City Research Online

City, University of London Institutional Repository

Citation: Grandal Gonzalez, T., Zornoza, A., Fraga, S., Castro, G., Sun, T. & Grattan, K. T. V. (2018). Laser Cladding-based metallic embedding technique for fiber optic sensors. Journal of Lightwave Technology, 36(4), pp. 1018-1025. doi: 10.1109/jlt.2017.2748962

This is the accepted version of the paper.

This version of the publication may differ from the final published version.

Permanent repository link: https://openaccess.city.ac.uk/id/eprint/18624/

Link to published version: https://doi.org/10.1109/jlt.2017.2748962

Copyright: City Research Online aims to make research outputs of City, University of London available to a wider audience. Copyright and Moral Rights remain with the author(s) and/or copyright holders. URLs from City Research Online may be freely distributed and linked to.

Reuse: Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

City Research Online: http://openaccess.city.ac.uk/ publications@city.ac.uk

Laser Cladding-based metallic embedding technique for fiber optic sensors

T. Grandal, A. Zornoza, S. Fraga, G. Castro, T. Sun and K. T. V. Grattan

***Abstract*— In many applications in industry, securely attaching fiber optic sensors to metallic structures is important for optimum monitoring, overcoming the limitations of glues and adhesives which are known to degrade under certain circumstances. To avoid that problem, creating a metallic bond to attach the sensors securely to the metal surface is important. Commercial fiber optics with metal coatings can be used but it is important not to damage the sensor itself which is written in the thin optical fiber. In this work, an alternative laser cladding technology has been studied for embedding metal coated fiber optics into which Fiber Bragg Grating (FBG) sensors have been written. A three-step strategy was selected for embedding the metal coating fibers to create the best conditions to allow high quality measurements to be made. This has been seen to allow good control of the embedding process to be achieved and to minimize the thermal and mechanical stress generated. The research undetaken has shown that it is possible to embed Cu and Ni coated fiber optics containing sensors to over 300µm with low losses, of between 0-1.5 dB (or 0-30%) and yet still enable satisfactory strain and temperature measurement results to be obtained. The research has shown that both Ni and Cu coated FBG-based fiber optic sensors could be embedded successfully and shown to give good mechanical and thermal response to similar non-embedded sensors and give excellent cross-comparison with the conventional gauge used for calibration. The results are therefore particularly encouraging for the use of sensors of this type when incorporated to create metallic 'smart structures' achieving durability of the sensors through the use of this innovative technique.**

***Index Terms*—Embedded fiber optic sensors, Fiber optic sensors, Fiber Bragg Grating, FBG sensor, harsh environments, metal coating fiber, smart structures, laser cladding.**

I. INTRODUCTION

A growing number of industry sectors need so-called 'smart' tools or structures to provide rapid and reliable condition monitoring. That way, the greater adaptability needed to meet the often-changing requirements of the production process can more readily be achieved and with that greater efficiency in the use and maintenance of the structures in which they are incorporated. To achieve those objectives, accurate and reliable sensing of the condition and performance of tools, machines or infrastructure and often the production process overall is required. One way of achieving such better monitoring is to use a fiber optic sensor-based approach, taking advantage of the well-known benefits of this innovative and flexible method [1]. To do so in this research, a laser cladding-based technique to embed fiber optic sensors into metallic structures has been developed and its performance studied. Laser cladding is an additive process wherein a high-energy laser source is used to melt metal-based powder or wire on to a metal substrate. It allows weld seams and coated layers with a very high quality of union to be obtained, in comparison to other methods. This arises due to aspects such as (i) highly localized material addition is used, so that the thermal damage is much lower than with any other method of repair such as plasma or electric arc; and (ii) the process is carried out quickly in an atmosphere protected by a continuous inert gas flow, thus obtaining a high quality in the generated geometry. Laser cladding can be used in two major ways with (i) the production of parts of composite materials and (ii) the repair of worn parts. In the production of parts of composite materials, this technique is used to produce hard, wear-resistant and/or corrosion-resistant surface layers. Among the different surface treatments used to improve the corrosion and wear resistance of metallic materials, laser cladding is an attractive alternative to conventional techniques due to the intrinsic properties of laser radiation: high input energy, low distortion, avoidance of undesirable phase transformations and minimum dilution between the substrate and the coating.

In addition, fiber optic sensors, more specifically Fiber Bragg Grating (FBG) sensors, are an attractive option for a wide range of sensing needs because of their particular features such as small size, high sensitivity, rapid response, immunity to electromagnetic interference, robustness in harsh environments and capability of being multiplexed along a single fiber optic channel [1]. In summary, a FBG sensor is a type of distributed Bragg reflector, designed and written into a short segment of optical fiber (typically <5mm), that reflects a narrowband of a particular wavelength of the incident light and transmits all other wavelengths. The measurand is encoded within what is a reproducible wavelength change characterizing the sensor. In many applications in industry, attaching the fiber optic containing the sensor(s) to a metallic structure is important to monitor the performance of that

Manuscript received July 31, 2017.

This paper was supported by the project Unidad Mixta de investigacíón NEXT-BEARINGS with reference IN853A 2015/2, funded by the Spanish general government administration and the Xunta de Galicia through GAIN and the Ministry of Industry, Energy and Tourism of Spain. Support from the Royal Academy of Engineering and the George Daniels Educational Trust is gratefully acknowledged.

T. Grandal is with the AIMEN Technology Center, C/Relva, 27 A, 36410 O Porriño (SPAIN) and is with the School of Mathematics, Computer Science and Engineering, City, University of London, Northampton Square, London, EC1V 0HB, United Kingdom (tania.grandal@aimen.es).

A. Zornoza, S. Fraga, G. Castro are with the AIMEN Technology Center, C/Relva, 27 A, 36410 O Porriño (SPAIN).

T. Sun and K. T. V. Grattan are with the School of Mathematics, Computer Science and Engineering, City, University of London, Northampton Square, London, EC1V 0HB, United Kingdom.

structure. In some applications, glues and adhesives are used for that purpose, but they can be subject to attack by chemicals, can offer less than optimum strain transfer for example and are known to degrade with time. To avoid that problem, creating a secure metallic bond to attach the sensors to a metal surface is important. Fiber optics with metal coatings can be used and in order to embed fiber optic sensors effectively into metallic structures using welding techniques, melting the metal coating is required, but doing this without damaging the sensor itself in the thin optical fiber. It is important to investigate techniques that can be used to optimize this process and the use of a material added during the welding process represents an ideal approach, because it offers the additional control over the embedding process that is needed to create a stable and reliable fusion of the fiber to the substrate. In so doing, it is possible to adjust the distance of the heat source from the sensor embedded in the thin fiber and thus avoid thermal damage which could render the sensor inoperable. Thus, to protect the fiber (and thus the sensor) during the embedding process is essential and for this an effective metallic coating on the fiber is needed. When specifying this, it is important to note that the metal forming the coating must have a melting point above that of the added material to withstand the high temperatures reached during the weld.

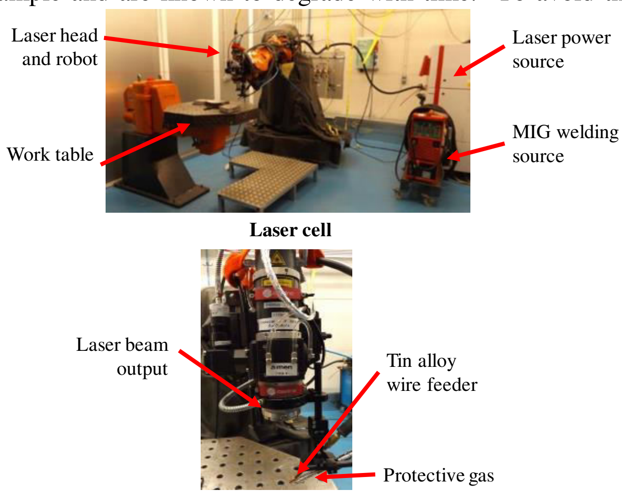


Fig. 1. Top: Illustration of the Laser cladding set-up used in this work, Below: Detail of the head laser set-up used.

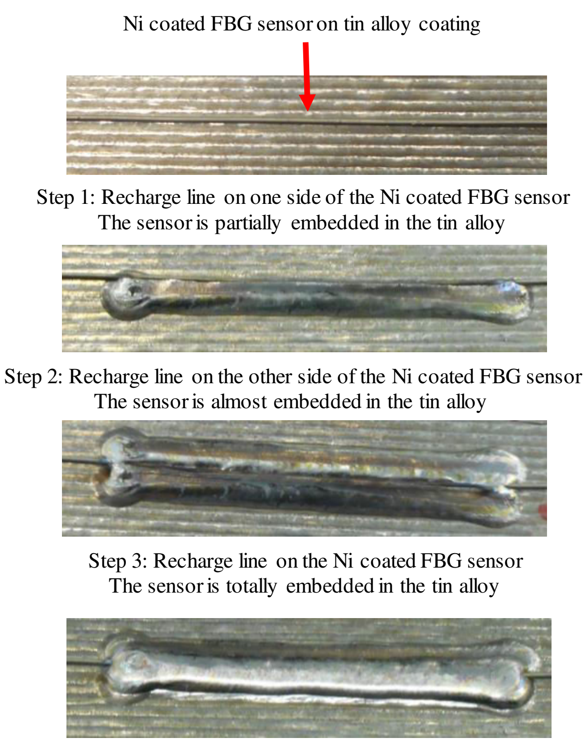


Fig. 2. Illustration of selected embedding strategy.

There are many methods which have been proposed for coating optical fibers and these have been discussed in the literature [2-6]. In this work, the approach taken was that the FBG-based sensors were coated with a 2µm thickness of Au, using a sputtering technique, following which the coating thickness was increased using (cheaper) Ni or Cu, to create an overall coating thickness which could be up to hundreds of micrometers, by using an electroplating deposition approach (which has been discussed in previous reports from some of the authors [7,8]). The first layer (of Au) is needed as a conductive layer, creating the substrate of the fiber to allow for the subsequent electroplating deposition process on it. Ni and Cu were selected for the metallic coatings of the FBG sensors, mainly because both have a high melting point but also are durable, inexpensive and easy to use for coatings of this type. In addition, the tin alloy has Cu in its composition and this guarantees a good bond between the copper coating and the materials which then are added. In the case of Ni, a good bond response can be achieved with most metals [9] and high resilience against thermal damage is achieved, because its thermal conductivity is lower than that of copper.

A number of different techniques can be used for embedding FBG sensors into metallic materials, but for practical applications in the tools or structures that are the focus of this work, not all are feasible. Xiaochun Li et al. [10] pioneered the field in 2001 when they embedded fiber optic sensors into stainless steel by using a combination of electroplating deposition and a laser layered manufacturing technology method. However, the electroplating technique was typically confined to small samples to be easily manipulated. Sandliu et al. [11] have embedded FBG-based sensors by using vacuum brazing of Inconel 600. The limitations of this technique are the size of the vacuum oven (which is only available for small specimens) and the high temperatures (900^{o}C) needed. Yulong Li et al. [12] have used ultrasonic welding technology to allow the embedding of FBG sensors into Al. However, this welding technology is limited when thick samples are used and the head welding (sonotrode-based) technique is unwieldy. Grandal et al. [7] have embedded FBG sensors in prior work by using a Tungsten Inert Gas (TIG) welding method and as this technique is completely manual, it was found that the quality of the results are heavily reliant on the experience of the welder and so reproducibility is an issue. In the last few years, laser additive manufacturing techniques have been studied with a view to achieving more effective embedding of fiber optics containing sensors and Havermann et al. [13] have been pioneers of a technique using Selective Laser Melting (SLM) for embedding such fiber optic sensors into stainless steel. This technique allows the embedding of thin coated fibers, of up to 350µm total diameter, because of its careful and effective control of the heat concentration but, as with the electroplating plus laser layer manufacturing technique, it application is limited by the size of the chamber available for the fabricating process.

As it has been discussed, the most feasible way to embed FBG sensors is by using welding techniques, in part because of their accessibility to manufacturing industries and the wide familiarity with the technique. The experience from the authors (seen in their prior published work) has been focused on embedding FBG sensors by employing welding techniques using both laser welding [8] and TIG technology [7]. Although these techniques show a number of advantages (and indeed in some areas disadvantages over competitor methods), they are the simplest for embedding fiber optic sensors and can be used with the manufacture both of larger, more complex structures or individual pieces. In that way, it is possible to embed the sensors during the manufacturing process, avoiding the need for post-processing, by creating a groove before the embedding process (with the SLM technique) or undertaking a post-mechanize process to achieve the desired quality (with TIG welding).

Metal coating	Thickness [μm]	Loss before embedding [dBm]	Loss after embedding [dBm]	Total LOSS [dB]	Laser Power [W]	Embedded length [cm]	Picture of the coating fiber	Cross-section of embedded fiber
Cu	480	0.60	1.10	0.50	2000	7.5		
	481	2.18	2.18	0.00	1500	5.0		
	399	11.26	12.35	1.09	1500	6.3		
Ni	455	20.63	39.33	18.70	2000	6.7		
	348	3.92	5.58	1.66	2000	7.2		
	252	2.65	broken	-	2000	5.6		
	413	4.98	6.02	1.04	1800	6.3		
	400	14.67	17.25	2.58	1800	4.8		
	242	2.87	broken	-	1800	7.1		
	237	2.08	3.60	1.52	1800	7.2		
	495	6.37	6.93	0.56	1500	7.8		
	347	2.54	3.44	0.90	1500	4.1		
	271	2.41	23.90	21.49	1500	5.7		

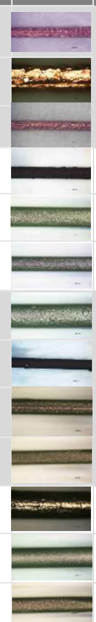


Fig. 3. Results of embedding Ni and Cu coating fibers by laser cladding with different laser powers used.

In this work, laser cladding technology is studied for embedding fiber optic sensors effectively. The laser cladding approach represents a special laser welding technique in which the laser is the heat source of the welding process. In such a laser cladding method, a material with a melting point lower than the materials being welded is added [14] and moreover, the laser cladding technology can be used as an additive manufacturing technique. The added material is deposited layer-by-layer when embedding the fiber optic sensors and for adding a coating on the steel substrate, to improve its mechanical response. The laser cladding technology discussed offers several advantages over other welding techniques, summarized as (i) the additional material can be placed precisely where desired; (ii) different materials can be both deposited and deposited onto; (iii) the deposits are fully fused to the substrate with little or no porosity; (iv) the minimal heat input also results in limited distortion of the substrate and reduces the need for additional corrective machining, thus offering greater processing flexibility and the possibility of selectively cladding small areas, etc. Laser cladding technology allows the creation of an effective embedding of the FBG sensors, achieving both high accuracy and high efficiency in the process and ensuring that the procedure is readily repeatability and reproducible. Thus, it is possible to control and adjust the key parameters as required, even during the embedding process, to assure the highest quality of the bond is achieved. Likewise, this technology offers a high flexibility when working with samples of large dimensions or with those having complex geometries.

In this research, metal coated FBG sensors are embedded into metallic structures based on ST-52 (carbon steel which contains high level of manganese) and then coated with a tin alloy ($SnSb_8Cu_4$) by using a laser cladding approach. The tin alloy is presented as a wire of 2.4mm diameter. The tin coating layer has a thickness of 3mm and therefore the total thickness of the embedded fiber must be as small as possible, in order not to interfere in the function of the coating layer. This added material was chosen because of its high mechanical properties such as high hardness and durability, and low melting point, which then offers the possibility of embedding lower thickness fibers because of the lower thermal loading induced in the coating layer during the embedding process, thus minimizing the potential for fiber (and thus sensor) damage. It is also worth noting that this is a good starting point for metals with a high melting point because it allows flexibility when experimenting with different embedding strategies.

In this paper, in Section II the strategy used and its optimization when embedding Ni and Cu coating fibers of different thickness is considered. In Section III, there is a discussion of the Ni and Cu coated FBG sensors which were embedded into specimens and their performance characteristics under elevated temperature and strain evaluated. Section IV discusses the conclusions of the study.

II. Strategy for Optimization of Embedding Process

The laser cladding setup employed in this work is illustrated in Fig.1, where in the upper figure (Top) the laser cell is shown, while in the lower figure (Below) a detail of the laser head for depositing the tin alloy wire is presented. The laser source used was a Laserline LDF 6000-40VGP diode laser with 6kW maximum optical power and the output coupled to a 0.4mm diameter optical fiber. The focal length of the optical system used in conjunction with the laser was adjusted to a distance of 182 mm, with the use of a specific optical system (Model OTS-2), and thus achieving a minimum beam diameter of 0.7mm. The laser head wire was fed with a MIG welding source (Model TPS5000 from Fronius) and supported by a RobactaDrive (also from Fronius), this being placed closer to the laser head. The robot used adjacent to where the laser head was mounted is a 6-axis robot (Model IRB4400

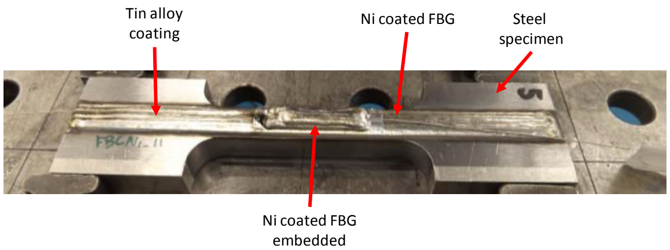


Fig. 6. Ni coated FBG sensor embedded into tin alloy by laser cladding.

from ABB). The wire diameter of the tin alloy is 2.4mm and the laser operational parameters were as follows – the laser power was 2 kW; the speed of the laser head was 40 mm/s and speed of the wire movement was 2.4 m/min. In this work, the major parameter adjusted in operational use is the laser power, in spite of the fact that other parameters such as focal distance, or the speed or position of the fiber have influence on the system performance. Prior work undertaken by the authors has shown that the laser power is the most critical parameter in achieving the best embedding of the FBG sensors, through this laser cladding approach.

The main objective of the research at this stage is optimizing the environment to achieve an excellent and durable bond between the metal coating of the fiber and the added material during the welding process, without allowing thermal damage to occur to the optical fiber and also avoiding the appearance of pores – in that way not compromising the sensitivity and performance of the sensor. In doing so, special attention has been placed on assuring the optimum placement of the fiber on the substrate and in creating a reliable and solid embedding strategy. Further, it is important that the embedding strategy developed will ensure that the fiber does not interfere with the wire, allowing added material delivery as needed and thus guaranteeing a reliable and repeatable embedding of the fiber. To achieve these requirements, it is clear that accurate and reproducible control of the laser cladding process is critical. After evaluating different embedding strategies, the following was selected as the best, because in using it the coated fiber was seen to suffer less thermal damage during the overall embedding process.

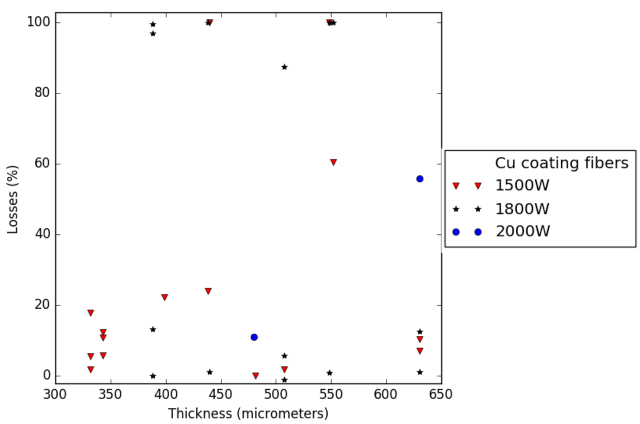


Fig. 4. Losses for the embedded Cu coated fiber optic as a function of thickness for different laser powers used.

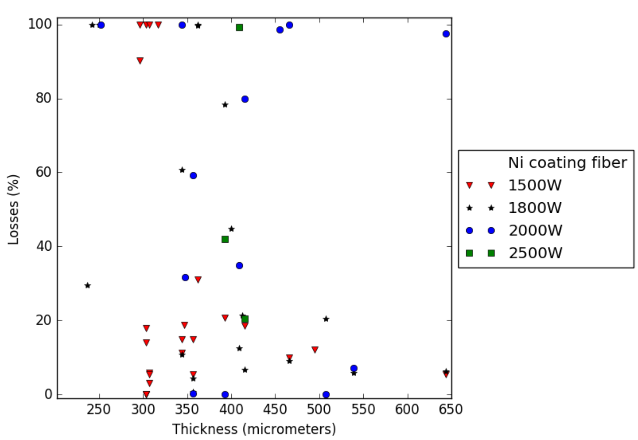


Fig. 5. Losses for the embedded Ni coated fiber optic as a function of thickness for different laser powers used.

The strategy used was to apply individual recharge lines longitudinal to the fiber to be coated. First, one recharge line on one side of the coating fiber was made, and then a further recharge line on the other side was created. Then a further recharge line on the previous lines was made to embed the fiber completely (as can be seen from Fig. 2). This strategy allows the heat to be supplied easily to the fiber and also each deposition track, to obtain an optimum fiber embedding, assuring the best bond between the layers and the coating fiber.

Initially, Cu and Ni coated fibers, using thicknesses of between 200µm to 500µm were embedded, employing different laser output powers (respectively 1500W, 1800W, 2000W) to determine which power level was optimum for the embedding process for the coated fibers and which is the minimum diameter of fiber which best resists the potential for fiber damage from the process. For these tests, commercial copper-coated fiber from IVG Fiber (Cu1300) was used with a copper alloy and carbon layers of 40µm. The copper coating layer of this fiber was re-covered with Ni and Cu by electroplating deposition, until reaching the desired thickness.

Destructive and non-destructive analysis was performed to evaluate the quality of the bond achieved. Here, the non-destructive tests consisted of measuring the loss in the fiber after each embedding layer was produced. The destructive tests carried out involved making transverse cuts in the embedded fibers to analyze the quality of the union between the fiber and the added material, achieved through an inspection of the cross-section. Fig. 3 summarizes the outcomes of the tests that were performed. The optical losses of the embedded fibers were mainly attributed to damage of the fiber due to insufficient coating. Also, the total losses seen in the fibers were not related to the embedded length, but were mostly attributable to local micro-bending of the fiber during the embedding process, as the longer lengths of embedded fibers did not show greater levels of losses. It was pleasing to note that most of the embedded fibers showed good bonding characteristics, with no significant difference seen between the performance of the Cu and the Ni coated fibers. The losses seen typically are in the region of 0.5 – 3.0 dB, giving results which are very acceptable, although exceptions were seen where the losses were higher or where the fiber was damaged or occasionally broken. The cross-section of such fibers shows a good bond between the coating fiber and the tin alloy, for both Ni and Cu. When examining the broken and high loss fibers, part of the coating layer of the fiber was seen to have melted during the embedding process. It was observed that this mainly happened for thicker coated fibers or when a higher power laser was applied, for several Ni coated fibers (of 455µm and the higher laser power of 2000W used or of 271µm and a laser power 1500W).

Once the strategy for embedding was optimized, several different fibers were coated with different thicknesses and these were embedded, following the same methodology that previously had been validated. In this case, just the losses were monitored – this parameter being used as the defining characteristic of good embedding. Fig. 4 and Fig. 5 show the results obtained. An analysis of these results shows that the laser power proved to be a critical parameter for the quality of the embedded fibers, with the work showing that the best results were obtained when using a power of 1500W. Ni coated fibers showed a higher resistance than Cu coated fibers to the effects of the embedding process. For the Ni coated fibers, the losses were seen to decrease significantly for coating thicknesses above 400µm, while for Cu coated fiber, the thickness threshold was not so clearly defined. However, in both cases, it was found possible to embed coated fibers over 300µm (of total diameter, with a 175µm coated layer). Tests showed that these were acceptable losses to allow the FBG-based sensors to function in a satisfactory way for use when attached to metal surfaces.

III. EMBEDDING FBG SENSORS AND CHARACTERIZATION.

Following completion of the study discussed on embedding coated fibers, the next step undertaken was to embed metal coated FBG sensors into metallic specimens. The FBG sensors used in this study were made by using irradiation of the fiber itself using light from a femtosecond laser (provided by Femto Fiber Tec) where the specimens were shaped and mechanized so tensile tests could be performed on them. The process used was as follows: the fibers into which the FBGs were written were first coated with a thin film (2 µm) of gold by sputtering deposition, after which they were electroplated with Ni or Cu, to create fibers with total diameters of 398µm and 508µm, respectively (as shown in Fig. 6). Following that, they were embedded by using the laser cladding approach, presented in the previous section (with a laser power of 1500W and 2.4mm wire diameter). Then, temperature and strain characterization tests were performed in an oven (Lenton TLK38) and using a tensile testing machine (MTS landmark 250kN) to apply reproducible temperature and strain variations to the fiber, as discussed below.

A. Temperature characterization

The temperature calibration of the samples was undertaken before the tensile tests were carried out. The specimens with the embedded fibers were subjected to heating over the temperature range from 50°C to 200°C, in steps of 30°C (as can be seen from Fig. 7, Fig. 8 and Fig. 9), showing for each three different calibration tests carried out on the sensors. The tin alloy used has a melting point of 250°C, and thus in this test the maximum temperature employed was 200°C. Fig. 7 shows a comparison between the temperature response of the Cu coated sensor, before and after being embedded. This figure shows the speed of heating for each case. When the Cu

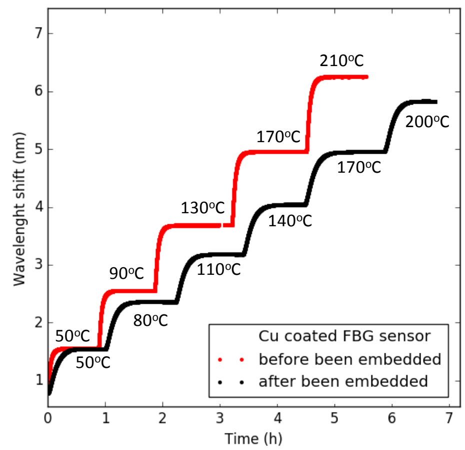


Fig. 7. Temperature response of the Cu coated FBG sensor before and after been embedded.

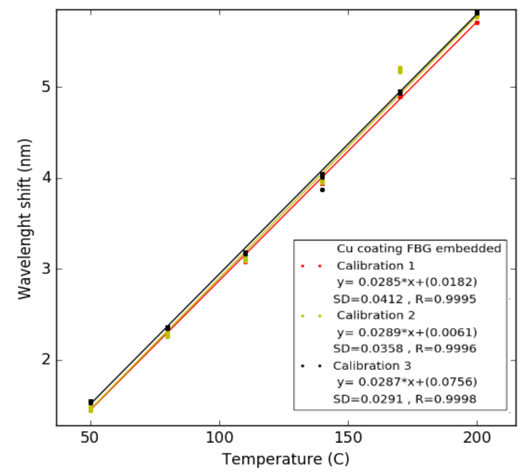


Fig. 8. Temperature characterization of the embedded Cu coated fiber optic sensors.

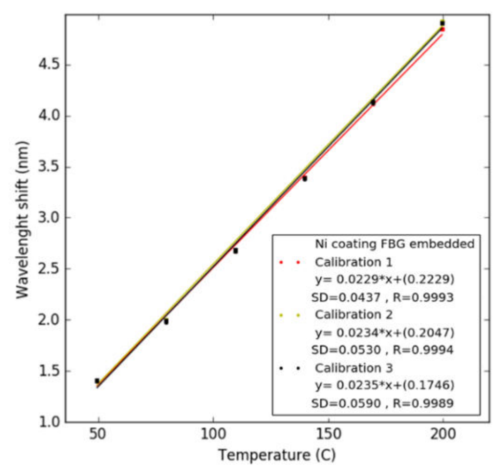


Fig. 9. Temperature characterization of the embedded Ni coated fiber optic sensors.

coated FBG sensor is embedded, the temperature stabilization occurs around 33% slower than in the case where the FBG sensor is not embedded. This arises because for the first case, the total metal piece where the sensor is embedded has to reach the required temperature for achieving the stabilization condition. Depending of the volume and the geometry of the piece, the temperature stabilization occurs at a different time. The thermal sensitivity of the Cu coated, FBG-based embedded sensor was determined to be 0.029nm/^{o}C (Fig. 8), while the sensitivity of Cu coated FBG sensor before being embedded was 0.030nm/^{o}C. For the Ni coated FBG-based embedded sensor was found to be 0.023nm/^{o}C (Fig. 9). The response of both sensors was also determined to be very repeatable (as can be seen from the figures), with a sensitivity found to be in accordance with the response of metallic coating sensors seen from prior work [4,7]. The thermal sensitivity difference which is seen in the Cu coated FBG sensor before and after been embedded could be due to the influence of the tin alloy material around the embedded sensor or to a coating loss (due to melting), caused during the embedding process.

B. Strain characterization.

After the temperature calibration was completed, several strain tests were carried out on the samples. The first test was undertaken by increasing the tension from 0 to 20kN, in steps of 2kN for the Cu embedded sensor and in steps of 5kN for Ni

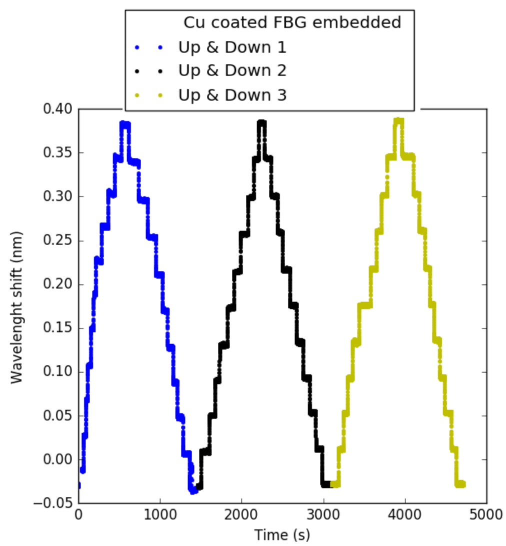


Fig. 10. Load response of embedded Cu coated FBG sensors for three different cycles of load application.

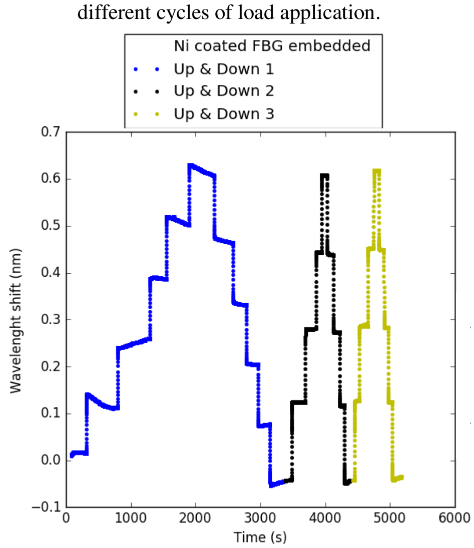


Fig. 11. Load response of embedded Ni coated FBG sensors for three different cycles of load application.

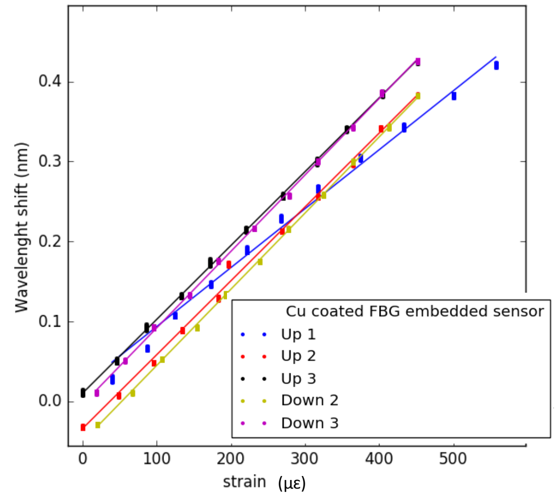


Fig. 12. Strain characterization for embedded Cu coated fiber optic sensors. The sensitivities of each linear fit are: Up1: 0.0007 nm/με, Up2: 0.0009 nm/με, Up3: 0.0009 nm/με, Down2: 0.0010 nm/με and Down3: 0.0010 nm/με.

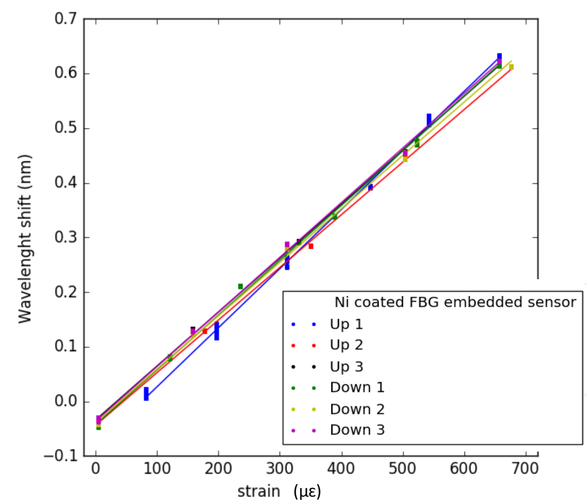


Fig. 13. Strain characterization for embedded Ni coated fiber optic sensors. The sensitivities of each linear fit are: Up1: 0.0011 nm/με, Up2: 0.0010 nm/με, Up3: 0.0010 nm/με, Down1: 0.0010 nm/με, Down2: 0.0010 nm/με and Down3: 0.0010 nm/με.

embedded sensor (as can be seen from Fig. 10 and Fig. 11). These tensile tests were repeated three times (to evaluate the repeatability of the response of the sensors) for the strain being applied (Up) and then removed (Down) in the regular strain steps shown. These two figures illustrate the regular 'steps' with the application of a further load increment over the total period of the test (1600 seconds for the embedding in Cu and 3500 seconds for embedding in Ni). It can be noted that the sensitivity to loading for both sensors is different. This arises from the different geometries of the samples, as the locations where the sensors where embedded were different and thus each cross-section was different as well.

In the next test, to undertake a cross-evaluation of the performance, a conventional gauge was glued on the surface of each specimen (where the FBG was embedded) to allow for a direct comparison of its response with the optical fiber sensor. The results of the investigation show that the response of both FBG sensors embedded is linear with the load and repeatable (as can be seen from Fig. 12 and Fig. 13). The measured sensitivity of the sensors (determined from the slopes of the graphs) was shown to vary between 0.9pm/με and 1pm/με, which is in accordance with the strain sensitivity measured for conventional, non-embedded FBG-based strain sensors (determined from prior work). The graphs illustrated show three measurements for the strain increasing (Up 1 to Up 3), followed by the strain decreasing (Down 1 to Down 3) for both Cu embedding (Fig. 10) and Ni embedding (Fig. 11) (it should be noted that the Down 2 steps for Cu coated FBG sensor was discarded because the response of the gauge was not linear, reflecting an experimental error when compared to all the others and as the Cu coated FBG embedded sensor showed in Fig.10). In both cases (seen in Fig. 12 and Fig. 13) the result from the first application of the strain (Up 1) varies most from the other calibrations because of the initial residual strain from relief at the beginning of the calibration process – it can be seen from the subsequent strain applications that this effect 'settles', as is seen in the other graphs.

IV. CONCLUSION

The results obtained and the analysis carried out has shown the success of the laser cladding welding technology used, demonstrating it successfully being used for embedding FBG-based fiber optic sensors into metallic structures. The work done has shown that it is possible to embed Cu and Ni coated fiber optics containing sensors over 300µm with low losses, of between 0 and 1.5 dB (or 0-30%) and yet still enabling satisfactory strain and temperature measurement results. In the research carried out, both Ni and Cu coated FBG-based fiber optic sensors were embedded successfully and shown to give a similar mechanical and thermal response to similar non-embedded sensors and give good cross-comparison with the response of the conventional gauge used for that purpose.

The results are therefore encouraging for the use of sensors of this type being incorporated to create metallic 'smart structures' given the similarity of the performance of the sensors to those used in the conventional way (i.e. not metal embedded) and through the significant improvement to the durability of the sensors seen through the use of this technique. FBGs can be written into fibers which sustain high temperatures so there is considerable potential for increasing the operational temperature with the use of suitable materials [15, 16]. Work is continuing to improve the quality and durability of the embedded sensors and to evaluate their performance in a number of different situations.

REFERENCES

[1] S. J. Mihailov, "Fiber Bragg Grating sensors for harsh environments", Sensors, vol. 12, pp.1898-1918, 2012. DOI:10.3390/s120201898

[2] E. Piñeiro et al. (2014, June). Coating process of Fiber Bragg Grating sensors for SHM applications in metallic structures. Presented at OSF23. [Online]. Available: http://dx.doi.org/10.1117/12.2059694

[3] R. Rajini-Kumar et al., "Performance evaluation of metal-coated fiber Bragg grating sensors for sensing cryogenic temperature", Cryogenics, vol. 48, pp. 142–147, 2008 DOI:10.1016/j.cryogenics.2008.02.007

[4] Y. Feng et al., "Temperature sensing of metal-coated Fiber Bragg Grating", IEEE/ASME Transactions on mechatronics, vol. 15, no. 4, AUGUST 2010, DOI: 10.1109/TMECH.2010.2047111

[5] S.T. Shiuete al., "Effect of the coating thickness and roughness on the mechanical strength and thermally induced stress voids in nickel-coated optical fibers prepared by electroless plating method", Thin Solid Films, vol. 485, pp. 169 – 175, 2005. DOI: 10.1016/j.tsf.2005.04.024

[6] H. Alemohammad et al., "Metal embedded optical fiber sensors: laser-based layered manufacturing procedures", Journal of Manufacturing Science and Engineering. Vol.133, 031015-1, JUNE 2011, DOI: 10.1115/1.4004203

[7] T. Grandal et al. (2016, July). Technique for embedding fiber optics in metallic structures for smart material applications. Presented at: EWSHM 2016, [Online]. Available: http://www.ndt.net/events/EWSHM2016

[8] T. Grandal et al. (2017, April). Laser Brazing metallic embedding technique for fiber optic sensors. Presented at: OFS25, [Online]. Available: http://dx.doi.org/10.1117/12.2263974

[9] R. Saravanan and M. Prema Rani, "Results and discussion on metals and alloys," in Metal and Alloy Bonding: An Experimental Analysis 1st ed. London, United Kingdom: Springer-Verlag London Limited 2012, ch. 3, sec. x, pp. 65–145.

[10] X. Li et al., "Embedding of fiber optic sensors in layered manufacturing"; Journal of Manufacturing Science and Engineering AUGUST 2003, vol. 125 Õ 577. DOI: 10.1115/1.1581889.

[11] S. Sandlin et al., "Use of brazing technique for manufacturing of high temperature fibre optical temperature and displacement transducer", Materials Science and Technology 2007 vol. 23, no 10, DOI 10.1179/174328407X226662

[12] Y. Li et al., "Ultrasonic embedding of nickel-coated fiber Bragg grating in aluminum and associated sensing characteristics", Optical Fiber Technology, vol. 18, pp. 7–13, 2012 DOI:10.1016/j.yofte.2011.09.004.

[13] D. Havermann et al., "Temperature and strain measurements with Fiber Bragg Gratings embedded in stainless steel 316", Journal of lightwave technology, vol. 33, no. 12, JUNE 15, 2015. DOI: 10.1109/JLT.2014.2366835

[14] G. Castro et al., "Laser additive manufacturing of high added value pieces", Procedia Engineering vol. 132, pp. 102 – 109, 2015, DOI: 10.1016/j.proeng.2015.12.485.

[15] S. Pal, J. Mandal, T. Sun, and K.T.V. Grattan, "Characteristics of potential fibre Bragg grating sensor-based devices at elevated temperatures" Conference: Technical Meeting on Advanced Sensors and Instrumentation Systems for Combustion Processes Location: London, UK, Meas. Sci. Technol., vol. 14, no. 7, pp 1131-1136, 2003.

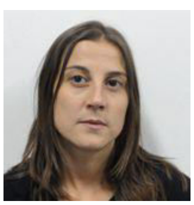
[16] S. Pal, T. Sun, K.T.V. Grattan, S.A. Wade, S.F. Collins, G.W. Baxter, B. Dussardier and G. Monnom, "Non-linear temperature dependence of Bragg gratings written in different fibres, optimised for sensor applications over a wide range of temperatures" Sensors & Actuators A – Physical, vol. 112, no. 2-3, pp 211-219, 2004.

BIOGRAPHIES

Tania Grandal has a bachelor's degree in Physics in the specialty of Optoelectronics from the University of Santiago de Compostela and a Master's Degree in photonics and laser technologies from the same university. She has been working in the development and application of fiber optic sensors, especially FBG sensors, for the monitoring of harsh environment and structures since 2012. Currently she is working as a research technician in AIMEN technology center, while pursuing the Ph.D. degree in Measurement & Instrumentation in the School of Mathematics, Computer Science and Engineering at City, University of London.

Ander Zornoza studied Telecommunication Engineering in the Public University of Navarre (UPNA)and started his PhD in fiber optic sensors right after finishing his Masters. His research has been focused in developing distributed sensors, and the experience he got from research stays in Italy and Portugal had a big impact in focusing his approach to his job. He realized that understanding the background of the sensing technology itself is as important as their application. In other words, understanding the application of the sensors helps to develop a better sensing technology. Therefore, after several years developing Fiber Optic sensors he became interested in one of their main applications: Civil Engineering. He obtained a Fulbright scholarship to study a Master in this field and complete his education in the United States. After the completion of the Fulbright scholarship and Master degree he defended the PhD thesis dissertation in Fiber Optic Distributed Sensors in the UPNA. Following his graduation started working in the Aimen technology center as a senior researcher, where contributes actively to research and development of sensing technologies for harsh environments and structural health monitoring applications. In 2015 was awarded a Torres Quevedo grant for young researchers.

Sergio Fraga graduated Physics in 2014 in University of Santiago de Compostela and obtained a Master's Degree in Photonics and Laser Technologies at the University of Vigo. From 2015 has been working at Aimen technology center as a research technician in the Robotic and Control department, developing sensing solutions based on fiber optic sensors.



Gemma Castro is European Welding Engineer and holds a degree in Mining Engineering. She has more than 10 years of experience in the AIMEN technology center where she works as R&D technical senior in different laser processing technologies, mainly laser cladding applied to Laser Additive Manufacturing and to the obtaining of wear and corrosion resistant coatings, but also in surface modification and laser welding. She has participated in a multitude of projects both domestic and international. Currently, she is a PHd student working on Laser Surface modification of AISI M2 tool steel to improve its wear behavior.

Tong Sun received the B.Eng. degree, M.S. degree in engineering, and the Ph.D. degrees in engineering for work in mechanical engineering from the Department of Precision Instrumentation, Harbin Institute of Technology, Harbin, China, in 1990, 1993, and 1998, respectively. She also received the Ph.D. degree in applied physics from City University of London, U.K., in1999. She was an Assistant Professor at Nanyang Technological University, Singapore, from 2000 to 2001, before she rejoined City University of London, in 2001, as a Lecturer. Subsequently, she was promoted to a Senior Lecturer in 2003, a Reader in 2006, and a Professor in 2008 at City University of London. She has been leading a research team focused on developing a range of optical fiber sensors for a variety of industrial applications, including structural health monitoring, early fire detection, homeland security, process monitoring, food quality, and automotive emission monitoring, and has been working closely with partners across disciplines from academia and industry, both in the U.K. and overseas. She has authored or co authored 130 scientific and technical papers. Prof. Sun is a member of the Institute of Physics and of the Institution of Engineering and Technology, and a Chartered Physicist and a Chartered Engineer, U.K.

Kenneth T. V. Grattan received the Bachelor's degree in physics from Queen's University, Belfast, U.K. in 1974, and the Ph.D. degree from the same University in 1978. In the same year, he became a Post-doctoral Research Assistant at Imperial College London, London, U.K. His research during that period was on laser systems for photophysical systems investigations, and he and his colleagues constructed some of the first of the then new category of excimer lasers (XeF, KrF) in Europe in 1976. His work in the field continued with research using ultraviolet and vacuum ultra violet lasers for photolytic laser fusion driver systems and studies on the photophysics of atomic and molecular systems. He joined City, University of London in 1983 after five years at Imperial College, London undertaking research in novel optical instrumentation, especially in fibre optic sensor development for physical and chemical sensing. The work has led into several fields including luminescence-based thermometry, Bragg grating-based strain sensor systems, white light interferometry, optical systems modelling and design, and optical sensors for water quality monitoring. The work has extensively been published in the major journals and presented at international conferences in the field, where regularly he has been an invited speaker. To date, he has authored more than 1000 Journal and Conference papers. Professor Grattan is a Fellow of the Royal Academy of Engineering in the UK currently is the Dean of the City Graduate School at City, University of London.