Embedding fibre optical sensors into SLM parts

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Abstract

Selective Laser Melting (SLM) facilitates the integration of additional functionalities such as
sensors into metallic parts. Such sensors can for example be embedded in sections of the parts
non accessible after manufacturing. Additionally they can be positioned close to the region of
interest. Depending on the type of sensor it is even possible to monitor the structural health of
the part itself. This paper discusses the integration of fibre optical sensors into SLM
manufactured coupons in a commercial, industry scale, SLM machine. Such systems have
merely limited accessibility for fibre handling. The embedment procedure as well as the
corresponding bonding quality is explained in detail. Measurement results of the embedded
sensor and limitations for the embedding procedure related to the use of commercial SLM
systems are presented. Additionally the need for further research is pointed out.

Keywords: Fibre optical sensors, Embedding, Production environment, Commercial SLM
system, Selective Laser Melting (SLM)

Introduction

Selective Laser Melting (SLM) is an additive manufacturing (AM) technology that currently
receives significant attention in the global production industry since it offers entirely new
possibilities and strategies for the manufacturing of functional metallic parts. The prime
benefits utilised are the option to produce highly complex internal and external geometries
and the possibility to design a part based on its core functional purposes, not on the
restrictions and limitations of the traditional manufacturing technologies. This results in SLM
parts typically exhibiting complex design features, bionic inspired shapes or topology
optimized lightweight structures that are of enormous interest for various industrial sectors
like medical engineering and aerospace. Another branch that starts exploiting the advantages
that AM, and SLM in particular, have to offer, is the power generation industry since SLM
facilitates not merely the manufacturing of high temperature loaded parts but also the
integration of functional elements like sensors into these work pieces. Thereby the sensors can
be placed in the immediate vicinity of the critical locations to be monitored. Thus the users of
power generation units get a more detailed monitoring and consequently a more
comprehensive understanding of the conditions within their systems, particularly during
operation. The most promising variables to monitor the status of a system or a single work
piece are temperature and strain. Knowledge of both parameters are essential to determine
structural health and ageing conditions which are of crucial importance for a safe operation
mode of highly dynamically and thermally loaded parts.

A class of sensors that is well suited for measurements in high temperature applications are
optical fibre sensors of similar or identical type widely used in telecommunications such as a

Corning SMF-28 fibre. There is a multitude of fibre sensor configurations available for a wide range of parameters with temperature and strain sensors being the most widely used as described by different authors, like Grattan [1], Majumder [2] and Li [3]. While Kashyap [4] explains that the sensing element can be for example a UV laser inscribed fibre Bragg grating which is a localised optical strain and temperature sensor, Islam [5] and Mathew [6] report on a Fabry-Perot type structure integrated into the fibre. Furthermore Srinivasan and Venkitesh specify in their book chapter [7] the usage of the fibre itself as a sensing element in which case the whole length of a fibre is the sensor and distributed temperature and strain date can be recorded along the fibre with high spatial resolution. Such fibre sensors are typically manufactured from fused silica material, which has a melting temperature of ~1720 °C and a strain point of typically 980 to 1050 °C. Hence, provided such fibres are handled and protected in an appropriate way they will survive a laser induced melt pool in a typical stainless steel material such as SS316 during a SLM process.

Significant benefits of fibre sensors are their small size – typically 125 µm diameter – no electrical power requirements at the point of measurement, immunity to electromagnetic fields to name but a few. Fibre optic sensors employed in the project described here are based on wavelength encoded measurands which can be transmitted without loss of fidelity over long lengths of fibre. If strain monitoring from within a structural component is required, Havermann [8] explains that the fibre requires to be bonded tightly to the component in order to transfer the component strain into the fibre, conversely, if temperature monitoring is required, there should be no strain transfer to the fibre as shown by Mathew [9]. Hence the exact mechanism and functionality determines the embedment strategy employed. In common with virtually all sensor technologies, fibre optic sensors are sensitive to temperature and to strain. This cross sensitivity has to be taken into account, thus – according to the patent of Willsch et al. [10] – a strain sensor needs in most cases to be accompanied by a temperature sensor.

The research presented in this paper deals with the embedding of optical fibres into 316 stainless steel coupons during the SLM manufacturing process on a commercially available machine. The procedure for the fibre integration is presented in detail focussing on the aim to achieve an appropriate bonding quality for sensing applications.

State of the Art

The integration of external elements into metallic parts during the manufacturing process has already been conducted by different research groups. The embedment of optical fibres is of particular interest since fibres facilitate the simultaneous measurement of two different values – temperature and strain – and induce merely tiny flaws or defects into the work piece due to their small cross sectional dimensions. Sandlin et al. [11, 12] successfully embedded fibre Bragg gratings (FBG) in demonstrator parts of Inconel 600 using a vacuum brazing process. Despite the different thermal expansion coefficients between Inconel 600 and the fibre material promising results regarding temperature and strain measurements have been achieved. Kong and Soar [13] as well as Mou [14] and Norfolk [15] demonstrated that ultrasonic additive manufacturing (UAM) is another technology that facilitates the embedment of optical fibres in aluminium parts. In addition to the embedding procedure Schomer [16] reports in detail on the characterization of embedded optical fibres and thus shows the potential of integrated sensing elements and the feasibility of the UAM process to do so.

Li [17] has shown in his dissertation for the first time that fibre embedment into metallic parts is feasible in powder based layered manufacturing. This approach was based on a hybrid manufacturing process with alternating additive – laser metal deposition (LMD) – and

subtractive process steps. The results achieved by Li for the LMD technology inspired various researchers to think about fibre embedding during different other manufacturing processes. Recently this led to a significant increase in the number of research activities and publications dealing with integration of optical fibres in metallic parts during the SLM process. Maier [18] reports the first steps in the direct integration of metallic jacketed fibres into stainless steel coupons on a SLM test setup. In another paper [19] Maier emphasizes the aspect of developing optical fibres as sensors that are capable to survive the thermal loads during the direct SLM embedding process. Havermann [8, 20] focusses on the description of an embedment strategy for optical fibres into stainless steel coupons on a SLM test setup. Furthermore he analyses the influences of various process parameters on the embedment procedure and the corresponding bonding qualities. In [21] Havermann shows promising results of strain measurements of integrated fibres. He even took these results a step further and applied the embedded fibres to measure the residual stresses in the SLM manufactured components themselves which allows a deeper insight into the SLM process and its characteristics [22]. Mathew conducted research on that topic as well, thereby focussing on the embedment of sensors for high temperature measurements up to 1000 °C [6]. All activities mentioned so far clearly reveal two challenges that need to be tackled by further experiment and investigations: all embedment trials have been conducted on a SLM test setup which allows the modification of many parameters and additionally offers excellent accessibility to the SLM process chamber which facilitates ease of handling of the fibres to be embedded and opportunities to tack down and hold in position. Whereas in commercial, industry scale, SLM system access is severely restricted, process interruptions are difficult to implement and fibre handling is awkward. The second issue is that the unidirectional application of the laser power results in a lack of bonding of the underside of the fibre. Although strain tests have shown that a single sided bonding is sufficient for 100% strain transfer, the remaining gap below the fibre is an issue which needs to be solved.

Focus of the present study

The research presented in this paper tackles the challenges described in the state of the art and thus focusses explicitly on fibre embedding on a commercially available SLM machine that leads to limitations and restrictions particularly with respect to accessibility compared to trials conducted on a SLM test setup. Additionally the potential parameter modifications are considerably more restricted in a commercial SLM machine.

Experimental Procedure

Preparation of the fibres

In order to ruggedise conventional optical fibres against the thermal processes of laser melting of high melt temperature metal powders surrounding the fibre, it requires to be protected by a thermal barrier in order to absorb the huge energy input of the laser during the SLM process and to provide a bonding layer between the fused silica fibre and the host material. The preparation of the optical fibres prior to the embedment procedure is currently a labour-intensive manual process that is of decisive importance for the subsequent process steps, however future automation should be able to address this issue. A cross section of the metallised fibre, showing the various layers that are vapour-deposited onto the silica core, is schematically illustrated in Fig. 1. The nickel coating facilitates an appropriate metallic bonding between the fibre and the surrounding coupon and acts as a thermal sink. The very thin chromium layer (<1 µm) acts as a keying layer between the fused silica and the electroplated Ni coating.
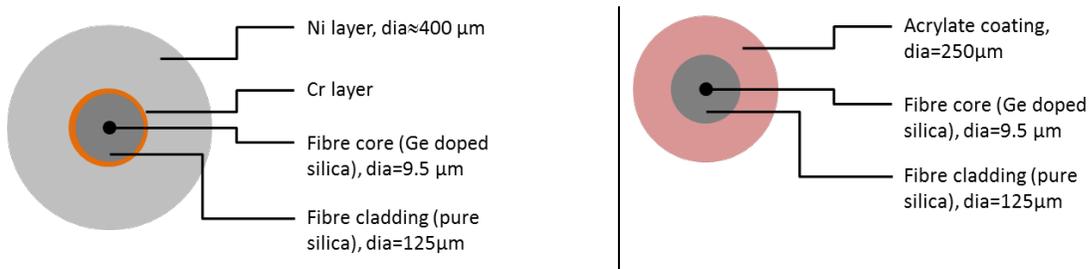
Fig. 1: Cross section of coated optical fibre; left: metallic jacketed part of fibre; right: acrylate coated part of fibre

SLM setup and embedding procedure

The experiments have been conducted on a Concept Laser M1 SLM machine with a process chamber of 160 x 230 mm. These dimensions lead to restricted accessibility to the manufacturing zone and limit the handling space, particularly for bending the fibres which however is inevitable since the SLM process requires a horizontal surface for the powder supply.

In Fig. 2 the entire embedding process is illustrated in an exploded assembly drawing showing the single steps that need to be executed. The coupon that is equipped with an optical fibre is produced in 316 stainless steel and has a bounding box of 24 x 9 x 9 mm. Preliminary tests revealed that the cavity into which the fibre is mounted ideally has an elliptic shape with the semi-axes a = 570 µm and b = 200 µm (Fig. 3), if the outer diameter of the metallised fibre is 400 µm. The depth of the cavity – represented by semi-minor axis b – is of particular significance since it determines the thickness of powder that has to be molten after applying a new powder layer onto the tensioned fibre. If this layer is too thick – i.e. distance x in Fig. 3 is too large – sufficient bonding to the already consolidated material of the coupon cannot be guaranteed.
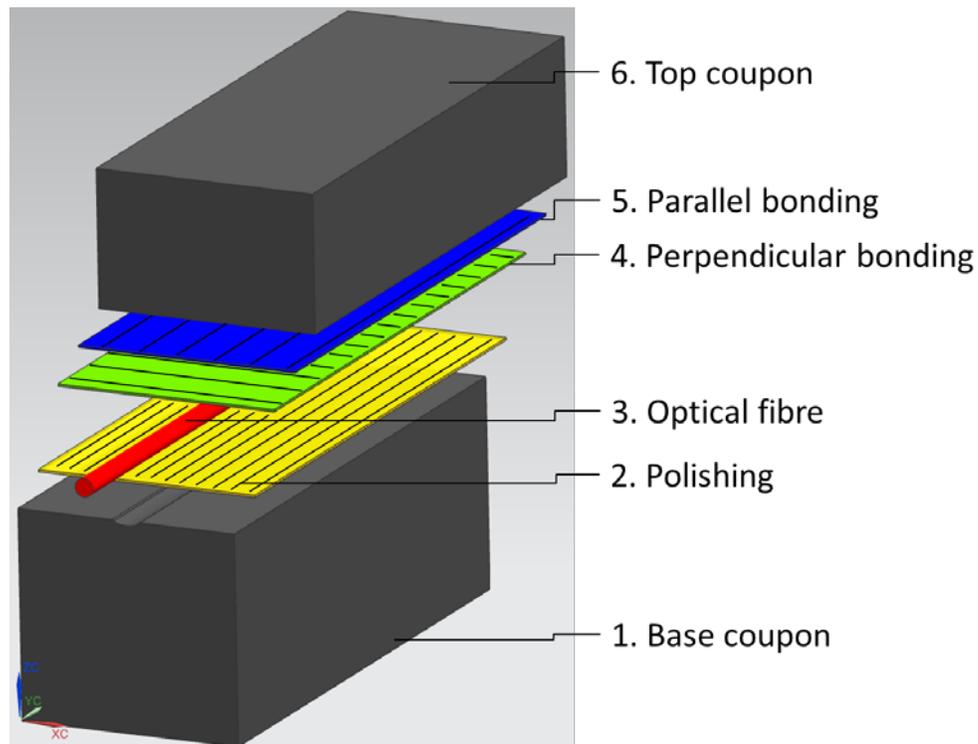
Fig. 2: Embedding procedure, exploded assembly drawing
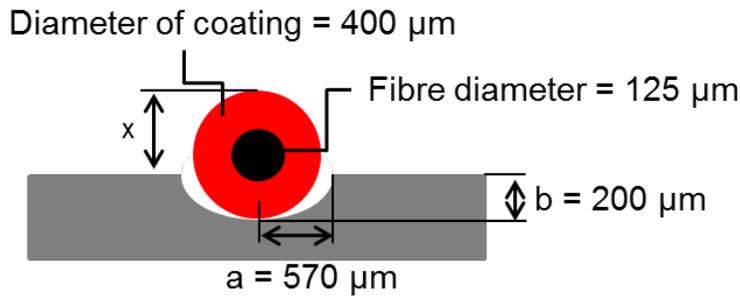
Fig. 3: Form of cavity: elliptic shape with semi-axis a and b; metallised fibre located in cavity

Further preliminary tests indicated a positive effect on the surface roughness within the cavity if the top layer of the cavity is scanned a second time after its manufacturing applying a specific scan strategy reported by Yasa [23]. This effect of polishing the surface of the cavity is based on sufficient remelting and is realised with a small hatch distance in combination with low scan speed. The scan tracks are schematically illustrated in Fig. 2 and run parallel to the axis of the cavity, i.e. in the direction the fibre will be embedded. Fig. 4 shows a qualitative comparison between the surface roughness of an as-built by SLM and an additionally laser polished cavity. The latter enhances the chances to achieve a decent bonding between the embedded fibre and the surrounding coupon, particularly on the underside of the fibre.
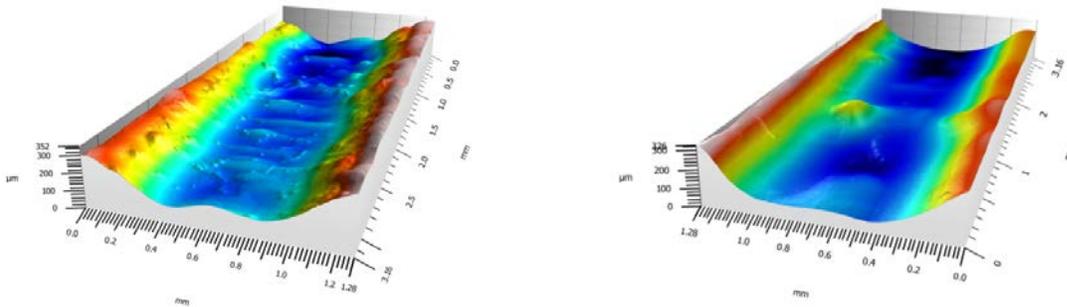
Fig. 4: Effect of laser polishing on the surface roughness within the elliptic cavity measured with GelSight; left: unpolished, as built by SLM surface; right: laser polished surface, one additional scan with vectors parallel to axis of cavity.

Tensioning of fibre

The next steps in the embedding procedure are the tensioning of the fibre and the bonding by a specific scanning strategy. Since the most fundamental aspect is so assure that the fibre survives the interaction with the laser, the scan strategy has been developed prior to the tensioning concept. Several different strategies have been tested using a nickel wire as a substitute for the optical fibres. All strategies first focussed on a fixation of the wire by spot-welding which is followed by the creation of a bonding layer in a second step. Fig. 5 illustrates a wobbling scan strategy to fuse the wire locally to the coupon and continue the SLM process on top of that layer. Although the fixation step proved successful, the further SLM build-up was not capable to properly fill the space between the wobbling scan tracks which resulted in voids and insufficient bonding between the first and the second part of the coupon. Based on that observation a bonding strategy that scans the entire coupon surface has been tested, eliminating the spot-wise scanning process step. The strategy that has been developed is divided into two scanning patterns that are shown in Fig. 6 as well as in Fig. 2,

named 4. perpendicular bonding and 5. parallel bonding. In the first step the scan tracks run perpendicular to the axis of the wire, in the second step parallel to it. Fig. 6 also demonstrates the way the wires are clamped on either side of the coupon – fixed clamping on one side and auto-adapting tensioning mechanism on the other. For the first scanning process the start point of the laser is of decisive importance to profit of the fibre mounting: it has to start at the fixed bearing and continue to the loose one enabling the wire to expand along the cavity but not to bend out of it in a consequence of the high energy input. The thermal extension would cause the wire to bend out of the cavity if it was fix clamped on either side. A test has shown that the optical fibre behaves exactly in the same way (Fig. 7).
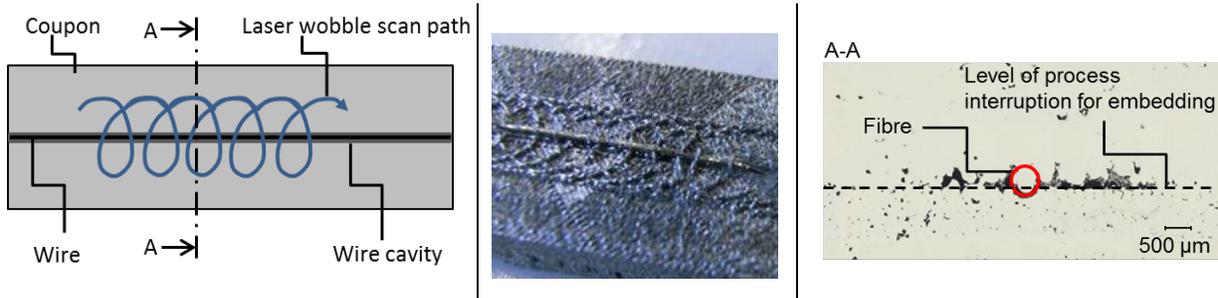
Fig. 5: Wobbling scan strategy; left: schematically illustrated scan strategy; middle: fixed wire by wobbling scan strategy; right: cross sectional image showing insufficient bonding between the two parts of the coupon.
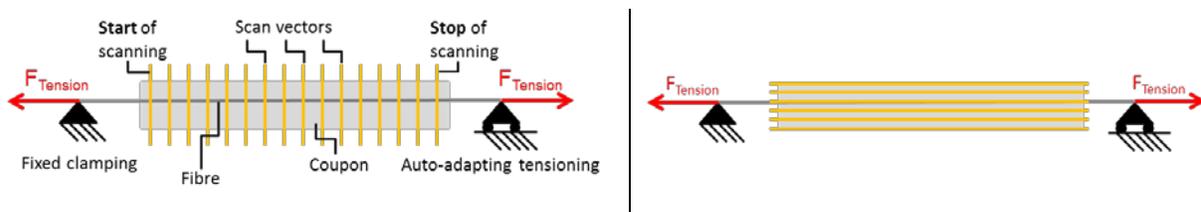
Fig. 6: Bonding scan strategy; left: 1ˢᵗ step – scan vectors perpendicular to axis of wire. Start at fixed clamping;   right: 2ⁿᵈ step – scan vectors parallel to axis of wire.
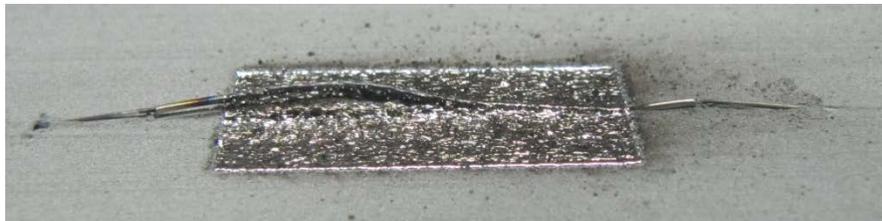
Fig. 7: Fibre fix clamped on both sides bending out of cavity due to induced heat of SLM process.

The precedent section has explained the importance of tensioning the fibre on one side. This is not trivial since the silica fibres are very brittle, particularly in the transition zone between the metallised and the acrylate coated sections. Furthermore the SLM process requires a cleared horizontal surface for the recoating step which implies that the fibre has to be bent out of the processing plane. Although the bending radius of the fibre has been chosen as large as possible in compliance with the restricted space for handling due to the process chamber of the SLM machine, i.e. 14.2 mm, the bending generates an additional load on the brittle fibres that has to be taken care of in the process parameters. The mounting of the fibre has been realised with a cross bar and screws for the fixed clamping, while a spring provides a preload on the fibre and keeps the fibre tensioned during its expansion as a consequence of the laser energy input. Fig. 8 visualises the tensioning of the fibre.
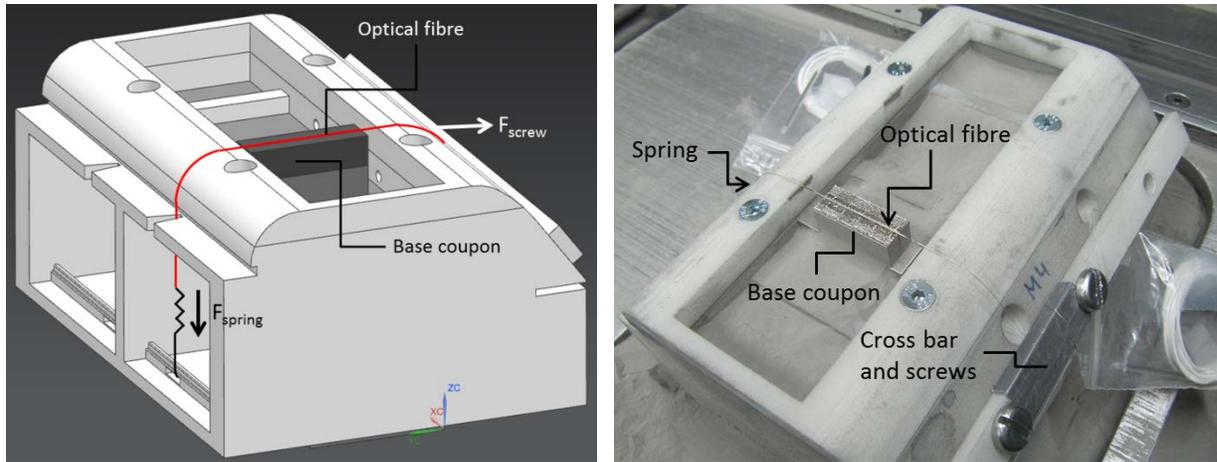
Fig. 8: Tensioning of optical fibre; left: mounting device and forces shown schematically; right: practical realisation of scheme shown left.

Table 1 lists the process parameters applied in the successful embedding. In the following sections these values will be discussed based on embedment and bonding results.

Results and Discussion

Table 1: Embedding Parameters *(the numbers in the first column refer to the numbers in Fig. 2)*

	Process Step	Area Energy Density	Remarks
1.	Build-up of coupon	2.4 J/mm^2	- Standard parameter for 316 stainless steel - Islands strategy (5 x 5 mm)
2.	Laser polishing of cavity	25 J/mm^2	- 1 layer - No islands, scan vectors parallel to axis of cavity
3.	Tensioning of fibre	--	- Fix clamping: cross bar and screws - Loose clamping: spring
4.	Perpendicular bonding of fibre (90° to fibre axis)	7.3 J/mm^2	After positioning of fibre: application of 1. powder layer before scanning - 1. layer: 50 µm; scanned 2x - 2.+3. layer: 30 µm; each scanned 1x - No islands, scan vectors orthogonal to axis of cavity
5.	Parallel bonding of fibre (0° to fibre axis)	7.3 J/mm^2	Application of 1. powder layer before scanning - 3 layers: 30 µm each - No islands, scan vectors parallel to axis of cavity
6.	Further build-up of coupon	2.4 J/mm^2	- 1. layer: 20 µm; scanned 1x - Standard parameter for 316 stainless steel - Islands strategy (5 x 5 mm)

Bonding quality

The bonding quality is analysed based on microscopic analysis of cross sectional images taken at different locations within the coupon. Since this requires a destruction of the embedded fibre, the evaluation of the bonding as shown in Fig. 9 has merely been performed on embedded nickel wire. The images clearly show two important results. While the bonding on the upper side of the wire has been realised without any pores or voids, there are still some issues regarding the bonding on the wire's underside. However, these flaws don't show a specific pattern – e.g. good bonding on one side of coupon, poor bonding on the other – which allows the conclusion that no systematic error is present. Consequently the embedment strategy can further be elaborated based on these results. However the bonding achieved would already be of satisfactory quality for temperature measurements.
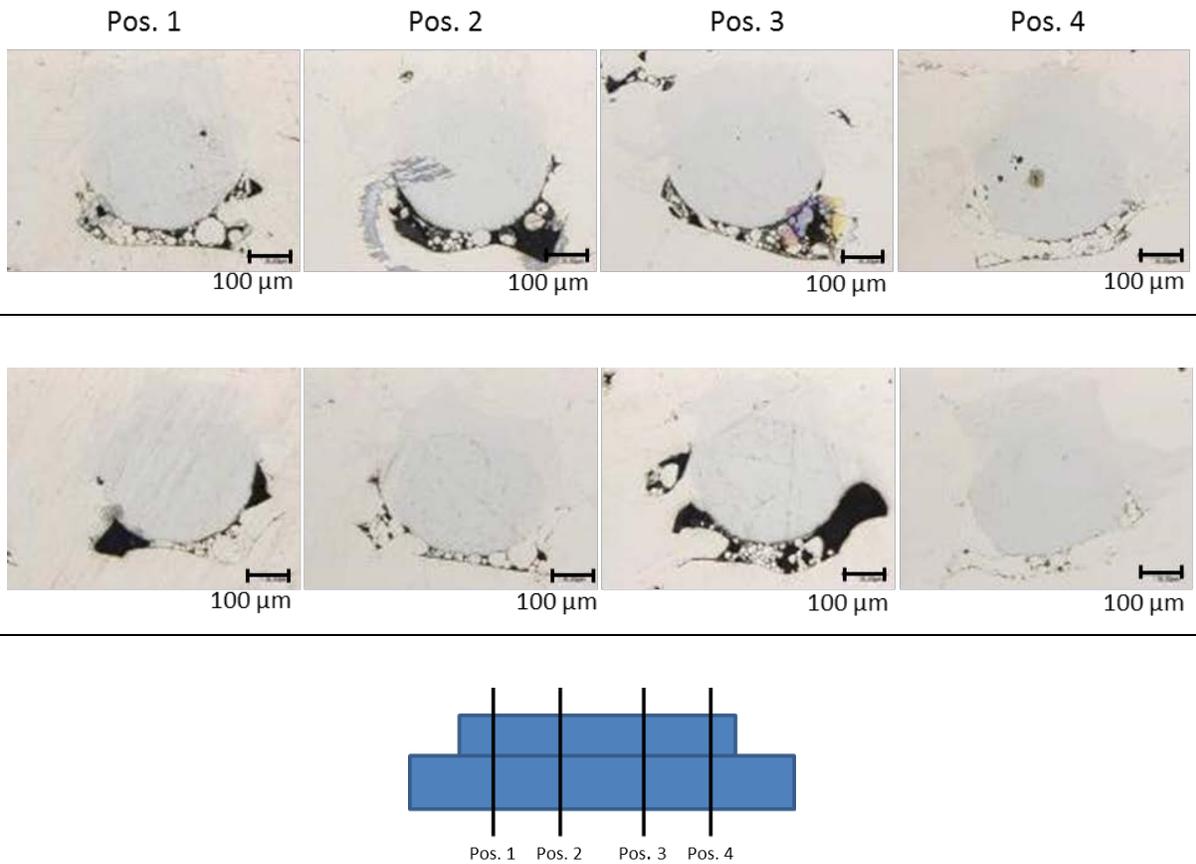
middle: coupon 2; bottom: positions within coupons where different cross sectional images have been taken

Sensing capability

The goal of this paper is a detailed description of the embedment procedure of optical fibres into 316 stainless steel coupons which sets the baseline for further fibre integration experiment. To prove functionality of the embedded fibre the transmissivity for laser light through the fibre has been assessed. Fig. 10 shows both scheme and real setup of the measurement. The result is presented in Fig. 11. The detector box records a current proportional to the incident light. The average of transmitted optical power through the metallised optical fibre prior to the embedment into the 316 stainless steel coupon is equivalent to 252.0 ±0.6 µA, while after the integration and embedment it decreased to an

average of 242.5 ±1.0 µA (Fig. 11), which represents a typical loss of 3.8 %. A variation in transmission of a few percent is easily attributed to changes in connector losses. As has been mentioned in the introduction, the measurand is wavelength encoded hence the system is largely immune to a wide range of loss mechanisms at this level. Wavelength encoded sensors remain operational even if the total losses add up to 90% of total loss. Thus, it can be deduced that the embedment procedure did not harm the optical fibre.
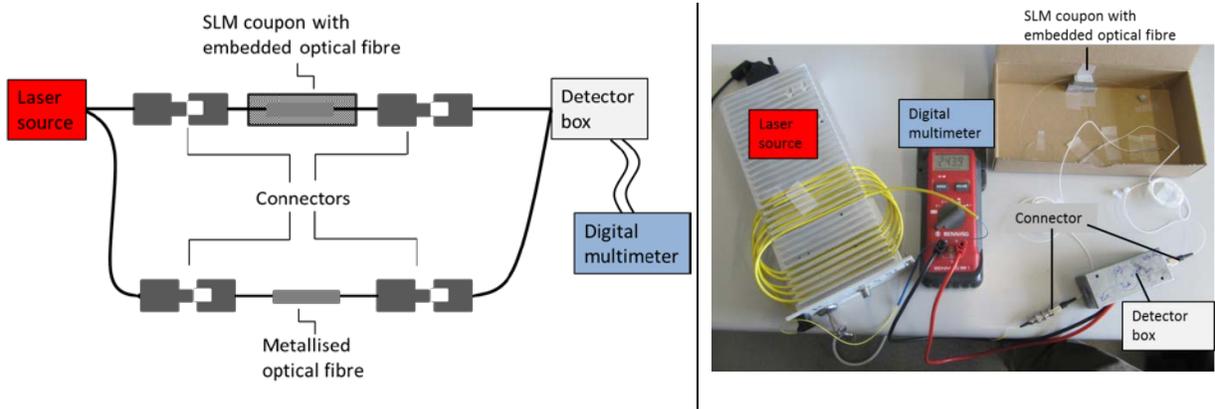
Fig. 10: Light transmissivity measurement setup; left: schematically; right: real measuring setup
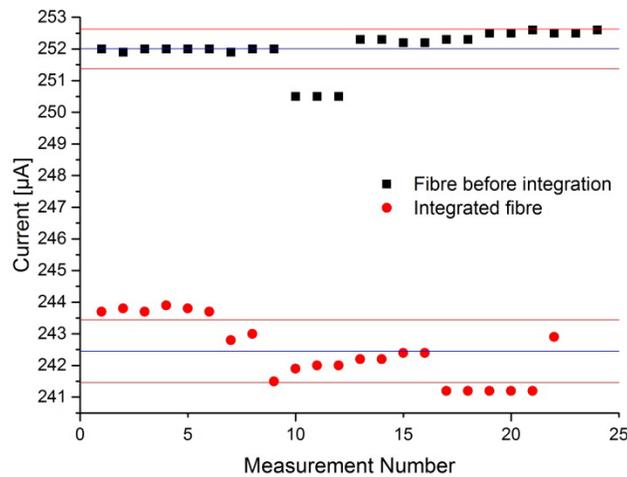
Fig. 11: Light transmissivity measurement through one fibre before and after its integration; mean ± standard deviation is shown for both conditions; several measurements have been conducted per condition to randomise the order and the influence of the connected elements

Conclusions & Outlook

The experiment and results reported in the previous sections show that it is generally feasible to embed optical fibres into metallic parts on a commercially available SLM machine. This is the first step of bringing fibre integration from an experimental lab-environment to real production facilities. However, there are still some hurdles to be overcome. Besides the labour-intensive work to provide the nickel coating of the fibre in desired dimensions, which is not yet an industrially developed process but is conducted on an experimental setup, the handling of the brittle fibres as such as well as in combination with the restricted accessibility of the SLM machine during the embedment process has turned out to be the major shortcoming of the procedure. Furthermore the current embedding equipment and setup facilitates merely an integration of the fibre in a horizontally orientated, straight line, i.e. it is

not yet feasible to embed the fibre in a way that it follows the contour of a specific geometry. The shortcomings described above have to be taken care of in future trials. However, first it has to be focused on repeatability of the experiment described in this paper. If those can be conducted with repeatable embedding quality and light transmissivity results, further analysis and measurements can be done. With regard to temperature measurements using the embedded fibres the bonding quality achieved so far and shown in Fig. 9 is sufficient, though for strain analysis within the surrounding material the fibre needs to be embedded without any flaws or pores which will be hardly possible to achieve with the approach shown in this paper. Another important conclusion of these experiment is that it is expected to be able to transfer the procedure to other materials, i.e. to embed fibres in materials used for high temperature applications in power generation industry.

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