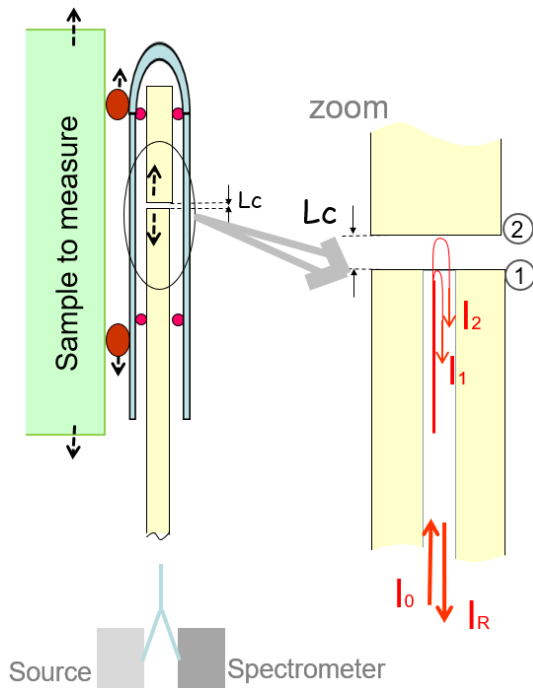


Fig. 1. Principle of the Fabry-Perot sensor: any variation of the gage length produces a similar variation in the Fabry-Perot cavity length, probed through interference of the reflections on both faces of the cavity.

III. ASSESSMENT OF THE ACCURACY AT HIGH TEMPERATURE

The following describes some tests performed to evaluate accuracy at a higher temperature.

A. Study of the thermal dilatation of material

Four similar FPS are used for that set of experiments: two sensors, with reference 180925_3 and 180925_5, are fixed on a 316 L stainless steel plate, and two sensors, with reference 180925_2 and 180925_4, are fixed on a tantalum plate. The dimensions of the plate are 10 mm x 50 mm x 2 mm. The four plates are inserted in tubular oven and the temperature rises to 400 °C, then decreases again to room temperature. This cycle is repeated several times, and each time the length of the cavity L_c is plotted as a function of the temperature given by a thermocouple placed near the plates. The graphs resulting from the different cycles are presented in Fig. 2 for the four tested sensors.

The different graphs show the good repeatability of the measurements and make it possible to determine an average value of the variation of the cavity length L_c when the temperature varies from 20 to 400 °C. This value is named $\Delta L_{c_{exp}}$ in the following and is compared to the expected theoretical value $\Delta L_{c_{th}}$.

With $18.5 \times 10^{-6}/^{\circ}\text{C}$ [4, 5] and $6.6 \times 10^{-6}/^{\circ}\text{C}$ [6] considered for mean coefficients of thermal expansion (between 20 °C and 400 °C) of 316L stainless-steel and tantalum materials respectively, the associated $\Delta L_{c_{th}}$ of a standard FPS are $7.5 \mu\text{m}$ and $-60.3 \mu\text{m}$ respectively. Small variations in the sensors built compared to the standard FPS implies slight variations in $\Delta L_{c_{th}}$. The revised theoretical values are reported in Table 1, as well as the experimental values.

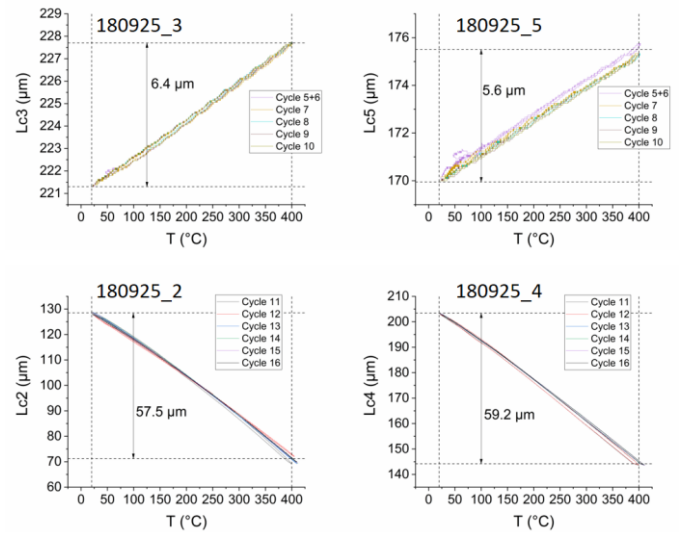


Fig. 2. Graphs of L_c versus the temperature for different cycles, for the four tested sensors.

TABLE 1
THEORETICAL AND EXPERIMENTAL VALUES OF ΔL_c
WHEN THE TEMPERATURE VARIES FROM 20 TO 400 °C
FOR THE FOUR TESTED SENSORS

n°	$\Delta L_{c_{exp}}$	$\Delta L_{c_{th}}$	$\Delta L_{c_{exp}} - \Delta L_{c_{th}}$
<i>On 316 L stainless steel plate</i>			
180925_3	6.4 μm	7.6 μm	-1.2 μm
180925_5	5.6 μm	7.3 μm	-1.7 μm
<i>On tantalum plate</i>			
180925_2	-57.5 μm	-60.8 μm	3.3 μm
180925_4	-59.2 μm	-60.5 μm	1.3 μm

The difference between experimental and theoretical value is ± 1 to 3 μm . This seems acceptable, especially considering that slight uncertainties about the temperatures and the positions of the boundings can lead to uncertainties of about 1 μm for $\Delta L_{c_{exp}}$ and $\Delta L_{c_{th}}$. For example, a variation of 0.2 mm in the gage length on the tantalum plates produces a change of nearly 1 μm in $\Delta L_{c_{th}}$.

B. Tensile tests

1) Description

The second set of experiments to assess the accuracy of the FPS at high temperature are tests of elongation with a tensile test machine. Unlike during thermal expansion evaluations, FPS remain at a set temperature when the tests are performed. 316 L stainless steel samples with a useful length of 100 mm are used, with a section of 6 mm x 2 mm.

During the various experiments, we plot stress-strain curves. The strain, given by ΔL_c divided by the gage length, is measured by the FPS and is compared first to the expected strain given by the Hooke's law:

$$\sigma = E \cdot \varepsilon, \quad (4)$$

where σ , E , ε are the strain, the Young Modulus, and the stress respectively. The values considered for E vary with the temperature [5]. But the comparison is limited to the elastic

domain of the stress strain curve, with a maximum strain of about 0.1 %.

On a larger range of strain, the output of the FPS is also compared to an axial extensometer with ceramic rods (Maytec), used with a gage length of about 20mm (Fig. 3). The error of this measurement is specified to be less than 10µm, error that is expected to be reduced with calibration of the device.

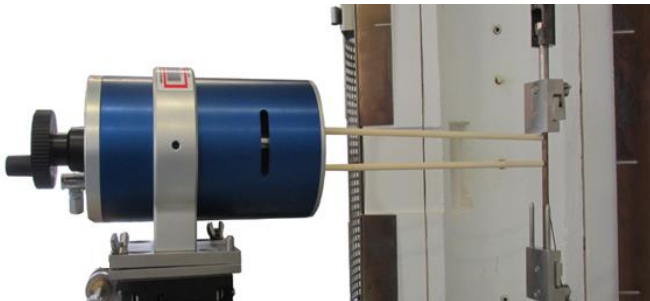


Fig. 3. Axial extensometer with ceramic rods in contact with the sample, on the opposite side of the FPS assembly.

After some statics tests on the elastic domain, a greater non-reversible elongation is achieved during a dynamic test with a constant elongation rate of 2.5 µm/s generated by the tensile test machine.

2) Results of the tests on the elastic domain

Fig. 4. presents the graphs obtained with tests on the elastic domain at high temperature. All tests indicate that FPS is accurate at high temperature on the low range of elongation tested.

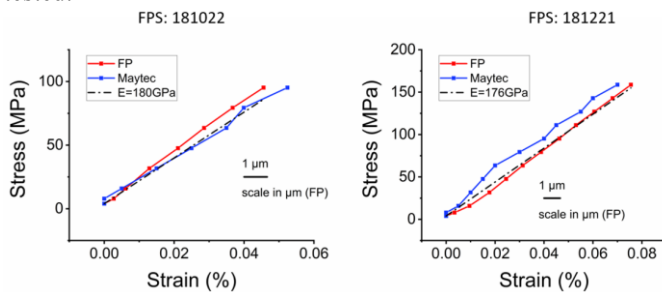


Fig. 4. Stress-strain curves at high temperature: 300°C for FPS 181022 (left) and 350°C for FPS 181221 (right) on the elastic domain. Both the FPS and the extensometer with ceramic rods (Maytec) are close to the theoretical values given by Hooke's law.

3) Results of the dynamic tensile tests

Fig. 5. presents the tensile stress-strain curve obtained with the FPS 181022, at 300°C, with a strain up to 1.5%. The plots given by the Maytec extensometer and the FPS are quite close.

In order to get a more precise assessment of the difference between the two sensors, the elongations data given by the Maytec extensometer is normalized to the same gage length (with a rule of three on the elongation measurements in µm) and the difference is calculated (Fig. 6). After filtering, the difference is limited to less than 6µm with an elongation of more than 200µm measured by the FP sensor.

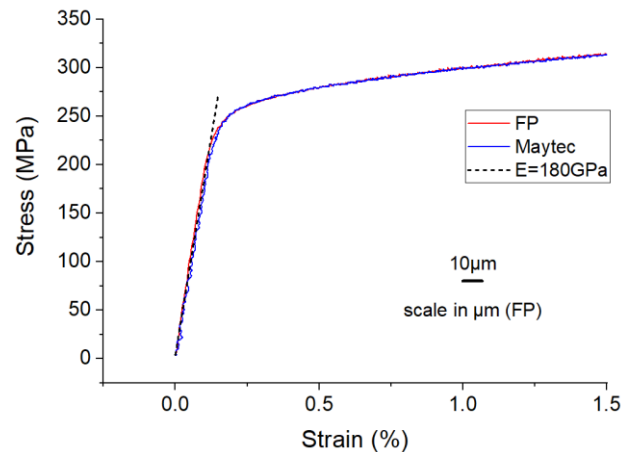


Fig. 5. Tensile stress-strain curve with FPS 181022, up to a strain of 1.5%.

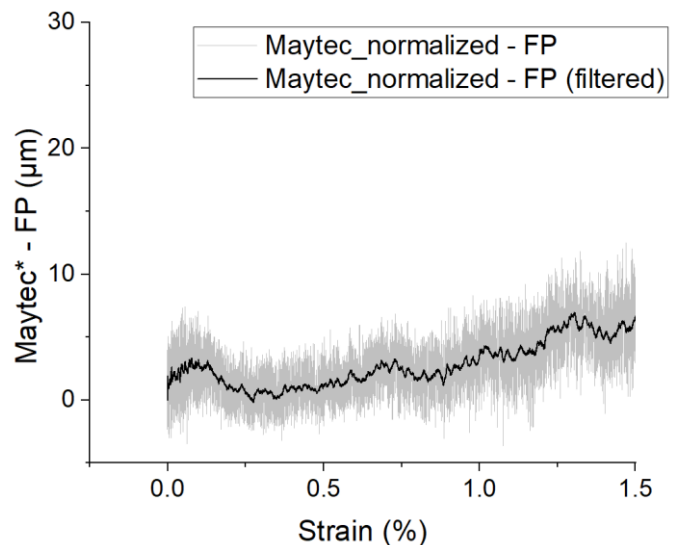


Fig. 6. Difference of elongation measured between FPS and Maytec (normalized to the same gage length) versus the strain on dynamic test with FPS 181022. The curve is noisy (grey); filtering the data given by the Maytec extensometer leads to the dark plot.

IV. CONCLUSIONS

The “measurements” of thermal dilatation and also tensiles tests have permitted to assess the accuracy of the FP sensor at high temperature (300°C to 400°C).

By comparison with Hooke's law on the elastic domain (low elongation, about 0.1% at maximum), the error is limited to about 1 µm. On the ranges within the specification of the sensor (1% to 2%), the error can be of some microns. The limited accuracy of the reference extensometer used did not permit to access more precisely the accuracy.

The sensor is designed to be nearly unaffected by gamma + neutron irradiation. This has been partially verified and is expected to be confirmed in a future irradiation (2020-2021).

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