Fiber Bragg Gratings embedded in plasma-sprayed ceramics for high temperature sensing

Alexandre Lerner, Aurélie Quet, Romain Cotillard, Laure Lago, Géraud Bouwmans, Guillaume Laffont

Fiber Bragg Gratings Embedded in Plasma-Sprayed Ceramics for High Temperature Sensing

Alexandre Lerner[1,2], Aurélie Quet[3], Romain Cotillard[1], Laure Lago[1], Géraud Bouwmans[2] and Guillaume Laffont[1]
[1]Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France
[2]Univ. Lille, CNRS, UMR 8523 – PhLAM – Physique des Lasers Atomes et Molécules, F-59000 Lille, France
[3]CEA, DAM, Le Ripault, F-37260 Monts, France
alexandre.lerner@cea.fr

Abstract: *In-situ* monitoring of femtosecond point-by-point written Fiber Bragg Gratings embedding in a ceramic material deposited by plasma-spraying was realized. High temperature measurements were successfully performed on the additively manufactured specimen up to 400°C.

1. Introduction

Optical fibre sensors (OFS) embedding in bulk materials by additive manufacturing has gained lots of interest in the last years [1]. The ability to perform measurement inside the materials allows structures monitoring with information not obtainable by surface-mounted sensors, especially in harsh environments.

High temperature resistant Fiber Bragg Gratings (FBGs) can be inscribed in optical fibers using femtosecond lasers. Specifically, point-by-point (PbP) written FBGs have shown to withstand temperatures as high as 1000°C [2].
The Bragg Wavelength Shift (BWS) $\Delta\lambda_B$ depends on external parameters variations such as temperature (ΔT) and strain ($\Delta\varepsilon$) following Eq. 1:

$$\Delta\lambda_B = (\kappa_T \cdot \Delta T + \kappa_\varepsilon \cdot \Delta\varepsilon) \quad (1)$$

Where κ_T and κ_ε are the temperature and strain sensitivity of the FBG, respectively.

Atmospheric plasma spraying (APS) allows the deposition of metallic or non-metallic particles onto a target substrate by feeding them through a plasma torch, leading to their full or partial melting [3]. Plasma sprayed alumino-silicates ceramics such as cordierite can be used as thermal barriers because of their low thermal conductivity and low thermal expansion [4]. Production of thick ceramic parts with this process is akin to additive manufacturing.

Krause *et al.* report OFS embedding by APS in Yttria Stabilized Zirconia (YSZ) [5]. Related works include Duo *et al.* embedding metal coated fibers in alumina coatings by wire flame thermal spray [6]. To the best of our knowledge, no study report FBG sensors embedding in thick plasma-sprayed ceramic structures.

In this work fs-written PbP FBGs arrays were monitored *in-situ* during their embedding in a few millimeters thick cordierite coating by APS. High temperature measurements (400°C) were performed with the embedded sensors to validate their potential usage in harsh environments such as for aerospace structures monitoring.

2. Experimental procedure

2.1. Fiber Bragg Gratings manufacturing

The FBGs sensors arrays were manufactured at CEA List LCFO facilities using a frequency-doubled Yb femtosecond laser. They were written PbP and directly through the coating of polyimide-coated single-mode fibers (Ø125 µm cladding). Each sensors array includes three 3 mm-long second-order FBGs equally distributed over 30 mm.

2.2. Optical fibre sensors embedding by atmospheric plasma-spraying

Ceramic plasma spraying was performed at CEA DAM Le Ripault facilities.

The embedding substrate (APS target) consisted of 2.5 mm thick plasma-sprayed cordierite on a stainless steel plate (Fig. 1a). The embedded sensors were comprised of a polyimide-coated FBGs array as defined previously, and a second one placed inside a polyimide-coated fused silica capillary. The latter, once embedded in the ceramic matrix, is designed to be insensitive to external strain, so as temperature and strain can be monitored simultaneously.

The sensors were fixed to the substrate, then positioned in the APS setup. Sensors BWS was continuously monitored at 5 kHz by a si255 optical sensing instrument (LUNA Innovations) during the embedding by APS.

2.3. Thermal testing

The instrumented structure was placed in a tubular furnace and submitted to temperature steps (2 h dwell time) from room temperature up to 400°C after a first annealing at 375°C. Temperature close to the specimen was continuously monitored using a type N thermocouple.

3. Results and Discussion

After embedding, the resulting structure is approximately 5 mm thick (Fig. 1b). In order to avoid potential edges effects on measurements, only the FBGs positioned in the center of the specimen are discussed here.

Fig. 1. (a) APS target for OFS embedding. (b) Embedded sensors in cordierite after the first thermal annealing.

The deposition of each layer is characterized by a peak in BWS in Fig. 2. Process was paused for $6 \leq t \leq 7$ min, and target surface cooling was reduced for $t \geq 18$ min. The measured BWS amplitude caused by temperature variations at the surface and strain in the bulk material decreases with increasing number of deposited layers.

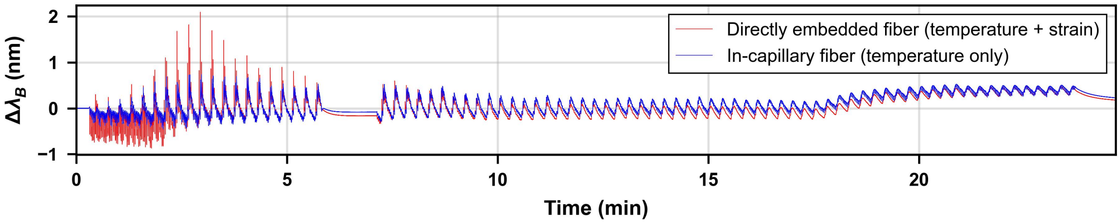

Fig. 2. APS embedding *in-situ* monitoring.

Once fabricated, the specimens were first annealed at 375°C which caused the ceramic material to separate from the stainless steel substrate, which is not detrimental. Further tests were conducted on this “free-standing” instrumented ceramic specimen, and are discussed hereafter.

Even being polyimide coated (maximum operating temperature ~350°C) both the directly embedded and the in-capillary sensors arrays allowed temperature measurements up to 400°C. At this temperature the polymer coating is deteriorated but this may not, in our case, severely interfere with the conducted measurements as the specimen are not sollicitated with significant strain levels. The directly embedded FBG show a BWS consistent with predicted values taking into account the higher linear thermal expansion coefficient $\alpha_{cordierite}$ of the surrounding material (Fig. 3).

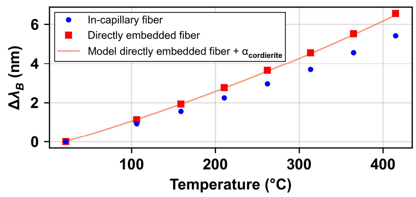

Fig. 3. BWS of the FBGs at the center of the specimen during thermal testing.

4. Conclusions

We successfully monitored the embedding of polyimide coated FBGs arrays in plasma-sprayed cordierite. High temperature measurement was performed with the embedded sensors. The instrumented specimen may be used for Structural Health Monitoring in harsh environments. APS *in-situ* monitoring will allow deeper understanding of the process dynamics at a local scale. For the conference, we will perform additional tests on specially packaged FBGs sensors arrays for high temperatures applications, embedded using the same APS process.

5. References

[1] N. Saheb and S. Mekid, “Fiber-Embedded Metallic Materials: From Sensing towards Nervous Behavior,” Materials **8**, 7938-7961 (2015).

[2] A. Martinez, I. Y. Khrushchev and I. Bennion, “Thermal properties of fibre Bragg gratings inscribed point-by-point by infrared femtosecond laser,” Electron. Lett. **41,** 176-178 (2005).

[3] P. Fauchais, “Understanding plasma spraying,” J. Phys. D: Appl. Phys. **37,** R86-R108 (2004).

[4] P. Rohan, K. Neufuss, J. Matějíček, J. Dubský, L. Prchlík and C. Holzgartner, “Thermal and mechanical properties of cordierite, mullite and steatite produced by plasma spraying,” Ceram. Int. **30,** 597-603 (2004).

[5] A. Krause, G. Pickrell, N. Pfeiffenberger, R. Bodnar and R. Greenlaw, “Thermal stress measurement and modeling in plasma spray deposits used for attaching fiber optic sensors,” Int. J. Mater. Mech. Eng. **1,** 32–37 (2012).

[6] Y. Duo, S. Costil, P. Pfeiffer and B. Serio, “Embedding properties of optical fibers integrated into ceramic coatings obtained by wire flame thermal spray” Smart Mater. Struct. **24,** 035027 (2015).