A guide to select strain sensors to be embedded in smart metal parts built by WAAM

Pascal Robert, Nicolas Beraud, Matthieu Museau, Henri Paris

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Pascal ROBERT[(a)*], Nicolas BERAUD[(a)], Matthieu MUSEAU[(a)], Henri PARIS[(a)]

(a) Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 38000 Grenoble, France*

** Institute of Engineering Univ. Grenoble Alpes*

** Correspondant(e) : pascal.robert@grenoble-inp.fr*

Resume: Additive Manufacturing gives designers freedom to explore new way of thinking smart parts. Smart parts can be defined as parts that react, adjust themselves and/or communicate. Such tasks can be performed through embedded devices or in an independent way when a change in their environment occurs, decreasing or replacing a human intervention. They are an important step toward the establishment of the 4.0 industry.
This study is focused on smart part with strain monitoring. Embedding sensors enable core measurement while ensuring protection of the device from outside impairment. Additive manufacturing makes it possible to embed such kind of sensor inside a part during the manufacturing process. These newly produced parts would be able to monitor their use and optimize their lifetime.
Wire Arc Additive Manufacturing is a good candidate to produce smart parts. However, this process uses gas metal arc welding technology to build metallic parts in an additive-minded way and thus imply high current and high temperatures. These consequences make it difficult for some kind of strain sensing technologies to be embedded soundly.
This paper benchmark various sensor technologies for monitoring part strain and groups them into three approaches: embedding electronic devices, embedding fibre optic sensors and embedding passive exogenous indicators. Each approach is presented through one of its major sensor technology, and their pro and cons are discussed. Finally, a guide is proposed and tested on three examples, to select the strain-sensing technology adapted to restrictions imposed by the specifications of each example and by the WAAM process.
Keywords : Smart parts; Wire and Arc Additive Manufacturing; Strain sensors; Core integration; Sensor selection guide

1 Introduction

The age of internet of thing is coming. Every day, a new connected refrigerator, a new connected car are sold. This phenomenon is enabled by the irruption of smart parts in the day-to-day life. The arrival of this kind of object in the industry is an important step in the establishment of the 4.0 industry (Porter and Heppelmann, 2015) and is notably favoured by the freedom given by additive manufacturing.

The purpose of smart parts is to replace or decrease human intervention in the performance of a task by reacting and or communicating internal or external data when changes occur in them or their environment (Meyer et al., 2009). The most commonly used method of creating smart parts is to embed electronic devices (sensors &/or actuator) during the manufacturing process.

Wire and Arc Additive Manufacturing (WAAM), is a process using gas metal arc welding technology in an additive manner to create metal parts (Williams et al., 2016). Its high deposition rate and ability to create parts without size restrictions are assets that interest industrial investors in this process.

By embedding a strain sensor in a metallic part, it can be possible to monitor its uses and enhance its lifespan. However, welding technologies develop high current and tension that are harmful to any kind of electronic devices.

This paper investigates several strain sensing technologies that can be embedded in a wire and arc additive manufacturing process to create a smart part. They can be clustered in three approach: embedding of an electronic device, embedding of an optical fibre sensor, and monitoring of an embedded indicator (often through non-destructive testing technology). A selection guide based on different criteria that can be adapted to different specifications is finally presented.

2 Sensor functional specifications

The research scope shall be reminded: only strain sensors are investigated; they must be integrated during the WAAM manufacturing process; the information sought must stem from core measurement of the strain in the part. Requirements of the sensor functional specifications are listed in the following table as "Main Function" or Constraints" and are intended to assist in the selection of a sensor technology.

Table 1 : Sensor Functional Design

MF1	To measure core strain accurately
C1	To be inserted during WAAM process with few requirements
C2	To be compact
C3	To obtain the sensing signal with few requirements
C4	To compute strain from signal easily
C5	To be economical
C6	To monitor strain continuously with few requirement
C7	To be adaptable to all kind of part (geometry and metal grade)
C8	To be robust
C9	To provide additional information easily

Numerous strain-monitoring technologies are reviewed in the literature. The technologies suitable to monitor core strain in a part made by WAAM process can be grouped into three approach. First, strain monitoring by embedding an electronic device such as a piezoresistive or a piezoelectric strain gauge. Second, using fibre optic sensor such as Bragg grating sensors embedded in the WAAM part. Finally, observing the strain of a passive physical indicator (a void or a sheet of a different material) embedded inside the part with a sensing technology. Many technologies used in non-destructive testing such as ultrasonic phased array detection or induction testing can be used to control the embedded indicator.

Some of the technologies studied such as laser telemetry, digital image correlation, vibrating wire sensor or coordinate measuring machine are discarded. They can monitor strain but not in a "smart-part" perspective.

3 Benchmark of Sensors

3.1 Embedding an electronic device

The piezoresistive sensor technology is a classic and economical way of controlling strain. It works by measuring the tension between the ends of an electronic circuit that is stick or embedded on a part which the strain has to be measured. The circuit is piezo-resistive and thus, it resistance change when it is strained. Measuring its tension variation hence enable to measure its resistance variation and thus, its elongation.
These sensors can be produced as thin film and be embedded in a part with not much volume hindrance. Thin film sensors are successfully embedded in a Stainless Steel Part during a Selective Laser Melting process by (Li, 2001) ,(Li et al., 2004). and (Choi et al., 2006).

A piezoelectric sensor produce a current when it is strained. By measuring this current, the strain of the part hosting the sensor can be calculated. (Hossain et al., 2016) embedded successfully this kind of sensor in a titanium part produced by Electron Beam Melting process.

It must be noted that these two kinds of sensors needed a thermo-electric protective case. Indeed, these sensors can be easily damaged by high current and temperature. Piezo-electric sensors can moreover lose definitely their ability to produce current under strain when they are heated above a specific temperature known as "Curie temperature" (350°C for the one used by Hossain). Furthermore, these sensors must be well bonded with their host part in order to measure strain correctly and thus, their protections must assure the bonding quality. (Figure 1) show how Li and Choi produced these cases. However, the protection thickness must be adapted to WAAM specificities (melting depth, temperature, current) that are different from the powder bed process used by Li, Choi and Hossain and may reach several millimetres.

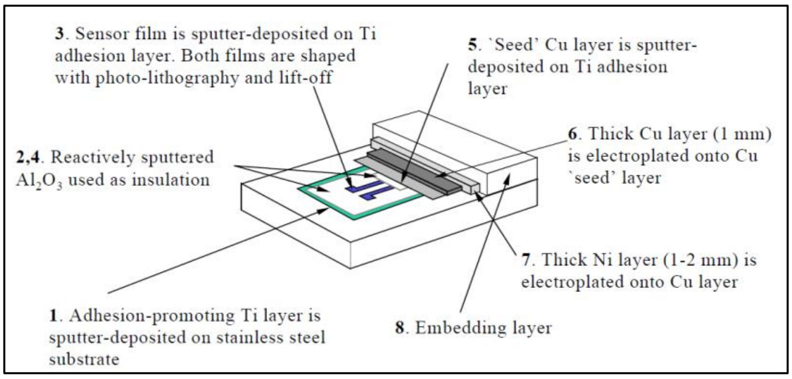

Figure 1 : Thin Film Strain Gauge encapsulation (Li, 2001)

The electric signal used as support of the information is easy to treat by the user to compute the part strain. Furthermore, this kind of device does not require heavy instrumentation to be monitored continuously. They require to be connected to wire and sockets that must be equally protected from WAAM conditions. A basic gauge measure strain in one direction but more complex sensors shaped as "rosette" can measure strain with the same accuracy on a whole plane. Easy access to terminals going out from the part has to be assured to plug it to an acquisition unit or to a wireless sensor node as a part of a wireless sensor network (Gupta, 2013). The sensor node may communicate with a transceiver using different technologies such as radio frequencies, wifi or Bluetooth (Karray et al., 2018).

3.2 Embedding an optical fibre sensor

Fibre Bragg Grating (FBG) sensors is a family of optical fibre sensor sensitive to temperature and strain. Those sensors are widely investigated in literature of smart part manufacturing. They are obtained by treating locally an optical fibre by UV to create an active part (a Bragg grating). It exists different type of Bragg grating. The classic one reacts as a notch filter to light going through the fibre reflecting only the spectrum centred on a specific "Bragg" wavelength determined by the Bragg grating pitch. When the active part is stretched, its Bragg wavelength shift and this value can be used to calculate the strain of the host part, see figure 2. A more thorough explanation on the production of these sensors and on their underlying mechanisms is presented by (Ferdinand, 2018).

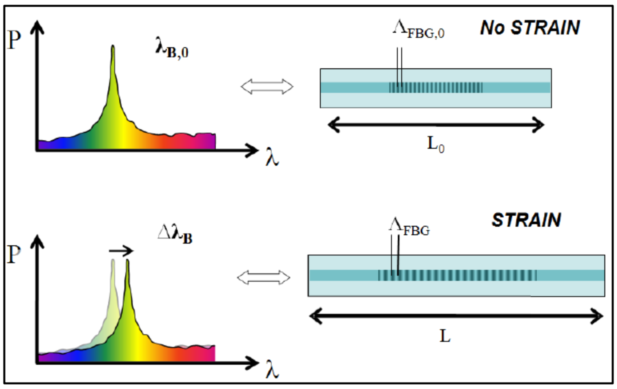

Figure 2 : Bragg Wavelength shift in the reflected spectrum of an FBG (Luyckx et al., 2015)

With fibre sensor, light convey the measure and interact hardly with the metallic host part where an electric signal would need special sheeted electrical wire to be conveyed throughout the part without being hindered by magnetic effect. Furthermore, silica is a good insolent and cannot melt because of the welding current used. Hence, optical fibre does not require any electrical insulation. However, the grating produced on the fibre can be erased if it is heated at more than 700°C. Furthermore, Silica fibre does not present a good bonding ability with metals. Hence, they need a protection for their integration during an additive manufacturing process. This protection is often bimetallic, the first one is sputtered on the fibre and is used as a seed to grow the second one as a thick nickel or copper layer by electroplating.

FBG sensors are widely used for health monitoring of big structure such as bridge, buildings, airplane wings and ships mast. Multiple Bragg Gratings can be written on a single optical fibre, it is ideal to control lengthy structures on multiple points. (Alemohammad et al., 2007) created a smart cutting tool for turning by embedding an FBG on a steel part by electroplating nickel.

(Li, 2001), (Li and Prinz, 2003) (Havermann, 2015), has embedded FBG in a stainless steel part during a SLM process. They used Nickel as a protective layer to assure the bonding with steel and have a protection presenting a mechanical behaviour close from the host part material. However, Havermann explains that slippage between the fibre and the protective layer could occur during the manufacturing process and results in pre-compressing the FBG.

Grandal embed in her various studies FBG in tin during Laser and Gas Tungsten Arc welding process, (Grandal et al., 2016), (Grandal et al., 2018). She used copper and nickel protection on the fibre and advised to embed it with three welding beads parallel to the fibre in order to improve the bonding and reduce localised micro-bending.

(Feng et al., 2010), (Zhang et al., 2013), (Mathew et al., 2016), (Kim, 2017), (Li et al., 2009) worked on numerical simulations of different behaviour of FBG sensor. They studied its temperature and strain sensitivity with or without different kind of protection. They study how the sheath material, thickness and bonding affect strain transfer to the fibre.

Work remain to be done in order to embed successfully an FBG during a WAAM process with high melting temperature material such as aluminium in a first step or steel in a second step.

It must be reminded that optical fibre sensors are brittle and dispendious. Moreover, spectrum analyser necessary to read the signal provided by fibres are expensive. The accuracy of these sensor is high (με) but is diminished by the protecting sheath. Hence, these sensors are interesting to control long structure when multiples grating can be written on one long fibre and provide multiple sensing points. They need however, a protective case to be integrated to a metallic part. Numerous studies and simulations are done in order to understand how these cases impact sensitivity of the FBG to temperature and strain. Solutions exist to dissociate strain influence from temperature influence in the FBG behaviour. Continuous monitoring require that the fibre is always connected to a spectrum analyser. It is thus, suitable for part where the fibre ingress location is static and easy to protect from environment hazard.

3.3 Embedding and monitoring of a passive exogenous indicator

By embedding an exogenous indicator inside a part and monitoring it with a selected technology, it is possible to monitor locally strain in a part. The main requirement is that the indicator must be differentiated from the host part by the sensing technology used.

Various technology used for non-destructive testing or structural health monitoring can be used in this way such as X-ray technology, Thermographic imaging, Ultrasonic testing or Induction testing. Non-destructive testing technology suitable for WAAM part are reviewed by (Chauveau, 2018), (Bacelar, 2017) and (Lopez et al., 2017).

Embedding an exogenous indicator give freedom to select properties of the indicator such as its size or its material. Hence, its hindrance on the part can be minimized by adjusting it shape and size and its bonding can be improved by choosing its material in respect with the sensitivity of the monitoring technology used. However, welding on a very thin sheet can make it melt easily without additional heat and current exchangers.

Various sensing technology are imaging techniques that scan the part through acoustic wave, x-ray or light spectrum emitted. They monitor the strain in the part by controlling the size of the indicator. These technologies need deep knowledge to calibrate them and expensive equipment in order to compute an image from signals sent and received. Many data are generated and sent to the acquisition unit in order to achieve the imaging and it might be challenging to control continuously strain from these technologies.

Other technologies can monitor strain in a part by controlling other indicator properties that change with strain. Potential drop, Magnetic Permeability Induction Testing (MPIT) and Eddy Current Testing are three of this kind of approach. The first one is sensitive to conductivity, the second one to magnetic permeability and the last one to both. All these technologies have inspection depth of few millimetres and are influenced by the microstructure of the host part. MPIT appears as the less limited and is presented in the next pages.

(Langevin et al., 1950), observed that certain grade of steel had magnetostrictive properties. It means that under strain, their magnetic properties change and more exactly their relative magnetic permeability. Hence, it is possible to measure the strain of a part by measuring the shift occurring in its relative magnetic permeability.
The relative magnetic permeability (μ_r) of a material define how it is interacting with a magnetic field. Some materials does not interact or hardly with a magnetic field and are called paramagnetic, ($\mu_r \approx 1$, e.g. aluminium). Some attenuate it and are called diamagnetic ($\mu_r < 1$, e.g. copper). Finally, some enhance it greatly and are known as ferromagnetic ($\mu_r >> 1$, e.g. steel).

It is possible to create a magnetic field with a coil alimented by an alternative current. The coil impedance is influenced by the behaviour of the magnetic field it creates. It means that, if a ferromagnetic material is seen by the field, the coil impedance shifts according to the volume and permeability of the material put through the field. Thus, if the magnetic permeability of the material changes due to strain, this strain can be calculated from the shift in the coil impedance. The impedance of a coil is measured through its phase and its magnitude, i.e. its delay between tension and intensity, and the attenuation of the tension generator at its terminals. By plotting its Bode diagram, it can be observed that a coil has three behaviour in function of signal frequency:

resistive, inductive and capacitive. By monitoring the impedance at the resonance frequency, i.e. at the inductive-capacitive regimen interface, a higher accuracy is reached in the impedance shift deduction and thus, in the permeability shift.

(Makar and Tanner, 1998), (Gorkunov et al., 2007), (Stupakov et al., 2007), (Swartzendruber et al., 1997) studied the magnetostrictive properties of various grade of steel. Gorkunov observe Figure 3, two behaviours matching with the elastic and plastic domains of a) St3, b) C45 and c) C45 quenched and tempered steel under strain.

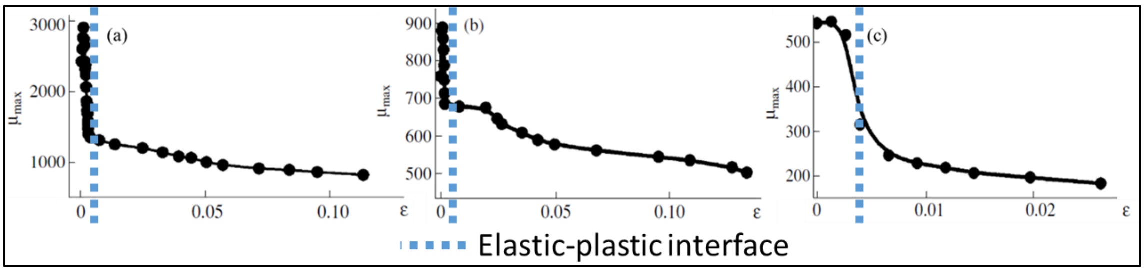

Figure 3: Magnetic permeability of three grade of steel under strain (Gorkunov et al., 2007)

(Arbenz, 2016) studied several systems for measuring the magnetic permeability of a part and developed her own system adapted to complex geometry.

To monitor a part strain of characteristic length (L) by using the permeability shift of an indicator, some requirements are needed. The part and the indicator must have very different permeability (μ). The indicator must be ferromagnetic (μ_d>>1), and the host part must be paramagnetic (μ_p≈1, aluminium or austenitic stainless steel), otherwise the host part limit the coil interrogating depth greatly. Their respective permeability behaviour under strain must be known and the insertion depth (δ) and the coil-part distance (d) must be accurate. An alternative voltage (u) with a magnitude (U) and a pulsation (ω) is applied to the coil. With these data, the indicator permeability influence on the coil impedance (Z) can be isolated with an LCR meter that measures its magnitude and its phase and linked to the part strain (ε), see figure 4.

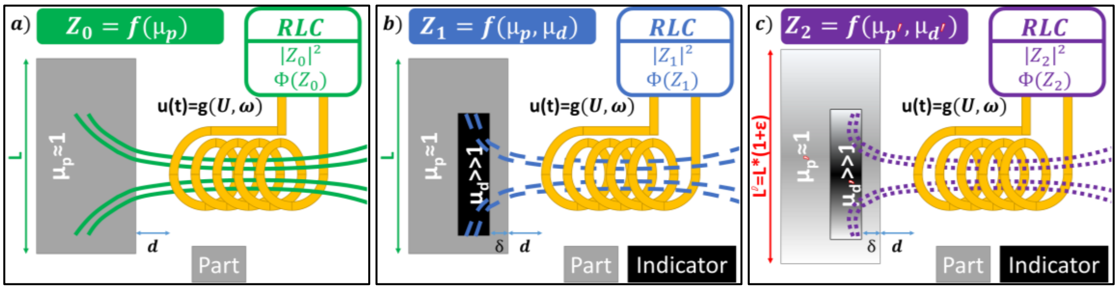

Figure 4: Inductive behaviour of a coil in font of: a) the host part not strained b) the host part and the indicator not strained c) the host part and the indicator strained

4 Sensor Selection Grid

A sensing technology of each approach is evaluated table 2 in its ability to perform requirements deduced from the functional design presented table 1. Five performance levels (0, eliminatory; 1, poor; 3 mediocre; 7 good and 9 excellent) are assigned to each technology to compute a score. These performance levels can be assessed by a panel of experts and are based in this paper on the characteristics of sensors technologies depicted previously.

Table 2 : Sensor Selection Grid

PF-C	STRAIN GAUGES	FBG	MPIT
MF1: To measure core strain accurately	Through thick protection 3	Through protection 9	Dependant to coil position 3
C1: To be inserted during WAAM process with few requirements	Requires heat and current protection 1	Requires heat protection 3	Requires heat and current evacuation 7
C2: To be compact	Very Invasive thick protection 1	Invasive long sensor with protection 3	minimally invasive 9
C3: To obtain the sensing signal with few requirements	Sockets, DC generator and embedded protected wires are mandatory 3	Ingress, Laser and Embedded and protected non sensing optical fibre is mandatory 3	Positioning area, AC generator and coil initial calibration are mandatory 7
C4: To compute strain from signal easily	Linear law with tension 9	Spectrum analyser needed 1	RLC meter needed 7
C5: To be economical	Very Economical sensor, protection needed 9	Expensive sensor and spectrum analyser; protection needed 1	Economical sensor, RLC meter needed 7
C6: To monitor strain continuously with few requirements	Need a Wifi or Bluetooth transfer device and a DC generator with a battery linked to the part 9	Need the spectrum analyser and the laser to be connected to the part and acquisition unit, ingress area need to be static 1	Need a Wifi or Bluetooth high rate transfer device and an AC generator with a battery linked to the coil fixed on the part 3
C7: To be adaptable to all kind of part (geometry and metal grade)	Need access to sockets 9	Best with long part, need access to ingress 1	Better with thin and paramagnetic part, need positioning surface 3
C8: To be robust	Sockets and electrical wire 1	Ingress and optical fibre, sensible to temperature 3	Can be recalibrated Can be monitored with another technique 9

C9 : To provide additional information easily	Easy multidirectional measurement 3	Easy multipoint strain and temperature measurement 9	No additional information 1

Next, weights are assigned to each function to give more or less importance in their fulfilment in regards to specifications of a particular subject case. These weights can be assessed by an expert group. Three different examples buildable by WAAM are selected: an airplane wing spar (Williams et al., 2016), a lifting hook (Jackson, 2018) and a frame of a Computerized Numerical Control (CNC) Machine. Their own requirements lead to different weight distributions in functions identified, presented Table 3.

Table 3 Functions weight distributions for three examples

WEIGHT\MF-C	MF1	C1	C2	C3	C4	C5	C6	C7	C8	C9
CNC Machine's Frame	9	3	7	1	3	3	9	9	3	9
Lifting Hook	7	9	7	7	9	9	7	7	9	1
Airplane Wing Spar	9	7	3	3	3	3	3	1	7	9

Finally, scores can be computed in order to select the sensor or technology the most suited for each case. Table 3 and 4 are multiplied together as matrix to produce scores listed Table 4.

Table 4 Score obtained by each technology for three examples

SCORE \ TECHNOLOGY	Strain gauge	FBG	MPIT
CNC Machine's Frame	**286**	228	243
Lifting Hook	358	200	**397**
Airplane Wing Spar	170	**232**	229

Hence, it can be seen that strain gauge is advised to monitor strain in a frame of a CNC machine, Fibre Bragg Grating sensor is suitable for monitoring strain in an airplane wing spar and magnetic permeability induction testing seems appropriate to monitor strain in lifting hook.

5 Conclusion

WAAM appear to be a suitable technology to produce smart parts. The research scope of this paper focuses on strain sensors. Different technologies and sensors were classified into three approach: embedding an electronic sensor, an optical fibre sensor or a passive exogenous strain indicator. They were analysed based on their ability to be embedded during WAAM process and their suitability for the host part requirements. Thanks to this study, the sensor selection grid is proposed and a guide is suggested to help the user to select the most suitable technology. Nevertheless, this study is still only based on the literature and future experiments need to be conducted to ensure that the advised technologies are suitable for measuring core strain in WAAM parts. Furthermore, the sensors scope can be broadened to temperature or acceleration.

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