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Technique for embedding fiber optics in metallic structures for smart material applications

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Abstract

In this paper a technique to embed fiber optic sensors (FOS) to metallic structures is presented and validated opening possibilities to smart metallic structures. The technique is based in widely adopted and low cost TIG welding. A detailed procedure for scaling up is presented in which, Ni and Cu coated fiber optics at first, and Ni coated FBG sensors at last are embedded in Tin coated forged steel ST-52 with Tin alloy wire. Tensile and temperature tests show stable measurements with 1.3pm/με and 24pm/ºC sensibility in the embedded sensor in a metallic specimen for strain ranges from 0 to 550με and temperature ranges from 50 to 200ºC.

1 INTRODUCTION

Smart structures and materials are a promising technological solution since they allow online health monitoring. They consist in a structure with embedded sensors, which are minimally invasive, in many cases provided by micrometrical fiber optic sensors (FOS). Smart composite structures with embedded FOSs already set a precedent, proving to extend functionality and reliability of the structure since their safety and performance are increased by the provided accurate damage and lifecycle prediction. Embedding sensors in composite fabrication process is quite straightforward because the temperatures reached during the process do not damage the FOSs. Also placing the fiber is feasible: resin or concrete are easy to handle while in the liquid phase during infusion. This is not the case in metallic structures. On first place, the same as for smart composites, the sensing technology to be applied must be minimally invasive. However, in metal embedding, harsher conditions are present during the fabrication process. In this paper FOSs are chosen as the most promising technology for this application due to their small size, immunity to electromagnetic fields, and possibility to withstand harsh environments (<1200ºC) [1]. However, fiber optics can be very fragile at high temperatures, like the ones given by metal melting temperatures or welding techniques, which can be near or well above 1000ºC. Some solutions and techniques have already been proposed to embed FOS, mainly fiber Bragg gratings (FBGs), in metals. All these techniques have one point in common: metallic coatings are applied to FOS to withstand the embedding process [2]. Furthermore, metallic protective coatings' material and porosity affects the fiber bond to the metal in which is embedded, and are responsible for slippage or coat delamination [3]. The first proposed solutions, using deposition techniques, needed large metallic coatings (2mm) to protect the FOS, resulting in an invasive embedded sensor [4]. Ultrasonic welding is another solution, although the low temperature of the process limits the applications of the sensors [5]. Vacuum brazing techniques, which give limited flexibility to operate with the FOS, have also been proposed and validated although they are complex and expensive due to the need of vacuum chambers [6]. Finally, the advent of 3D printing of metallic parts using Selective Laser Melting (SLM), which is expensive and not very accessible, have shown some promising results for embedding FOS [3,7,8]. In this case very precise control of the manufacturing can be achieved, so the damage of the fiber can be minimized, allowing thin protective coatings of the fibers (350µm). Although the bond between fiber-coating-metal is not very good and slippage can happen [3], this technique is able to measure residual stresses during the manufacturing process or temperature isolated from strain [7,8].

In this paper we present a novel solution based on Tungsten Inert Gas (TIG) arc welding process. In TIG welding a non-consumable tungsten electrode is used to produce the weld. TIG welding is a simple and widely used technique, it can be performed with different types of wire materials, depending on the application, and is performed by a worker, as shown in Figure 1. For this paper we have chosen a Tin based wire (SnSb8Cu4), with a low melting temperature (220ºC), and forged steel ST52 with a thin Tin coat as the metal where the FOS, a FBG, will be embedded. Even if this melting temperature can be considered quite low, the process is still representative for other metallic materials, since during the welding process high temperatures are reached, around 800ºC. In TIG welding, the worker has the possibility to correct, stop or readapt the welding in case the FOS's integrity is in danger, unlike in SLM, vacuum brazing, deposition or ultrasonic embedding. Also TIG welding technique is low-cost when compared to other techniques for FOS embedding and the required equipment is widely available in the metal-mechanic industry.

Figure 1: TIG welding process.

Being TIG welding a simpler and lower cost technique, this paper presents a detailed procedure of the steps taken at each stage for feasible scaling up to obtain embedded sensors with good properties. Each section of the paper presents each of the steps taken. In first place preliminary tests with fiber optics for the optimization of the embedding process are presented in section 2. This preliminary tests were done in two different phases: 2.1) some preliminary tests to perform a coarse tuning of the process regarding welding power and metallic coating. 2.2) fine tuning to asses coated fiber thickness, embedded length and material. Finally, with the optimized values obtained coated FBGs were welded into actual metallic specimens to be characterized in tensile tests, in section 3. The conclusions of the paper are presented in section 4.

2 PRELIMINARY TESTS WITH OPTICAL FIBERS

2.1 Coarse tuning of embedding process

A red light fault detector was applied in the coated SMF28 fiber optic to monitor the effect of TIG-welding. So, it is easy to visually inspect the degradation of the fibers depending if light travel through the embedding or not. The tests were based on trial and error. Coatings in the range from 165µm to 1200µm of total diameter were tested for Cu and Cu+Ni. In the latest, commercially available Cu coated fiber (125µm diameter of fiber + 40µm of Cu (20µm radius); 165 µm total diameter) was electroplated with a thicker Ni layer [2]. Welding currents between 50A and 80A were tested. Figure 2 shows a successful test with 660µm total diameter Cu+Ni optical fiber embedded with 60A of welding current. A set of tests, presented in table 1, showed that currents over 60A damaged the fiber and coatings under 500µm could barely withstand the welding. Also, currents below 50A would end up in poor welding quality. Therefore, coatings near 500µm and currents of 60A were chosen for the following phase. It should be noted that the training acquired by the worker was of the essence for successful embedding. For example, it was noted the importance of applying the arch not directly on the coated fiber, but on a side. Cu coated fibers were also way more fragile than Cu+Ni, due to lower melting point compared to Ni. Tin alloy wire has some amount of Cu material but Ni does not, so we kept both materials for the next phase, in case there are substantial differences in the bonding of the two materials.

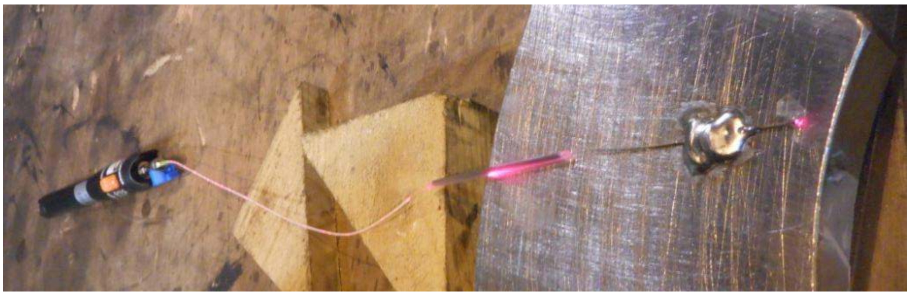
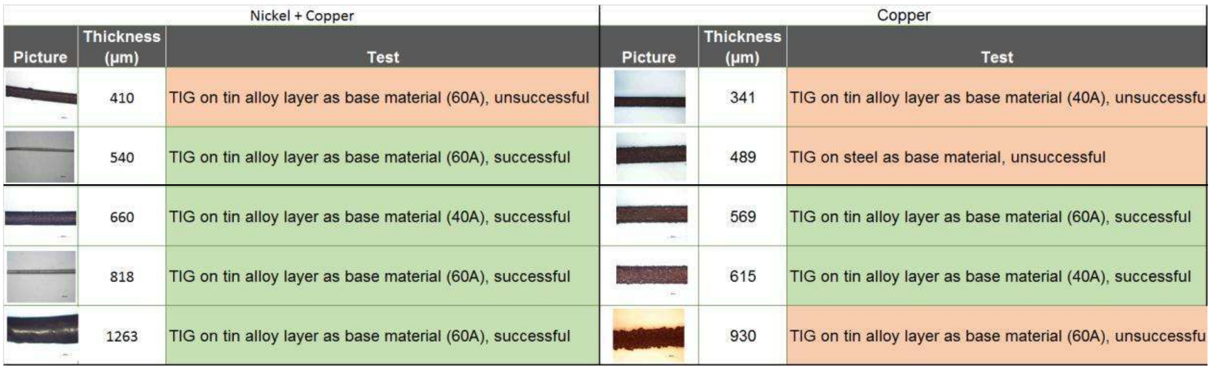


Figure 2: Photos of embedding tests for coarse tuning.



Nickel + Copper			Copper		
Picture	Thickness (µm)	Test	Picture	Thickness (µm)	Test
	410	TIG on tin alloy layer as base material (60A), unsuccessful		341	TIG on tin alloy layer as base material (40A), unsuccessfu
	540	TIG on tin alloy layer as base material (60A), successful		489	TIG on steel as base material, unsuccessful
	660	TIG on tin alloy layer as base material (40A), successful		569	TIG on tin alloy layer as base material (60A), successful
	818	TIG on tin alloy layer as base material (60A), successful		615	TIG on tin alloy layer as base material (40A), successful
	1263	TIG on tin alloy layer as base material (60A), successful		930	TIG on tin alloy layer as base material (60A), unsuccessfu

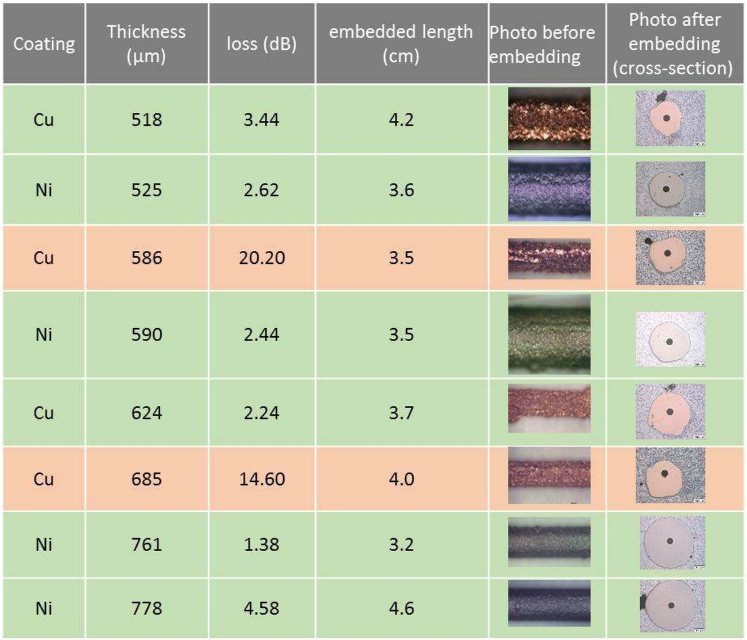
Table 1: Results of embedding tests.

2.2 Fine tuning of embedding process

In this section, eight optical fibers with Ni and Cu coatings where embedded in metal with TIG welding at 60A currents with Tin wire in Tin alloy coated forged steel ST52. The optical fibers were pre-strained for a uniform tension embedding. The thickness of the coatings was between 525µm and 778µm and the length of the embedded section was between 3cm and

4.6cm, as shown in Figure 3. The loss of each fiber was measured, and a photo of the cross-section to estimate the bonding of the fiber to the metal was also taken, as summarized in table 2. The loss obtained in all cases does not exceed 4.6dB but for the two cases depicted in orange in the table, where the fiber was clearly damaged. Note that the loss was not related to thickness or length of the embedded part of the fiber. Loss was attributed to microbending of the fiber during the process, which was subjected to small differences during the manual embedding process. Therefore, 500µm total diameter coated fibers (125µm fiber(SiO2) + 40µm(Cu)+335 µm(Ni)) withstand the process with acceptable loss at 60A welding current. The cross-section photo shows very good bonding of the coated fiber to the metal in both cases, Ni and Cu. In some cases, mainly in Cu coated fibers, small pores can be observed (the black dots in the limit between coat and embedding metal). So, Ni+Cu coated fibers show a better bond. Also it should be noted that for the Ni+Cu coated fibers, it is clear that the inner Cu layer (20µm) in contact with the fiber, does not interact in the welding and embedding process.

Figure 3: Example of embedding tests for fine tuning.



Coating	Thickness (µm)	loss (dB)	embedded length (cm)	Photo before embedding	Photo after embedding (cross-section)
Cu	518	3.44	4.2		
Ni	525	2.62	3.6		
Cu	586	20.20	3.5		
Ni	590	2.44	3.5		
Cu	624	2.24	3.7		
Cu	685	14.60	4.0		
Ni	761	1.38	3.2		
Ni	778	4.58	4.6		

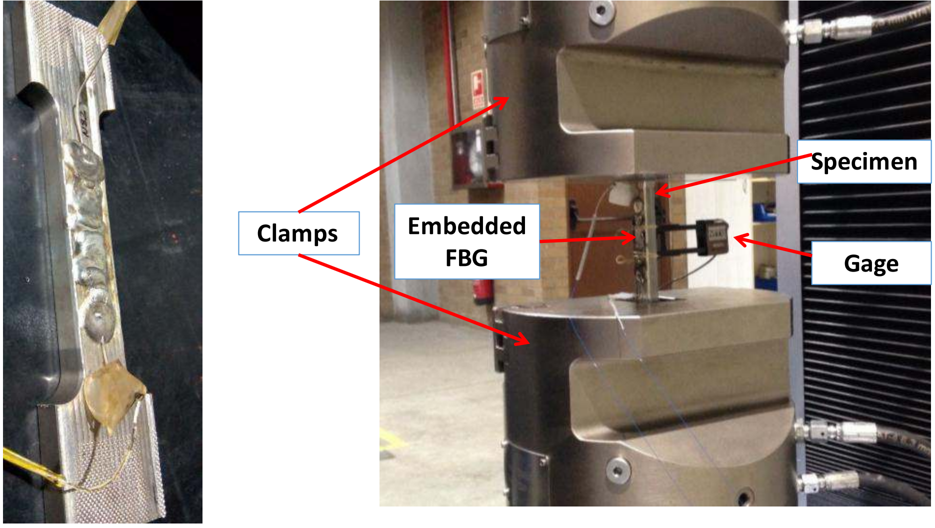
Table 2: Data obtained from different tests embedded in metal with TIG.

3 FBG SENSOR EMBEDDING IN METALLIC SPECIMENS

Now that the process has already been optimized, in this section actual fiber optic sensors, specifically FBGs, are embedded in metallic specimens. These specimens have been shaped and mechanized so tensile tests can be performed on them. In this case the fiber with the FBG is first coated with a thin film (1 µm) of Gold, before electroplating, since a conducting layer is needed on top of the SiO_2 of the fiber cladding. Ni was chosen as the protective coating, which in section 2.2 showed a better behavior regarding bonding. Therefore, fiber was electroplated with Ni for a total diameter of 619µm. The results in previous tests presented in section 2 are used for the parameters of TIG welding and embedding process: a 619µm Ni coated FBG is embedded with 60A welding current with Tin wire in Tin alloy coated forged steel ST52 specimens. Figure 4 (a) shows an FBG embedded in a specimen. Once the sensor is embedded, its response to strain is characterized in a tensile test.

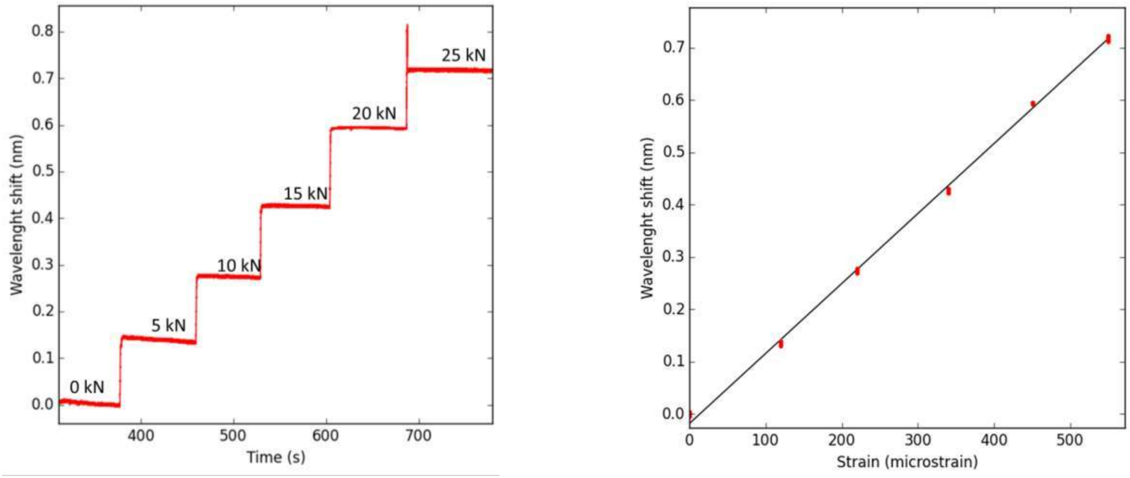
3.1 Strain characterization

Figure 4 (b)presents the setup for the tensile tests. The specimen is clamped in the tensile testing machine, where strong longitudinal force is applied gradually in 5KN steps, from 0KN to 25KN, which corresponded to strain range from 0µε to 550 µε. The temperature of the laboratory was constant during the tests to avoid cross-sensitivity between strain and temperature. A strain gage monitors the specimen's strain for control and characterization. So, wavelength shift and the measured strain from the gage are saved for each step. Figure 5 (a) shows the relationship between wavelength shift and load during the testing time. The good behavior of the sensor can be observed, since it is stable, without slippage. In Figure 5 (b), the response to strain is characterized, where a linear behavior is observed in the range from 0 to 550 µε. The sensibility of the sensor is 1.3pm/µε which is in good agreement with the usual FBG strain sensitivity, proving the validity of the embedding technique.



(a) (b)

Figure 4: (a) FBG embedded in metallic specimen (b) tensile test setup.



(a) (b)

Figure 5: (a) Response of the sensor to load during tensile test and (b) Strain characterization of the sensor.

3.2 Temperature characterization

The specimen with the embedded fiber was also introduced in a furnace, where the temperature was varied from 50ºC to 200ºC at 25ºC steps, while the wavelength shift of the FBG was saved for each step. Figure 6 presents the dependence of the wavelength shift of the embedded sensor to temperature. The sensitivity of the sensor is 24pm/ºC, which is in accordance with the Ni coated sensors sensitivity [9].

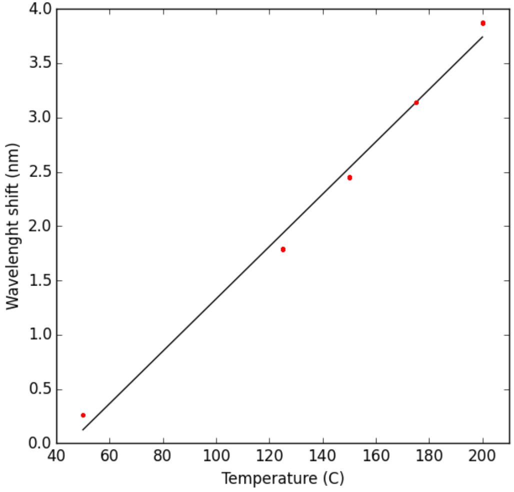


Figure 6: Temperature characterization of the sensor.

4 CONCLUSION

In this paper a technique for embedding FOS in metals has been successfully validated. The technique is based on TIG welding and allows SMART metal construction. Tin alloy wire in TIN coated forged steel ST52 was used. Adequate coating of the fiber has been demonstrated of the essence for successful fiber optic embedding. In this paper coatings of the order of 500µm (total) diameters, consisting of Ni and Cu have been proposed and demonstrated. Ni coatings showed better bonds, with less pores. Finally, a specimen with a 619µm (total) coated FBG has been fabricated and validated in strain and temperature characterization tests, showing a stable response and a sensitivity of 1.3pm/µε and 24pm/ºC in the range from 0µε to 550µε and 50ºC to 200ºC. TIG welding is a well-known low-cost and widely adopted technique in the metal-mechanic industry. So, this opens the possibility for widespread adoption of FOS embedding in metallic structures, since, the presented procedure could be extrapolated to develop FOS embedding techniques with other materials, wires, FOS and techniques.

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Figure 7: logos of supporting sponsors.

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