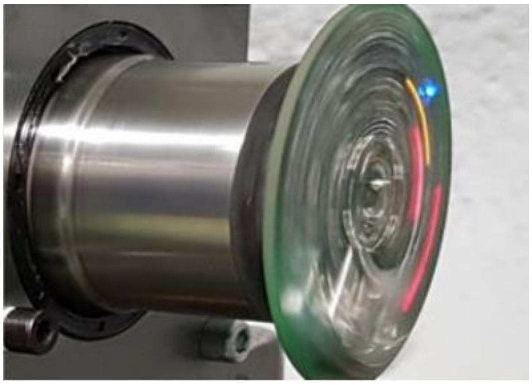
RESEARCH REPORT

VTT-R-01037-20



DIVALIITO - Smart spare parts methods and possibilities

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Confidentiality: Public

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Summary

This report is a DIVALIITO project document for Smart spare parts work package describing the methods and possibilities of embedded intelligence in digital spare parts using additive manufacturing. The report was written to see what kind of technologies have been presented in literature dealing with additive manufacturing and embedded intelligence also to give the companies participating in the DIVALIITO project some examples and ideas on what they could be benefitting from and to be realized as a demonstrator use cases during the DIVALIITO project.

Embedded intelligence can mean sensing elements added on the surface of the parts or elements added inside the parts. In majority of the presented cases in this report, the elements have been added during the manufacturing process. Embedded intelligence can be used e.g. in improving the communication, detecting or condition monitoring of the digital spare parts simultaneously having the sensors well protected from the environment. The used sensors and technologies should be selected depending on what phenomena is intended to be measured. Nevertheless, the application of sensors and manufacturing the components with functional sensors inside the parts is not always straightforward. Especially when embedding traditional electronics in metal AM components, the accumulated heat during the manufacturing process can destroy the sensing elements and special care needs to be taken in the design taking into account the possibilities and limitations. Typically, for plastic components the embedding process is easier with lower temperatures. The process interruptions to enable the embedding of sensing elements can reduce the mechanical properties of the parts and should be investigated case by case.

Confidentiality	Public

Espoo 30.11.2020

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Preface

This report is a DIVALIITO project document for Smart spare parts work package describing the methods and possibilities of embedded intelligence in digital spare parts using additive manufacturing.

Espoo 30.11.2020

Author

Contents

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligence
AM	Additive Manufacturing
AMRC	Additive Manufacturing Research Centre
CAD	Computer Aided Design
CB	Carbon Black
CNT	Carbon NanoTubes
COTS	Commercial Off-The-Shelf
GPS	Global Positioning System
IR	Infra Red
LED	Light Emitting Diode
MEMS	MicroElectroMechanical Systems
OEM	Original Equipment Manufacturer
RFID	Radio Frequency Identification
R_m	Ultimate Tensile Strenght
$R_{p0.2}$	Yield Strength
RTD	Resistance Temperature Detector
SLM	Selective Laser Melting
SMA connector	SubMiniature version A connector, coaxial radio frequency connector
TPU	ThermoPlastic Urethane
UAM	Ultrasonic Additive Manufacturing
UC	Ultrasonic Consolidation
UHF	Ultra High Frequency
USD	United States Dollar
WP	Work Package

1. Introduction

The main idea of DIVALIITO Smart Spare Parts work package was to study how and what sensors could be integrated with additive manufacturing (AM) and what kind of new opportunities smart spare parts would open. The final goal of the work package was to manufacture a few demonstrators that would have relevance to the companies involved in the project. The materials of the study were dealing with plastics and metals. This report was done to give ideas on what technologies the demonstrators could be utilising.

2. Embedded intelligence

Embedded intelligence together with additive manufacturing can be realized using different AM materials. At the time of making this report, typically plastic parts have been more popular for the embedding, but embedding in metal materials was also feasible and already carried out in a few cases. Embedding in plastic makes it possible to transfer radio waves, the transfer of which may be obstructed when used to embed intelligence inside metal parts. The metal parts however can hold more industrial relevance with better mechanical properties. Different suitable technologies, the existing developed solutions and ideas for further possibilities are described more in detail in the following chapters.

2.1 Phenomena that can be measured using various sensors

Integrated sensors can be used to improve the efficiency of the products. This kind of approach has been taken with a Pratt & Whitney aircraft engine that was fitted with 5000 sensors. The data were then processed by artificial intelligence (AI) to fine-tune the engine performance. With this 10% to 15% reduction in fuel consumption and improvements in noise and emissions were achieved. [1] Another example of the added benefits of an embedded sensoring has been presented by Villilä [2]. He has said that with a pressure sensor for a single mould in plastic moulding industry, he has achieved yearly savings of approximately 50000€. This was achieved with better understanding of the process and the events happening in the mould. The accumulated data can also be used for monitoring wear and preventing the manufacture of faulty parts. Another type of failure can be occurring with wired sensing elements. The wired elements can be a significant source of failure in no-fault-found systems in automotive to aerospace applications [3]. To limit such failures the elements can be manufactured inside the components to protect them from the environment.

To give some ideas about different type elements that could be embedded, in the following tables (Table 1, Table 2) various types of sensors have been listed. This list was meant to act also as a preliminary inspiration for the smart spare part demonstrators manufactured in this work package.

Table 1. Various types of sensors, elements and phenomena that they can measure [4, 5].

Sensor	Capabilities and limitations
Accelerometer / motion sensor	Can be used for condition based monitoring
Acoustic emission sensor / Microphones	Can be used for condition based monitoring (e.g. bearings, valves, cavitation). Based on MEMS
Altimeter	Measures altitude of an object above certain fixed level. Can be based e.g. on measuring atmospheric pressure or using sonic waves or radio signals
Antenna	Transfers signals and data
Barometer	Measures air pressure
Camera	Can take photos of the process for further analysis (evolution, defects etc.)
Displacement sensor	Measures the amount the object has moved. Can be based on optical, eddy current, ultrasonic, laser focus or contact
Flex sensor	Measures deflection or bending
Flow sensor	Can be used to measure flow of gases and liquids. Can be mechanical, pressure-based, optical etc.
Force sensor / touch sensor	Can be used e.g. to measure applied force or when the part is touching a surface
Gas detector	Can be used to detect e.g. gas leaks, volatile organic compounds
GPS and Glonass	Position / location of the part based on satellites. Needs to have connection to the satellites (not always usable indoors)
Gyroscope	Measures orientation in relation to Earth's gravity
Humidity / moisture sensor	Measures humidity / moisture
IR sensor (transmissive / reflective)	Monitoring e,g. temperature, moisture, sound, heat in the surroundings
Level sensor	Measures how level the component is
Light sensor / photo transistor	Can measure the ambient light

Table 2. Various types of sensors and phenomena that they can measure. [4, 5]

Sensor	Capabilities and limitations
Magnetic sensor	Detects changes in magnetic field (flux, strength, direction). Can be utilised e.g. as a miniaturized compass (MEMS sensor)
Optical fibre	Can measure vibration and strain. High temporal resolution. Infinitely configurable. [6] Very sensitive to noise. Requires light source.
pH meter	Can measure acidity / alkalinity of the processing liquid
Position sensor	Measures the position in relation to reference point
Pressure sensor	Can be based on multiple technologies e.g. piezoelectric or capacitive
Proximity sensor	Measures distance. Can be e.g. based on ultrasound transducers
RFID antennas and sensors	Identification, location tracking. Can be used without batteries Not transmitting from inside metallic enclosure
Smoke detector	Typically based on more simple technology e.g. optics or ionisation than gas sensors
Strain sensor	E.g. piezoelectric. Measures strain and indirectly e.g. deflection
Temperature sensor	Thermocouple, bimetallic strips, Resistance Temperature Detectors (RTD), thermistors Measures temperature (e.g. wasted energy, increased friction)
Torque sensor	Can measure torque on a rotating system (engine, crankshaft, gearbox etc.)
Ultrasonic sensor	Various uses from surface to defect detection
Velocity and motion sensors	Encoders, tacho-generators, pyroelectric sensors
Wireless power transfer	Can be used as wire-free charging of portable devices (e.g. powering sensors in moving machine parts)

2.2 Examples of structures with embedded intelligence

This chapter is showing examples of different structures that have embedded intelligence. Different cases are presented to give ideas what kind of structures there are already and to possibly give new ideas on how to utilize embedded intelligence in new kind of products such as in digital spare parts. In most of the parts additive manufacturing have been utilised but a few cases with embedding in traditionally manufactured components with added intelligence are included.

Embedded intelligence can mean sensing elements added on the surface of the parts or elements added inside the parts. In majority of the cases presented in this chapter, the elements have been added during the manufacturing process. It is good to keep in mind that the addition of intelligent elements or sensors during the manufacturing process can be more expensive than if carried out after the manufacturing. For example, if the intelligence can be added afterwards with e.g. drilling and inserting the element in the cavity, the costs may be lower and the replacement of the elements easier. In certain processes, such as in laser- based powder bed fusion (L-PBF), this can be a good way of using already available commercial sensors without the need of thermal protection. Without adequate thermal protection e.g. in L-PBF process the reflow temperatures of the sensors (e.g. in the range of 200 °C) can be exceeded and the sensors destroyed. However, the embedding during manufacturing might be the only option in certain parts if the element locations are such that are not accessible once the part manufacturing is complete. Embedding during the manufacturing can also result in more accurate data collection (e.g. closer to the spot of interest) and protection of the components during the part lifetime.

With the embedding of electronics it needs to be kept in mind that the components are able to survive the conditions and the environment that the smart spare part will be used in. For example, excessive vibration or corrosive environments can destroy the sensors. One option e.g. in the case of high vibration is using an elastic mass on which the sensor is attached and the vibration reduce sufficiently.

2.2.1 Improved communication & antenna structures

3D printed microwave patch antenna via fused deposition method and ultrasonic wire mesh embedding technique is presented in Figure 1. Compared to traditional patch antenna fabrication method, this 3D printed antenna can be fabricated with lower cost and the fabrication process is more convenient and faster [7]. Multilayer patch antennas have also been manufactured with an offset of 5° from the build plane [8]. Additional examples of 3D printed antennas are 3D printed 2.4 GHz wifi antenna [9] and a 3D printed antenna printed on a cubesat sidewall surface using ultrasonic embedding (a custom ultrasonic horn) [10].

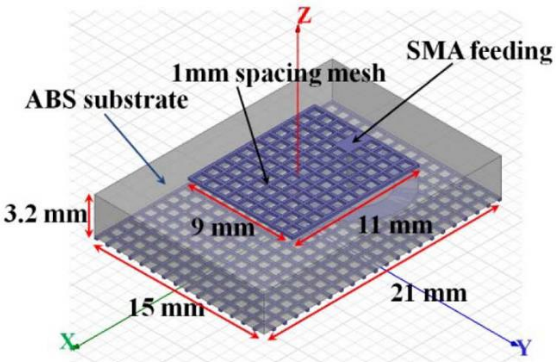

Figure 1. Schematic of the microwave patch antenna made of embedded wire mesh [7]. © 2015 IEEE[1].

Antenna structures can also be created inside a 3D printed component utilising the concept of patch antennas where conductive layers are manually placed inside the component during the part manufacturing process (Figure 2). Added benefit is the creation of multifunctional panes with possible volumetric efficiency and weight savings [11]. The presented antenna structure

[1] © 2015 IEEE. Reprinted, with permission, from Liang M. et al. 3-D printed microwave patch antenna via fused deposition method and ultrasonic wire mesh embedding technique, IEEE Antennas and Wireless Propagation Letters, 14, 2015, pp. 1346-1349.

was created with an FDM printer. Another multilayer approaches to create antenna elements have been presented e.g. by Arnal et al. [12] and Ketterl et al. [13].

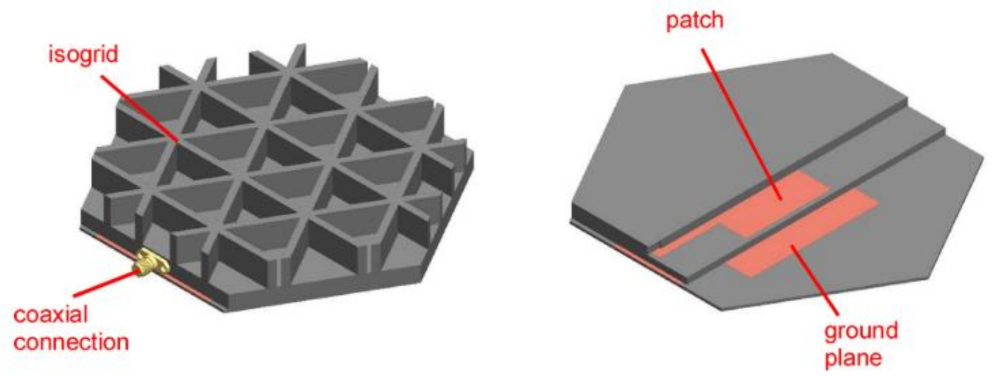

Figure 2. Structure schematic with two conductive layers and SMA (SubMiniature version A) connector [11]. © 2018 Elsevier[2].

2.2.2 Detectability and counterfeit prevention

The identification of a genuine product can be carried out e.g. by placing specific elements inside the spare part that require special knowledge or equipment to detect correctly. Identification could be important e.g. in the aerospace sector where critical failure of the spare parts could result to fatalities or substantial financial losses. The possible results of the counterfeit products to one's personal health can also come into play in the medical sector where additively manufactured products can be used inside of a human body. One of the identification methods is the embedding of small elements inside the part that will be analysed using CT and show the correct QR code only when inspected in correct orientation [14]. A more simple approach has been conceived and trialled before by VTT. Digital ID was manufactured inside an FDM printed ABS component using a filament with magnetic fillers ($BaFe_{12}O_{19}$) to create detectable magnetic codes. It was then possible to read the codes with an external reader (Figure 3). [15]

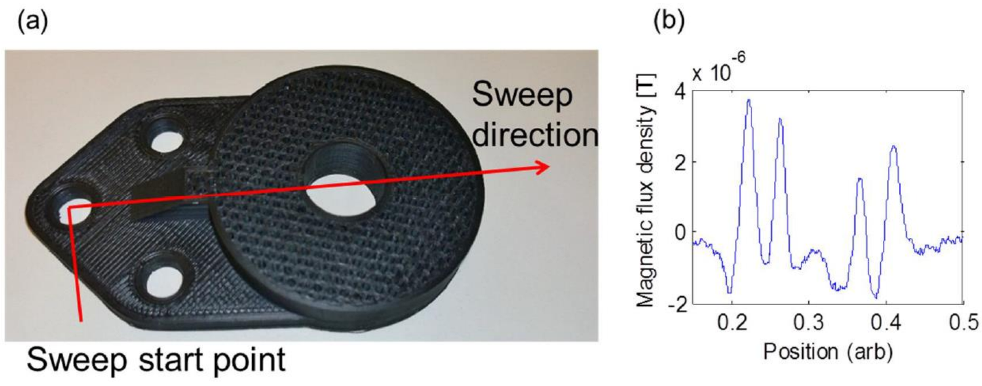

Figure 3. Printed ABS part with a code consisting of four magnetic lines embedded inside [15]. © 2020 VTT Technical Research Centre of Finland Ltd.

Embedded RFID has also been utilised in a study by Akmal et al. [16]. They studied embedding conceptual medication and RFID transponders into AM implants using different AM techniques. Examples of plastic implants are presented in Figure 4. Material extrusion, vat polymerisation, binder jetting and powder bed fusion were all found to be successful with embedding RFID and providing the RFID signal from within the implant and the implant was

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[2] © 2018 Elsevier. Reprinted from MacDonald E. et al., Fabricating patch antennas within complex dielectric structures through multi-process 3D printing, Journal of Manufacturing Processes, June, 34, 2018, pp. 197-203 with permission from Elsevier.

able to identify itself and communicate the patient specific information. Conventional materials (ABS+, Clear Resin V4, ZP150 powder and PP powder) were used for the manufacturing of the implants. Similar approach of embedding RFID tag with NFC inside 3D printed polymer ring has also been presented [17].

3D printing can also be used to manufacture the RFID sensors. Akbari et al. [18] used direct writing and microdispensing to print passive ultra high frequency UHF RFID graphene tags on different materials and cured in an oven or photonically. 3D direct printing and microdispensing may allow the printing of small features without masks and reducing the amount of material needed.

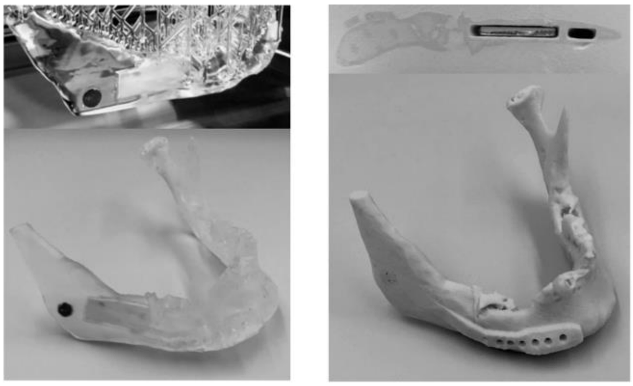

Figure 4. Examples of a plastic implant with embedded intelligence manufactured using vat photopolymerisation (on the left) and binder jetting (on the right) [16]. © 2018 Akmal et al.[3]

Passive RFID tags have also been manufactured using a 3D direct write method using graphene on environment friendly substrates (paper, cardboard, wood, textile) [19]. One challenge with the RFID tags is that they cannot be embedded inside metal parts, but they can be assembled e.g. into specially designed cavities on the part surface. Another approach of the utilisation of RFID tags in metals has been taken in healthcare where errors in process flow can have fatal consequences. It is possible to identify e.g. surgical instruments reliably and/or automatically by embedding an RFID tag on or inside the instrument. With metal objects, specific attention has to be taken on the communication of the RFID tag and that the metal shell should not be completely closed thus leaving at least a dielectric gap. However, in a study by Paz et al. [20] if using a low frequency range (125 kHz), the tags can be read although encased in a completely closed metal shell. A shell thickness of 1.4 mm gave a read range of 12 mm and the thickness of 1.7 a read range of 7 mm. With a thicker 1.8 mm shell the tag was unreadable. For high frequency range (13.56 MHz), really thin wall structures are required (0.15 mm) which are hard to manufacture even with L-PBF. In addition to identifying the components, RFID tags can be used for tracking the location of parts e.g. with a triangulation method to know the exact location of the component in warehouse or in operation. [21]

2.2.3 Condition based monitoring

To monitor the condition of a component, several approaches can be taken. The method for the condition based monitoring should be based on the environment that the part is used in and the expected malfunction mechanism of the part. If e.g. the component gets faulty with increased wear, a simple form of a wear indicator could be the addition of a wear indicator layer. This could be a passive layer and when in wears out, it could be detected with visual inspection e.g. with a distinct colour on the wear surface indicating the approach of a critical failure. However, in more sophisticated approaches the condition can be monitored with an

[3] © 2018 by Akmal J. S. et al., Implementation of industrial additive manufacturing: Intelligent implants and drug delivery systems, Journal of Functional Biomaterials, 2018, 9, 3, p. 14. Creative Commons Attribution 4.0 License https://creativecommons.org/licenses/by/4.0/

embedded sensor tracking increased vibration, increased temperature etc. In the following some examples of use cases to monitor the condition of the component in use or the manufacturing process have been presented.

Embedding electronics inside metallic AM component successfully can be challenging as typically e.g. in L-PBF and EBM methods the manufacturing temperatures exceed the temperature durability of the electronic sensors. One way of protecting sensor elements in metal AM parts is encasing them in a prefabricated insulating material during the assembly phase. This method has been utilized in a smart sensor embedded in an EBM and an SLM part where sensor was assembled inside an alumina housing with cavities (Figure 5). With this proof-of-concept part, pressure and temperature sensing capabilities were tested using compressive cyclic loading and hot fire testing in a combustion chamber testing. Embedding sensor can be used to extend the life time when used in harsh environments and can provide valuable data to increase efficiency. [22, 23]

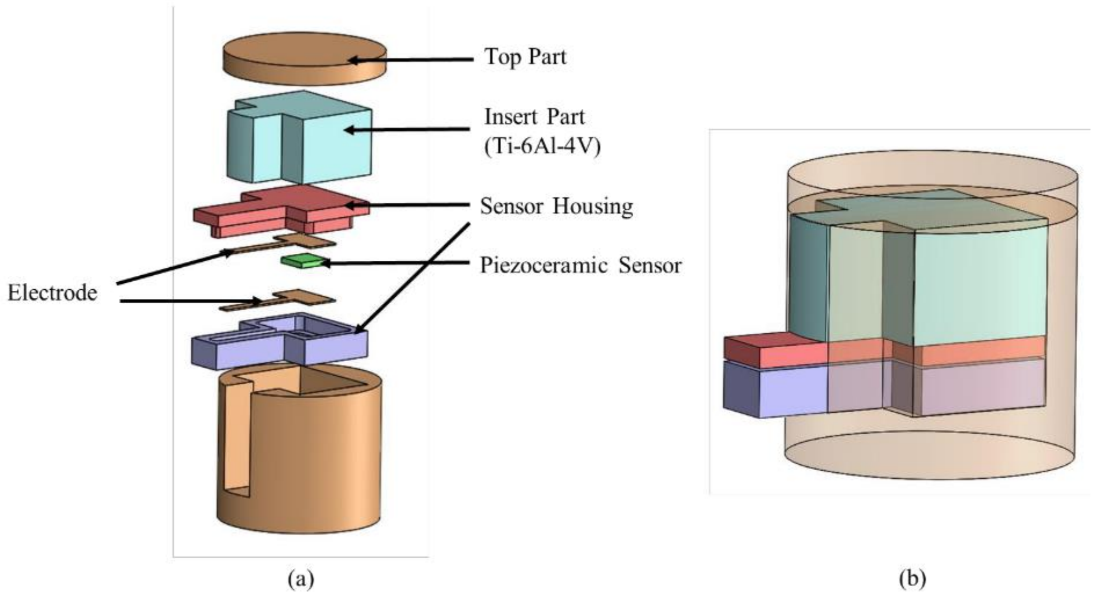

Figure 5. Schematic diagram of smart parts, (a) components of sensor assembly and (b) assembled diagram [22][4].

Another use case for embedding electronics inside a metallic component has been presented by VTT Technical Research Centre of Finland [24]. In this case, the target was to carry out a proof-of-concept study for condition based monitoring purposes with embedded accelerometers. The application was a shaft piece designed to hold two MEMS accelerometers inside. The sensor embedding was carried out by pausing the L-PBF process and mounting the sensors inside the specifically designed cavities in the part. After the sensor assembly the part printing was continued and the top half of the component printed on top of the bottom part. The process was carried out successfully with both sensors working after the printing. The final component was machined and a PCB with wireless data transfer attached to the end of the shaft. The printed smart shaft can be seen in Figure 6. Generally, the cavity design when embedding sensors inside the metal parts can be of significant importance since it affects both the manufacturing process and the sensing capability.

[4] Republished from Hossain M. et al., Smart parts fabrication using powder bed fusion additive manufacturing technologies, Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, 2017.

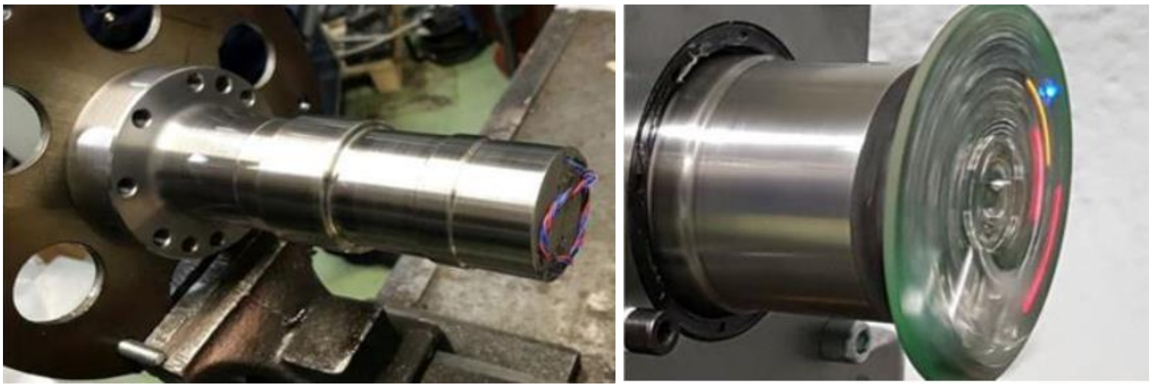

Figure 6. 3D printed metal smart shaft that has an accelerometer inside and wireless data transfer. © 2020 VTT Technical Research Centre of Finland Ltd.

L-PBF has also been used by Petrat et al. [25] to create a structure with cavities for LED and wires. The cavity was closed with Laser Metal Deposition (LMD). Position and the build-up strategies were enough to reduce the temperature of LMD for the electronic structure to withstand the accumulated heat.

Other type of embedded electronic structures made possible by AM inside a metal part have been presented by Wu et al. [26] who demonstrated a “smart screw” that is able to monitor compression and bending of a M24 bolt (Figure 7, Figure 8). The measurement was based on a capacitance shift of the inductor due to gap changes inside the bolt. Selective Laser Melting and Ti6Al4V powder was used to manufacture the screw with the spiral inductor and cylindrical capacitor.

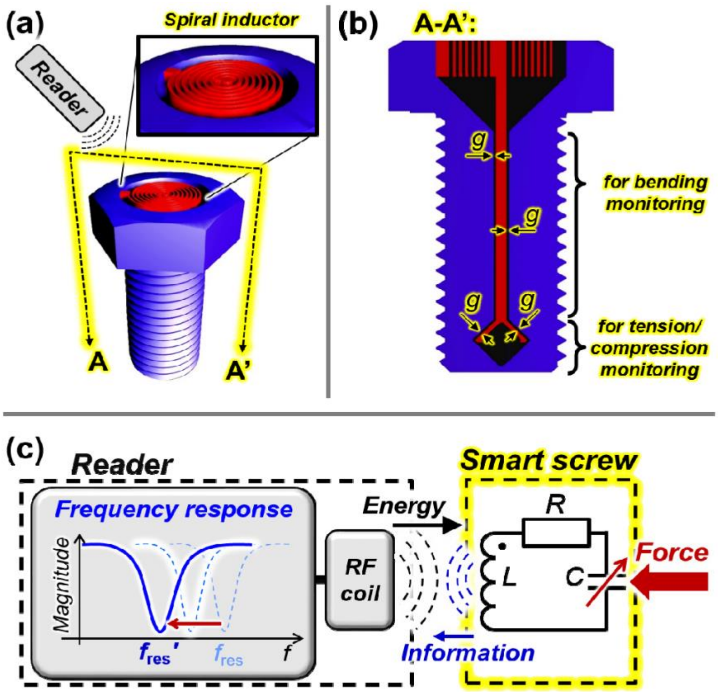

Figure 7. “Smart screw” with deformation sensing function. a) Smart screw with spiral inductor, b) designed gap g for capacitance and c) illustration of the sensing principle with equivalent circuit diagram [26]. © 2017 IEEE[5]

[5] © 2017 IEEE. Reprinted, with permission, from Wu S.-Y. et al., 3D Printed “Smart Screw” with Built-in LC Sensing Circuit for Wireless Monitoring, 2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), Kaohsiung, 2017, pp. 926-929.

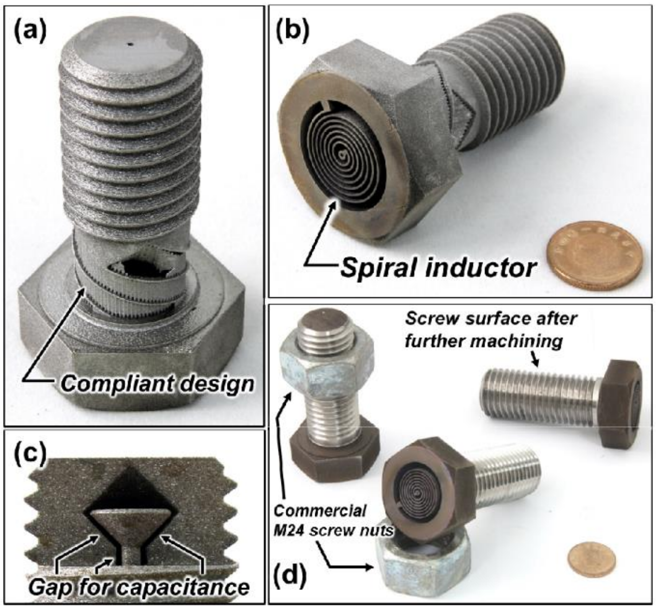

Figure 8. (a) Smart screw with compliant design for feasibility test; (b) closer view of the spiral inductor; (c) cross-sectional view of the gap for capacitance; (d) pilot production result of real-scale smart M24 screws with commercial screw nuts threaded [26]. © 2017 IEEE[6]

Etteplan has also demonstrated a 3D printed metal component with integrated circuit board with sensors inside and the metal shell acting as an antenna [27]. The embedded electronics comprise sensors tracking acceleration, temperature, air pressure and air humidity. The printed component is presented in Figure 9.

Figure 9. Etteplan's printed demo device with sensors tracking acceleration, temperature, air pressure and air humidity. © 2020 Etteplan.

Condition based monitoring can also be based on thermocouples embedded inside the spare parts to increase the understanding of the conditions that the component is experiencing and to better estimate the component lifetime. One such solution has been presented by Stoll et al. [28]. Standard temperature sensors Pt 100 were embedded in an SLM process successfully without degrading or damaging the sensing capability. For the sensor integration, a cavity was designed for the SLM part in a manner where the sensing element was able to be inserted close to the surface for temperature measurement. The sensor was embedded in the cavity

[6] © 2017 IEEE. Reprinted, with permission, from Wu S.-Y. et al., 3D Printed "Smart Screw" with Built-in LC Sensing Circuit for Wireless Monitoring, 2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), Kaohsiung, 2017, pp. 926-929.

structure during process interruption. Using heat conductive paste around the sensor was seen to shorten the temperature measurement response time.

Fabrisonic has also presented embedded thermocouples using Ultrasonic Additive Manufacturing (UAM) for the embedding inside metal parts to measure internal thermal response from a heat plate [29]. UAM has also been used to manufacture sensors inside rocket fuel plumbing. There was a need to gather data on pressure and temperature gradients to better understand how NASA's engines were behaving. In the "SensePipe", fibre optic sensors were embedded in the walls of a cryogenic fuel pipe. Fibre-based sensors were selected based on their smaller size and ability to collect data over the entire length. To cut down cost, an existing pipe was milled into its outer diameter to create a landing strip with a small groove for each fibre. After fibre insertion, additional material was printed on top and then excess material machined. Based on the testing, the pipe was able to provide reliable data. [30]

Condition monitoring can also be based on different types of strain gauges. Foil strain gauges inside a plastic screw component have been presented by Gräbner at al. [31] who presented embedded strain gauges screen-printed on a 6 µm thick foil inside plastic materials printed with microstereolitography. The concept of a strain gauge inside a smart screw is presented in Figure 10. They used inner and outer strain gauges with different layout relative to the screw. The inner strain gauge is designed for temperature compensation and as it is close to the centre of the screw lies at almost zero strain. The parts were printed in an upright position and the printing paused to place the strain gauge foil manually onto the washer disk. The printing platform was removed from the printer for the embedding. In this study, two plastic materials for the screw were used: hard and brittle HT140M and more elastic ABS Flex. The foil was polyester foil (Mylar) and the electrical tracks were printed in the first step with silver filled, stretchable conductor paste (DuPont PE873), cured for 20 min at 120 °C in an oven and in the second step carbon-based ink (Henkel ECI 7004LR E&C) was applied. The electrical connection of the strain gauges was carried out with electrically conductive adhesive (Panancol Elecolit 3025). The smart screws can be used e.g. to apply a suitable torque on the screw or inspecting the creep of the screw material after fastening.

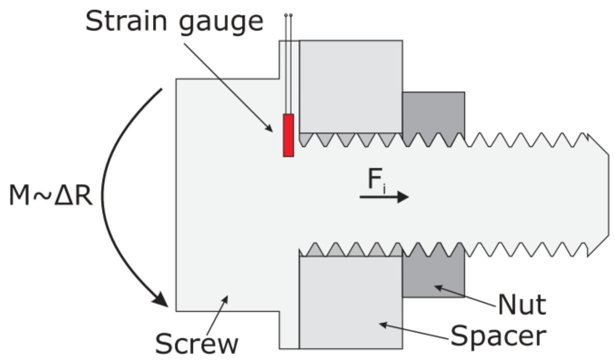

Figure 10. Concept of a smart screw with a thin strain gauge integrated into a spacer disk. Torsional moment M proportional to resistance change ΔR allows determination of the pre-stressing force F_i [31]. © 2018 Gräbner et al.[7]

Fraunhofer ILT is utilising printed sensors to replace conventional foil strain gauges that commonly need to be applied manually to the component. They are using inkjet or aerosol jet to deposit an insulation layer and the conducting paths. The post-treatment, conventionally carried out in a furnace, is carried out with laser radiation. This way the whole component does

[7] © Gräbner D. et al., 3-D-printed smart screw: Functionalization during additive fabrication, Journal of Sensors and Sensor Systems, 2018, 7, 1, pp. 143-151. Creative Commons Attribution 4.0 License https://creativecommons.org/licenses/by/4.0/

not need to be heated above its damage threshold but local heating of the printed material to remove solvents and melting the remaining particles is possible. [32]

Optical fibres have small cross sectional dimensions and thus induce tiny flaws or defects into the parts. They facilitate the simultaneous measurement of two different values, temperature and strain. An example of optical fibre embedded in a stainless steel 316L part using an L-PBF process has been presented by Stoll et al. [33]. They used a multi-step embedding process where the base coupon was polished, optical fibre laid and then bonding was carried out in perpendicular direction followed with a bonding phase in parallel direction before printing the top coupon. A challenge in the process was having a proper bonding of the optical fibre inside the metal part with the fibre sensing functionality working (Figure 11). The same approach with embedded optical fibres has also been presented before by Havermann et al. [34].

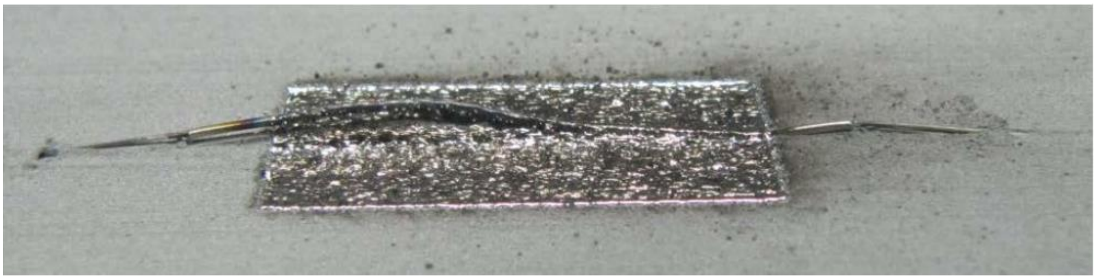

Figure 11. Fibre fix clamped on both sides bending out of cavity due to induced heat of SLM process [33][8].

Another manufacturing method to embed optical wires inside metal parts is to use ultrasonic consolidation (UC) or ultrasonic additive manufacturing (UAM). The advantage of UC in embedding in comparison e.g. to L-PBF is that it uses sound waves to weld metal layers together in low temperatures process that does not damage sensors or electronics (Figure 12) [6]. Ultrasonic consolidation has been utilised also in manufacturing electrical circuitries combining conductive and insulating materials [35] and Fabrisonic has used UAM to embed optic strain sensors into the brackets and struts of drones [29].

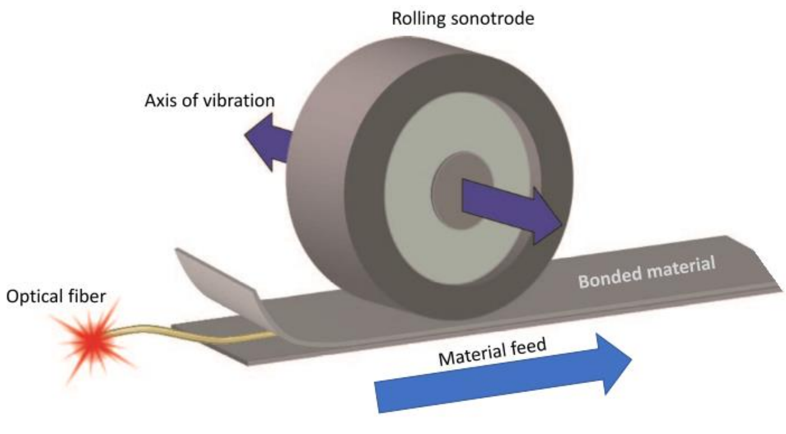

Figure 12. Conceptual illustration of how UC works, showing how stock material is fed into the rolling sonotrode. Sensors can be inserted between layers for embedding, such as the optical fibre shown here [6]. Figure credit SPIE publication[9].

For plastic parts the embedding process can be easier than in metal AM processes due to lower temperatures. Embedded wires inside 3D printed parts have been manufactured e.g. by

[8] Republished from Stoll P. et al., Embedding fibre optical sensors into SLM parts, Proceedings of the 27th Annual International Solid Freeform Fabrication, 2016, pp- 1815-1825.
[9] Credit to SPIE publication: Suter J., Larimer C., Denslow K., Monitoring solid metal structures with a nervous system embedded with ultrasonic 3D printing, Proc. SPIE 10598, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2018, p. 12.

using an FDM printer in combination with a wire embedding tool [36]. This method can be used to connect e.g. multiple component placed manually inside the part. Similar kind of approach in embedding electronics has been utilised in a CubeSat version that had a commercial off-the-shelf (COTS) accelerometer, microcontroller, Bluetooth circuit board for data transmission and integrated microUSB connector for programming the microcontroller and battery charging (Figure 13) [37]. In addition to embedding wires, conductive traces can also be generated on FDM printed polymer materials with laser ablation if the polymer filament has been filled with conductive metal particles. Laser is used to selectively evaporate the polymer binder and melt the metal particles thus forming a conductive trace [38]. Yet another method to embed wires in polymer materials is a THREAD process developed by Advanced Manufacturing Research Centre (AMRC) [39].

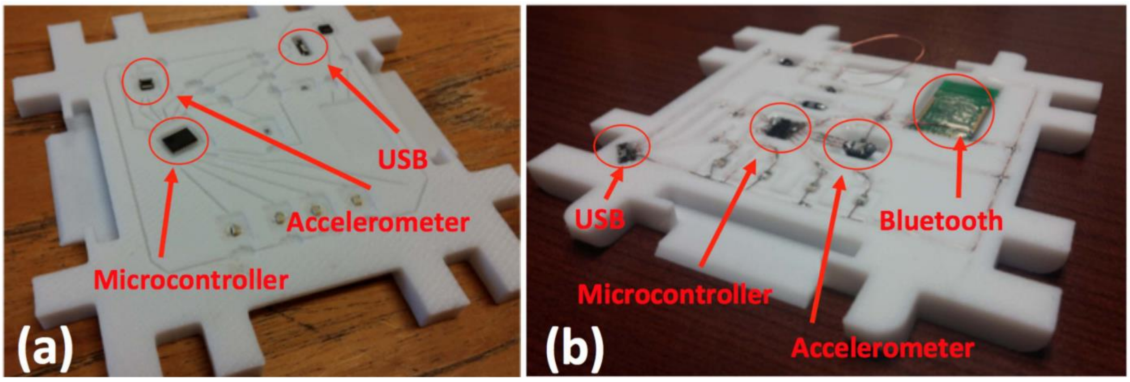

Figure 13. Printed CubeSat version with (a) pre-wire embedding and (b) after thermal wire embedding [37]. © 2015 IEEE[10].

FDM together with subtractive technologies (micromachining and laser ablation) combined in a multi3D system can be utilised e.g. in creating 3D printed antenna structures. Conductive inks dispensed to channels or embedded wires were used to connect the embedded components (Figure 14) [40]. Inkjet printing can also be can also be integrated with other additive manufacturing technologies and thus be able to produce dissimilar materials of interest in an area based manner. Uniform sized droplets are dispensed and selectively deposited on a substrate. When the ink is loaded with functional materials, components such as electronic circuits can be created. Typically some sort of post-processing for the ink material is needed before the functional structure is ready. [41]

[10] © 2015 IEEE. Reprinted, with permission, from Shemelya C. et al., Multi-functional 3D printed and embedded sensors for satellite qualification structures, 2015 IEEE SENSORS - Proceedings, 2015, p.4.

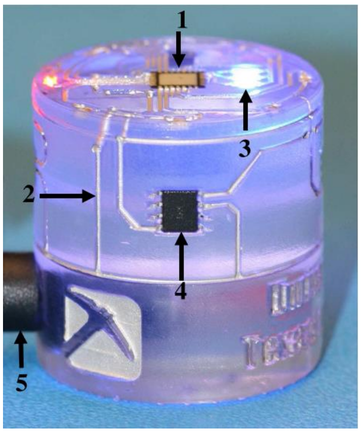

Figure 14. Magnetic flux sensor system with curved surfaces and modern miniaturized electronic components (surface mount). 1 microcontroller, 2 conductive ink interconnect, 3 LEDs, 4 Hall effect sensors and 5 power supply connector [40]. © Springer Nature 2014[11].

An approach to print capacitive sensing elements using FDM has been presented by Leigh et al. [42]. This method can e.g. be utilised in sensor pads that detect touching. A filament with a carbon black (CB) filler as the conductive material was used. The advantage of CB in comparison to copper in conductive polymer composites is that it is not as prone to oxidation and becoming non-conductive as finely divided copper. The design and photographs of the manufactured components are presented in Figure 15. In addition to CB also carbon nanofibers and graphite flake microparticles can be added to thermoplastic polymers to create conductive blends suitable for 3D printing. For applications in aqueous media, polystyrene was identified as the most versatile and best performing matrix material [43]. Also multiaxial force sensors have been manufactured using FDM printing with two different materials simultaneously. Also these kind of sensor structures can be utilised in condition based monitoring. [44, 45]

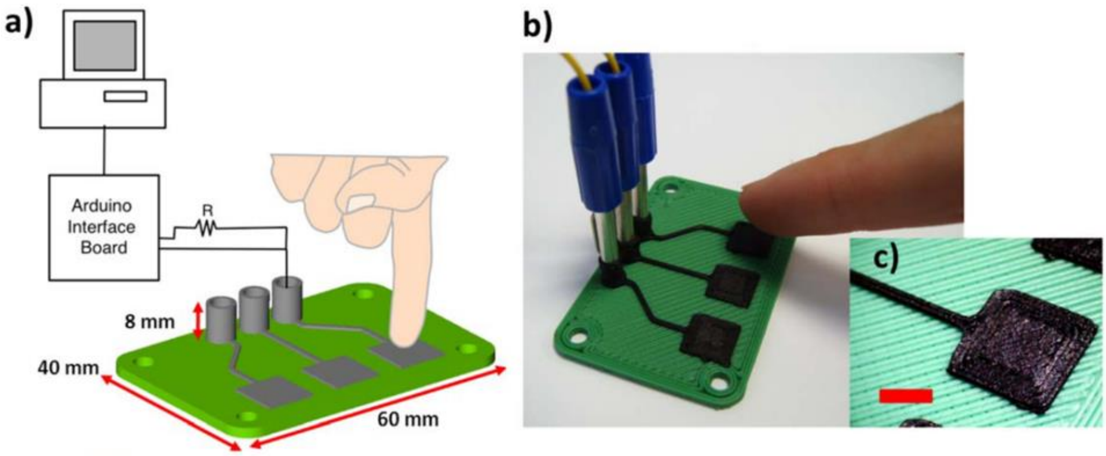

Figure 15. 3D printing of capacitive interface device. a) the CAD design of the printed interface device and the simple circuit used to detect inputs, b) a photograph of the printed device, c) a macro image of the printed sensor pads (scale bar 5 mm) [42]. © 2012 Leigh et al.[12]

A more complex structure in a plastic component as a hybrid printing approach utilising a Tabletop nScrypt 3Dn hybrid 3D printer has been presented by Carranza et al. [46]. The

[11] © Springer Nature 2014. Reprinted by permission from Springer Nature: Espalin D. et al., 3D Printing multifunctionality: Structures with electronics, International Journal of Advanced Manufacturing Technology, 14, 5-8, 2014, pp. 963-978.

[12] © 2012 Leigh S. et al., A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors, PLoS ONE, 11, 7, 2012, pp. 1-6. Creative Commons Attribution 4.0 License https://creativecommons.org/licenses/by/4.0/

dielectric (ABS plastic) and the conducting silver paste (CB028) were printed using the nScrypt's nFD and Smart pumps and the electrical components manually inserted post-process. The electrical components were one NE555DR integrated circuit, one 100 kΩ resistor, one 51 kΩ resistor, one 1 kΩ resistor, one 1 μF capacitor, and an APD3224SURCK-F01 red LED. The models of the circuit and the printed structure and the image of the actual printed is presented in Figure 16. The model of the circuit presents well the possibility of having the conducting lines in complex orientations not only on one level made possible by the hybrid printing while the manufacturing is carried out by a single printer system.

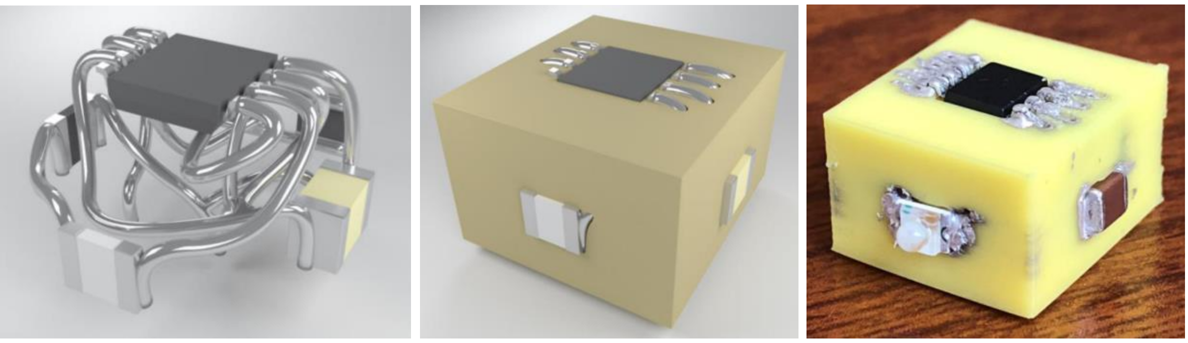

Figure 16. Hybrid printing approach with modelled circuit and structure (on the left and centre) and the printed part (on the right) [46]. © 2019 IEEE[13]

One example to provide more information from the manufacturing process is a case presented by Walker et al. [47]. Intelligence of sand cast moulds was increased with the addition of specific cavities to integrate sensors and to collect high fidelity data including environmental metrics, such as temperature, pressure, humidity, and acceleration, rotation and magnetic flux (Figure 17). For wireless sensing systems, Dialog IoT Sensor system was used. The system had sensing for three axes of magnetic field, an inertial measurement unit providing three axes each of rotation and acceleration and an environmental sensor with relative humidity, pressure and temperature. The commercial Bluetooth system was sufficiently inexpensive (~45 USD) to be considered disposable and was used buried within cores. The Bluetooth sensor systems are able to operate to a maximum of 85 °C and can be stored up to 150 °C.

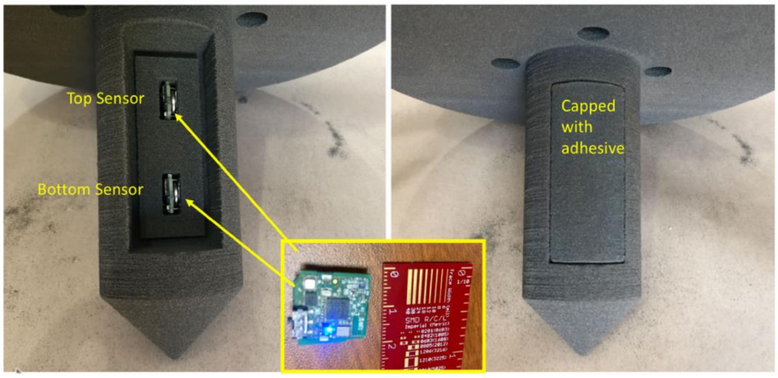

Figure 17. A Bluetooth sensor system embedded inside an internal core of a sand cast mould [47]. © 2018 Walker et al.[14]

The temperature during laser cladding manufacturing process has also been monitored in situ. DED was used to manufacture tensile test bars that have pre-manufactured cavities to which

[13] © 2019 IEEE. Reprinted, with permission, from Carranza G. et al., Design and Hybrid Additive Manufacturing of 3D/Volumetric Electrical Circuits, IEEE Transactions on Components, Packaging and Manufacturing Technology, 2019 PP. 1-1. 10.1109/TCPMT.2019.2892389.

[14] © 2018 Walker et al. 3D Printed Smart Molds for Sand Casting, International Journal of Metalcasting, 12, 4, 2018, pp. 785-796. https://doi.org/10.1007/s40962-018-0211-x. Creative Commons Attribution 4.0 License https://creativecommons.org/licenses/by/4.0/

then metal inserts with screen-printed strain and temperature sensors were embedded. The combined structure was then laser cladded successfully with sensors surviving and also measuring the temperatures during cladding. [48]

2.2.4 Other examples

One challenge for the electronics embedded inside a protective structure is the supply of power. Depending the power consumption of the system, the electronics need to be wired to a power source, the battery needs to be recharged or batteries replaced or the system itself needs to be able to harvest energy. One example of an energy harvesting system is a sensor based on Bluetooth communication without the need of a battery. A Wiliot chip glued to a simple antenna printed on plastic or paper can be used to authenticate the proximity of a product by transmitting an encrypted serial number along with weight and temperature data from a device the size of a postage stamp. The tag is able to harvest energy from the ambient radio frequencies, such as Wi-Fi, Bluetooth, and cellular signals and use them to power the ARM processor that can be connected to various sensors. [49] [50]

Intelligence can also be embedded in the parts in the form of changing properties due to elapsed time or external stimulus. For example, newly developed metamaterials can be used to change the mechanical properties of a component under magnetic fields [51]. The metamaterial fluids are injected into a hollow lattice structures and then the application of an external magnetic field causes the fluid to stiffen. Subsequently, the overall 3D printed structures stiffen almost instantaneously. The change is easily reversible and highly tunable by varying the strength of the magnetic field. Similarly, 3D printed magnetic devices can be manufactured using ferrofluids and liquid metals as presented by Lazarus et al. [52]. They used room temperature liquid metals (e.g. gallium alloys such as galinstan) to fill cavities inside 3D printed components. These can be used to create inductors, transformers and wireless power coils. An example of such a structure is presented in Figure 18.

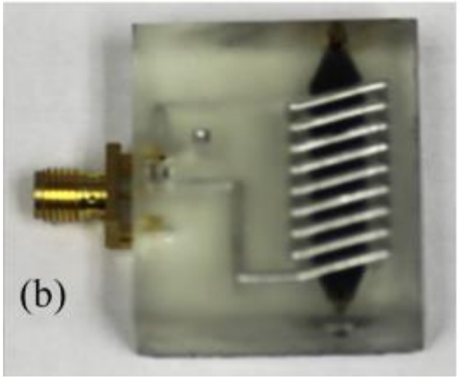

Figure 18. 3D printed plastic part with cavities filled with liquid metal conductor and ferrofluid core. The part is acting as a solenoid [52]. © 2019 Elsevier[15]

Intelligence can also be embedded in the form of printed, stretchable sensor matrix in the way that Forciot is providing [53]. The sensor matrix is composed of thin layers of stretchable and conformal materials and can be integrated into demanding elastic environments . The force measurement system can be used to measure dynamic force and pressure distribution and with additional on-board sensors temperature and motion. External power supplies, replaceable batteries, rechargeable batteries with wireless or USB charging and for limited applications energy harvesting as parallel option can be used.

[15] © 2019 Elsevier. Reprinted from Lazarus N. et al., Creating 3D Printed Magnetic Devices with Ferrofluids and Liquid Metals, Additive Manufacturing, 26, November 2018, 2019, pp. 15-21 with permission from Elsevier.

2.2.5 Reduction of mechanical properties due to process interruptions

In many cases, the embedding of some intelligence to the parts requires pausing of the manufacturing process. This may lead to reduction on mechanical properties. A study on the impact of process interruption on tensile properties of stainless steel 316L parts has been presented by Stoll et al. [54]. They assessed the effect of process interruption of samples manufactured with L-PBF machine (Concept Laser M2) using tensile test bars. Test bars were manufactured in horizontal and vertical orientation (Figure 19) with a process interruption of at least 60 min to ensure cooling of the powder bed and the parts to room temperature. In the process continuation, interruption layer was scanned once before the application of a new powder layer. Some bars were also manufactured with three scans on the interruption layer upon continuation. As a reference, tensile bars manufactured in a single step were used. All specimens were printed cylindrical and the final geometry was achieved by turning after printing. No heat treatment process was applied. The results showed that there is a significant drop in the mechanical properties if the L-PBF process is interrupted. For the vertical samples, yield strength $R_{p0.2}$ dropped 18.5% and ultimate tensile strength R_m 17.5% in comparison to the reference samples. For the horizontal samples, decrease was 13% for $R_{p0.2}$ and 11.5% for R_m.

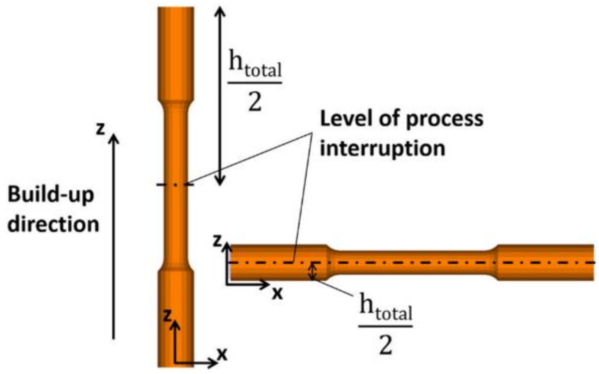

Figure 19. The orientation of the vertical and horizontal tensile bars and the level of process interruption [54]. © Springer Nature 2019[16]

The influence of the process interruption was larger for the vertical samples and explained to be due to the orientation of the interruption plane to the load during tensile testing. Further studies are needed to investigate if the reduced mechanical properties can be mitigated e.g. by modifying the process parameters for the first layers after the process interruption. Nevertheless, the possibility of reduction in mechanical properties due to process interruption needs to be taken into account when carrying out design for the parts or systems that have embedded intelligence.

3. Summary

This report was written to see what kind of technologies have been presented in literature dealing with additive manufacturing and embedded intelligence. The idea was also to give the companies participating in the DIVALIITO project some examples and ideas on what they could be benefitting from and to be realized as a demonstrator use cases during the DIVALIITO project. In the manufacturing of most presented use cases, additive manufacturing was utilised but a few cases with embedding in traditionally manufactured components with added

[16] © Springer Nature 2019. Reprinted by permission from Springer Nature: Stoll P. et al., Impact of a process interruption on tensile properties of SS 316L parts and hybrid parts produced with selective laser melting, The International Journal of Advanced Manufacturing Technology, 2019, https://doi.org/10.1007/s00170-019-03560-1

intelligence were included. Embedded intelligence can mean sensing elements added on the surface of the parts or elements added inside the parts. In majority of the cases, the elements have been added during the manufacturing process.

Embedded intelligence can be used e.g. in improving the communication, detecting or condition monitoring of the digital spare parts simultaneously having the sensors well protected from the environment. The used sensors and technologies should be selected depending on what phenomena is intended to be measured. Nevertheless, the application of sensors and manufacturing the components with functional sensors inside the parts is not always straightforward. Especially when embedding traditional electronics in metal AM components, the accumulated heat during the manufacturing process can destroy the sensing elements and special care needs to be taken in the design taking into account the possibilities and limitations. Typically, for plastic components the embedding process is easier with lower temperatures. The process interruptions to enable the embedding of sensing elements can reduce the mechanical properties of the parts and should be investigated case by case.

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