Integrating Fiber Fabry-Perot Cavity Sensor into 3-D Printed Metal Components for Extreme High-Temperature Monitoring Applications

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Integrating fibre Fabry-Perot cavity sensor in to 3D printed metal components for extreme high temperature monitoring applications

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Abstract—This paper reports methods of embedding into 3D printed metal components a fused silica capillary designed to accept an in-fibre Fabry-Perot cavity based extreme high temperature sensor. The components are manufactured in stainless steel (SS316) by additive manufacturing using selective laser melting (SLM). The temperature sensor consists of a standard single mode optical fibre with the F-P sensor located at the distal end of the fibre with the fibre being inserted into the capillary. The capillary is either directly embedded into the structure during the SLM build process or brazed into the structure in between the SLM build process and the advantages and disadvantages of these two manufacturing approaches are discussed. Temperature sensing of up to 1000°C inside the metal with accuracy better than ±10°C is reported. The capillary can be directly embedded in the component which needs to be monitored, or it can be embedded in a metal coupon which can be attached to a component by conventional welding technology, including the use of Laser Metal Deposition (LMD). In the case of LMD, the sensor coupon can also be fully encapsulated by over cladding the coupon.

Index Terms— Additive layer manufacturing, Fabry-Perot cavity, fibre optic sensor, selective laser melting, sensor packaging, smart metal, temperature sensor

I. INTRODUCTION

Condition monitoring of structural components and machinery at elevated temperatures is a critical issue for both economic and safety reasons. Many industrial applications require sensors for real-time process condition monitoring and asset management to ensure reliable operations. For example, monitoring stress corrosion cracking and spalling in high temperature steam systems, condition monitoring of risers and wellheads of oil and gas industry, monitoring thermal or mechanical load on blisks, blades, vanes and heat shields of turbines, etc. The ability to continually monitor component temperature has the prospect of allowing an operator to run a power plant at optimum elevated temperatures with extended maintenance intervals whilst avoiding unexpected shutdowns through continuous knowledge of component health. Sustained high temperature turbine operation leads towards power plant efficiency gains [1]. Operation at increased temperatures also enhances its efficiency, however higher temperatures increase issues with component life time, accelerating its wear and wear rate. Therefore, metal embedded high temperature sensors are gaining increasing importance in the energy industry.

Fibre optic sensors can operate safely in harsh and hazardous environments under the presence of electromagnetic fields, ionizing radiation and in areas with risks of explosion due to their all optical nature.

Many of the above applications require sensors that must be capable of sustained high temperature operation in excess of many hundreds of degrees, and hence fused silica optical fibre sensors are an obvious choice; the high strain point of 990-1100°C (depending on its water content) of fused silica [2] means that fibre optic sensors have the potential to operate at temperatures up to, or slightly in excess of, 1000°C. Fabry-Perot (F-P) type in-fibre optic sensors are a design concept which is suitable for temperature measurement in this range [3, 4]. We have shown in [3] that such F-P sensors have good long-term stability at high temperature (above 700°C) over extended periods of time.

Selective laser melting (SLM) is an additive manufacturing process that can be used for many different applications [5-9]. Additive manufacturing involves building up structures layer by layer and this opens up the prospect of incorporating valuable internal features or components into parts during their manufacture. Fused silica fibre can be directly embedded in to metallic components using this process, however the application temperature range is limited to 450°C.
due to the mismatch of the coefficient of thermal expansion and hence fibre detachment or breakage [10-14]. In order to circumvent this problem a fused silica capillary is embedded into the metal component to enable the installation of high temperature compatible F-P fibre sensors. The techniques used for embedding the capillary are direct embedding using SLM and a hybrid approach using brazing and SLM. Preliminary results were reported at the conference OFS24 [15]; here we present a significantly extended study including enhanced sensor packaging; sensor response to thermal cycling; analysis of the measurement repeatability; and stability at high temperature over extended periods of up to two months. It is also shown that the sensor coupon survives the high laser heat of Laser Metal Deposition (LMD) process such that it is possible to weld or attach such sensor configuration to other metallic parts by using LMD process.

In this work the temperature measurements are independent of the induced strain from the host metallic structure, therefore it is suitable only for temperature measurements. If strain measurement at high temperature is a key objective, then the solution explained in [16] can be used. Also, a combination of both these methods can be used to monitor temperature and strain simultaneously.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. F-P sensor

The sensor concept is shown schematically in Fig. 1. The in-fibre F-P sensor is formed between two reflections along a length of optical fibre. The first reflection point (M1) is an in-fibre reflective splice, using a thin layer of Chromium [3]. The fibre is cleaved at a distance of about 50-100 µm from the splice to form a low finesse optical cavity between the reflective splice and the Fresnel reflection (M2) at the fibre end. Details of the sensor fabrication and its temperature response are given in [3]. The typical cavity reflection spectrum of the sensor is shown in Fig. 2. In order to incorporate our sensor into engineering structures, and to avoid any strain transfer during temperature measurement, the fibre optic sensor is freely-floating inside a fused silica capillary.

B. Direct embedding of capillary using SLM

To manufacture the smart metallic test component, a fused silica capillary (Z-FSS-150240, Postnova, inner and outer diameters 150 µm and 240 µm respectively) of length ~150 mm is sealed at one end using an electric arc. Approximately 60 mm of the polyimide jacket (10 µm thick) is subsequently removed from the sealed end by dipping it in hot (200°C) sulphuric acid. A ~80 mm long metallic jacket is deposited on the capillary in order that it can be ‘welded’ into place using the SLM process without damaging the fibre. A silver (Ag) layer was first deposited using an electro-less deposition process [17-18]; a solution containing silver nitrate (Tollen’s reagent) and a reducing sugar (glucose) react to form Ag, which is deposited on the capillary. The Ag layer acts as the anode for a subsequent nickel (Ni) electroplating process in a Ni-sulphamate bath [10-11]. The thickness of the Ag and Ni layers of the jacket are 4±1 µm and 140±5 µm respectively. A Ni layer of this thickness is required to act as a thermal barrier during the SLM embedding process.

Fig. 1. Schematic structure of the F-P cavity. M1 is partial reflective Cr splice and M2 is cleaved end of fibre. Light is guided in the core region, and the outer fibre diameter is typically 125 µm. The sensor is interrogated from the lead in/out fibre on the right.

The basic approach to embedding is to use the SLM process to manufacture a ‘U’-shaped groove with dimensions tailored to the diameter (~500 µm) of the metalized capillary (see Fig. 3). The capillary is placed in the groove, and the build process of the part is continued to completion.

Fig. 2. Spectra recorded from the F-P cavity before (black) and after (red) inserting it inside the SLM sample

Fig. 3. Embedding process in three steps: (1) Building the ‘U’-shaped groove with SLM on SS 316 substrates, (2) Nickel coated capillary placed in the groove and (3) final encapsulation by continuing SLM process.
The surface of the U-groove was examined using a 3D surface profiling microscope Alicona IFM G4. The measured surface profile of a typical U-groove, together with an example cross section is shown in Fig. 4(a) and 4(b) respectively. The bottom surface of the U-Groove was measured to have a peak to peak roughness (Rz) of 9 µm. The edges of the SLM part are always slightly higher than the interiors with a Δz between 40-100 µm due to surface tension (Fig. 4. (c) and (d)). This can result in significant point like stress on the capillary at the ingress/egress point to the embedded structure [19] and it also prevents proper fitting of the capillary in to the groove. To avoid such problems, the U-groove is designed to be 200 µm wider and deeper towards the end of the structure. A 3D printed structure containing such an embedded sensor is shown in Fig. 5.

After the embedding process the other end of the capillary is cleaved using a fibre cleaving tool. The cleaved end is then heated using a small electric arc to slightly melt the sharp edges in order to prevent them from damaging the sensor fibre. A 125 µm diameter F-P sensor with a cavity length of ~70 µm and the fibre jacket removed over a length of 150 mm is inserted into the capillary. A sufficient gap (10 mm) is maintained between the sensor and the end of the capillary to avoid back reflection coupling into the fibre. The capillary-fibre interface is sealed using a 40 mm long fibre splice protector to encapsulate the capillary-fibre interface. This also provides vibration damping and an environmental seal, protecting the fibre/capillary from damage and contaminants. A schematic diagram of the F-P sensor inside metalized capillary is shown in Fig. 6. The F-P spectra were identical before and after embedding (Fig. 2) implying that no transmission loss has been introduced during the embedding process. It is worthwhile to mention here that the capillary to fibre sealing used in this work should remain outside the high temperature process environment for its stable operation. This is possible by increasing the length of capillary as required. Another possible solution is to use a high temperature compatible adhesive, e.g. a mix of water glass and glass frits, to seal the capillary to fibre interface, perhaps over coated with metal.

The cross-sectional image of the direct embedded sensor test component is shown in Fig. 7. Although well-attached at the top, this approach tends to result in voids below the capillary as shown, which could weaken the part. An alternative approach using a brazing process was therefore developed, as described below.
C. Embedding capillary using brazing technique and SLM

In order to minimize any gaps around the capillary high temperature brazing in a vacuum furnace was used. Initially a SS316 U-groove was built using a commercial SLM machine as explained in [20]. The U-groove made (SLM1 part) is identical to the one described above, built using the custom SLM system (Fig. 3). Ridges are created on top of SLM1 part (see Fig. 8) at either side of the U-groove to prevent brazing material from flowing out of the cavity during brazing process. These ridges are cut down to restart the SLM2 (see Fig. 8) process. To remove potential surface contamination and entrapped gases, the SLM part is degassed in vacuum at 1025°C for 10 min prior to brazing.

This method was tested with a metallized capillary of diameter 315±5 µm and a Ni-Cr-Si-B-Fe filler metal powder (Amdry 770, Oerlikon Metco, solidus temperature 971°C, liquidus temperature 999°C) in the form of a paste produced by mixing the alloy powder with a cellulose nitride-based binder [21]. The smaller metallic jacket used in this method is because additional brazing material layer will be deposited on top of it before the SLM process. To remove volatile solvents and to temporarily fix the capillary in the groove the entire setup was dried at 100°C for 1 hour in air. Finally, the capillary was vacuum brazed to the coupon at 1000°C for 10 min. The temperature was controlled using thermocouples placed in the heating zone next to the metal coupon. Upon melting, the braze alloy wets the fibre Ni metallization layer as well as the walls and bottom of the groove thereby embedding the capillary into the material and providing a sound bond. The top SLM layers (SLM2 in Fig. 8) of the part are also built on top of the brazed coupon after placing the coupon back into the SLM machine and restarting the build process. A cross sectional analysis of the brazed sample is shown in Fig. 8.

Even though the capillary was broken for this sample, the results shows great reduction in the gap underneath the embedded capillary. The remaining small void may be formed either by shrinkage upon melting of the loosely packed powder, outward diffusion of Si and/or B into the steel coupon or due to the incorporation of a cavity upon placement of the capillary and paste in the first place. It is also visible that the top part of the capillary is damaged during the second SLM process. This might be avoided by increasing the depth of the U-groove and bringing the capillary further down in the U-groove such that there is sufficient thickness of brazed alloy to overcome the thermal load of the SLM process. It is also possible to overcome this damage by increasing the thickness of the metallic jacket around the capillary.

D. Attaching the sensor test component to functional components using LMD process

In order to demonstrate the feasibility of attaching the sensor configuration to a real functional component (e.g: blisks, blades or heat shields of turbines) a laser metal deposition (LMD) process was applied. LMD uses a laser beam to form a melt pool on a metallic substrate, into which powder is fed. The powder melts to form a deposit that is
fusion bonded to the underlying substrate. The required geometry is built up layer by layer. Both the laser and nozzle, from which the powder is delivered, are manipulated using a gantry system. A fibre embedded within an SLM build coupon was bonded to the surface, or incorporated into the bulk geometry of a component using LMD. The SLM encapsulation of the sensor configuration gives additional protection from the high thermal load of the LMD process.

LMD work was carried out using a Trumpf DMD505 laser deposition system. The process parameters used were laser power 750 W, spot size 1.2 mm, scanning velocity of 400 mm per minute and with a standoff focal distance of 7 mm. The feed rate of metal powder, carrier gas and argon shielding were 1.75 g per minute, 3 liters per minute and 3 liters per minute respectively. An image of the LMD embedded SLM test component and a schematic of its cross section are shown in Fig. 9. A high temperature F-P fiber sensor (see II.A) was inserted into the LMD embedded SLM test component. In order to avoid the droplet like material deposited at the corners of SLM sensor coupon to SS316 base component interface (see Fig 9(a)) and hence to improve the quality of the welding process an alternate welding procedure is used as shown in Fig. 10 (a) and (b). In Fig.10 only the lower part of the two sides of the sensor test component is welded to a turbine heat shield element of General electric (GE) using the LMD process. Spectra of the F-P sensor before and after integrating inside the LMD embedded SLM test component were identical, demonstrates that the silica capillary and the SLM test component survived the laser heat during the LMD process. Sensors integrated by this method were tested to monitor in-process high temperature.

E. Temperature testing results

Thermal cycling of the sensor test component was carried out in a tube furnace (Carbolite). The reflected spectrum was recorded using a swept wavelength interrogator (sm125, Micron Optics, 1510-1590nm, 5pm step, 1Hz) and analyzed in LabVIEW software [3]. Extraction of the sensor temperature involves multiple stages of data manipulation, including non-linear least square fitting of a sinusoidal function to the spectral data [3, 22]. The fundamental frequency of the spectra and the phase shift of the sinusoidal fitting were extracted from this data while the furnace temperature was varied. An N-type thermocouple attached to the metallic coupon, 2 mm away from the F-P sensor provided an independent measurement of temperature using a PREMA 3040 precision thermometer.

Thermal cycling of the embedded sensor was carried out with an initial cycle from ~30°C to 200°C and back to ~30°C. After each cycle the upper temperature of the next cycle was increased by 100°C until it reached 900°C following which the step increment was reduced to 50°C. The heating and cooling rates were set to 3°C/minute and 2°C/minute respectively. The sensor was kept at each upper temperature for approximately 20 minutes before the cooling process started to ensure thermal equilibrium and monitor drift. The...
temperature calibration curve obtained during the cycling process is given in Fig. 11. A second order polynomial fits well to the calibration curve as shown in Fig. 11. The non-linear response of the sensor is due to the nonlinearity of the thermo-optic coefficient of fibre material SiO$_2$ [23].

Fig. 11. Temperature response of the embedded sensor and a second order polynomial fit to the temperature calibration curve of the sensor.

The calculated repeatability of the temperature cycling up to 950°C is ±9°C (see Fig. 12). Further studies are required to understand the variations in run-to-run, which shows a kind of periodic nature in Fig 12. The observed good repeatability during several initial thermal cycles is better than our previous observation where the sensors showed some drift. The reduced drift here is due to the sensor sitting inside a sealed silica capillary which isolates it from external environmental and mechanical influences. Sensor drift was ~25°C after cycling to 1000°C. The measured temperature sensitivity of the sensor at 400°C is ~7.7 mrad/°C which corresponds to a temperature resolution of 3°C for the sensor interrogation system used with a measurement speed of 0.5 Hz, including the signal processing time. Sensors with different cavity lengths were manufactured and tested, and results are as shown in Fig. 13, the similar sensitivity of the packaged sensor in the metal compared to the sensitivity curve of free sensors given in Fig. 13 demonstrates that the embedded sensor is well isolated from any external strain influences. The very smooth (typically 0.1-0.2 nm rms roughness) inside walls of the capillary avoids any frictional force on the sensor making it strain free. The embedded capillary, meanwhile is under compression that prevents its damage due to CTE mismatch during the thermal cycling process.

Detailed studies of the long-term stability of the F-P sensors are reported in [3] demonstrating long term stability of ~10°C over 300 hours. The long-term stability of the embedded sensor at 1000°C given in Fig. 14 shows that drift of the embedded sensor is in accordance with the stability results given in [3]. After 10 hours at 1000°C, the temperature is increased to 1050°C but then the sensor starts showing some random response because of the breakage of Ni jacket and the capillary ~25 mm away from its SLM ingress/egress point. Considering the stability of the Ni jacket above 1000°C, the strain point of fused silica (around 1000°C) and melting temperature of the Ag coating (962°C), it is worth mentioning here that for any critical applications this sensor configuration is not recommended for use above 950°C.

Fig. 12. Repeatability of sensor response inside the metal and during the temperature cycling experiments. (a) For thermocouple temperature of 50°C and (b) for temperature of 400°C. (NB: star marks of the temperature values are overlapped by the dots of phase values)

Fig. 13. Theoretical and experimental values of sensitivity of F-P sensors as a function of cavity length.
The cross-sectional image of the embedded sensor test component were taken after the temperature cycling experiments shown in Fig. 7. The test component was subject to over 1000°C for ~50 hours. It is clear from the picture that the silica capillary is not damaged due to the CTE mismatch of the host metal. Cracks in the Ni jacket are visible in Fig. 7, which we believe is due to the Phosphorous content [14] entered in it from the Ni-Sulphamorous bath during its deposition.

![Image 1](image1)

**Fig. 14.** Stability of the embedded sensor at 1000°C. Apparent temperature drift given in right side of the plot is also from the sensor.

The LMD embedded SLM test component with integrated F-P sensor was also temperature tested by heating it from room temperature (20°C) to 800°C with a heating rate of 2°C/minute. It was then maintained at this temperature for ~1500 hours (Fig. 15). The sensor showed small levels of drift over time which was assumed to be due to the annealing effects and dopant diffusion. The sensor spectra also showed a small phase change (inset of Fig. 15). Additionally, a reduction in the peak to peak amplitude of the sensor signal was observed (inset of Fig. 15) over time. This did not affect performance for temperature sensing because of the particular signal analysis routine used to extract phase information of the signal. The total temperature drift of the sensor over the 1500 hours at 800°C was approximately 50°C. This drift is mainly because of the initial annealing of the fibre during heating, once at sufficient time at high temperature the stability is much better as explained in [3]. These results show the possibility of attaching an SLM test component to any functional surfaces of a component by LMD for real time structural health monitoring.

![Image 2](image2)

**Fig. 15.** Temperature response of the F-P sensor inside LMD embedded SLM test component. (Inset) Spectra of the sensor after 4 hours at 800°C and 61 days at 800°C

III. CONCLUSIONS

In conclusion, a robust method to strain isolate and integrate an in-fibre F-P cavity based high temperature sensor in to SLM built metallic components is described. The sensor consists of an optical fibre end and a reflective splice to form the optical cavity. Silica capillary encapsulation isolates the sensor from any external mechanical influences and prevents fibre breakage due to CTE mismatch while sensing inside structures. Additive manufacturing via SLM is used to embed a metal-coated capillary into metallic structures and the sensor is inserted into the capillary and sealed to permit in-situ temperature monitoring at highly elevated temperatures. The metallic jacket provides thermal shield and protects the capillary or sensor during the SLM process. The repeatability and then the accuracy of the embedded sensor are found to be better than ±10°C for thermal cycling. Compared to direct embedding the brazing method reduces the gap underneath the embedded capillary. The results reported in this paper demonstrate the feasibility to monitor temperature up to 1000°C inside 3D printed metallic components. The sensor packaging technique demonstrated is useful for protecting fibre optic sensors during the embedded sensing application in high temperature environments. The feasibility of attaching the packaged sensor configuration to functional metallic components using the laser metal deposition process is also demonstrated in this paper.

Compared to previously reported metal embedded fibre optic temperature sensors by other authors [10-14] the smart metals demonstrated in this paper have twice upper temperature range of operation. The feasibility of incorporating embedded intelligence into the components of power generation industry exposed to very high operational temperatures for their process optimization has also been demonstrated by a SLM-LMD hybrid process. 3D printing is believed to be the manufacturing technology of the future. This paper has demonstrated methods to integrate optical fibre sensors into 3D printed components giving them functionality.

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