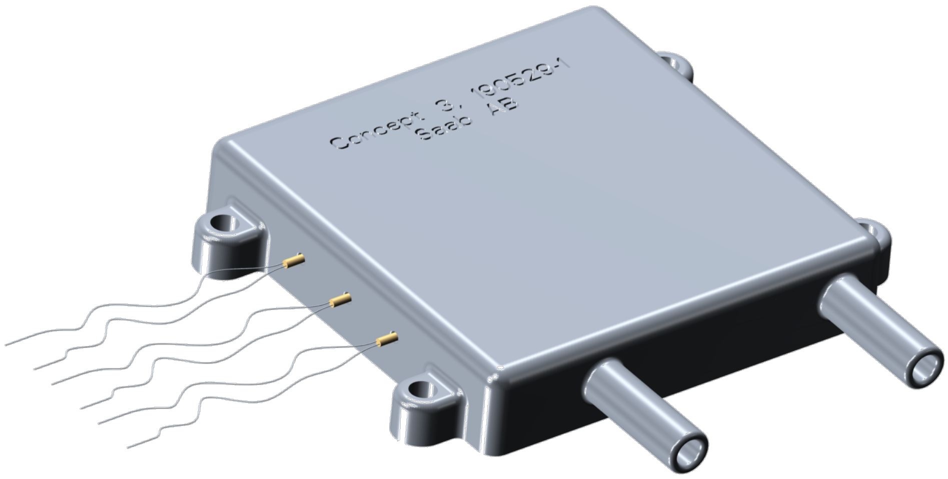

Integration of electrical components in metal additively manufactured products

- Master's Thesis in Product Development

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Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden 2019

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Cover: A simplified cooling plate with three integrated temperature sensors
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Abstract

As the development in additive manufacturing (AM) is moving at a fast pace, Saab Group – Defence and Security wants to examine all the aspects of the technological development's impact. Traditionally AM has been used to print complex homogeneous non-functional structures, but as a result of major achievements in recent years the possibility to print functional structures has paved the way. A lot research has been done regarding the integration of electrical elements in polymeric AM, but little has been done in metallic AM. The reason for this is the operating temperatures jeopardising the electrical elements survivability. The combination of the physical and virtual domain in the same framework improves maintenance decision and revolutionises safety. Thus this is a key enabler of the upcoming industry 4.0.

The report aims to explore and evaluate different intelligent structural-health-monitoring systems which can be integrated into metallic AM parts. This was initially done by deriving a simplified cooling plate which lays the foundation of the further described case study. According to the literature findings, the most promising AM methods has shown to be ultrasonic additive manufacturing (UAM) and selective laser melting (SLM). Furthermore, piezoelectric sensors, thermocouples and resistance temperature detectors has been evaluated. In total 20 different concepts were generated and four of them passed the established screening criteria, among which manufacturing complexity and compatibility with AM where some.

The four concepts were then divided into three cooling plates based on their characteristics and a fourth cooling plate was representing the baseline solution (a cooling plate with no sensor). A pause-build procedure was implemented in order to integrate Pt100 temperature sensors into an aluminium alloy with SLM and thus form the proof of concepts. In the end, metal prototyping of the concepts with integrated temperature sensors was accomplished. Although, the prototyping plan had to be revised towards the end with additional post-processing. A CT-scan of one of the printed prototypes was conducted in order to observe appeared defects. Through observations and analyses, learnings and conclusions could be obtained to determine the feasibility and limitations of sensor integration in AM products.

Keywords: Additive manufacturing, AlSi10Mg, structural health monitoring, sensor integration, smart structures.

Acknowledgement

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Nomenclature

Abbreviations

AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CNC	Computer Numerical Control
CT	Computed Tomography
DED	Direct Energy Deposition
DfAM	Design for Additive Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EOS GmbH	Electro Optical Systems GmbH
ET	Eddy Current Testing
IC	Integrated circuits
LBM	Laser Beam Melting
LS	Laser Sintering
MT	Magnetic Testing
NDT	Non-Destructive Testing
PBF	Powder bed fusion
PCB	Printed circuit board
PT	Penetrant Testing
RT	Radiographic Testing
SHM	Structural Health Monitoring
SLM	Selective Laser Melting

SLS	Selective Laser Sintering
UAM	Ultrasonic Additive Manufacturing
UC	Ultrasonic Consolidation
UT	Ultrasonic Testing

Greek symbols

α	Temperature coefficient [°C^{-1}]

Roman symbols

E_A	Applied energy density
P	Laser power
SP	Scan spacing
U	Scanning velocity

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1. Introduction

1.1 Background

Saab Group - Defence and Security operations are divided into five business areas, among which the Surveillance area is one. Saab Surveillance works towards effective solutions in monitoring, security and decision making. This area further provide various of systems for detecting and protecting against the diversity of different threats. The product portfolio covers airborne, land-based and naval radar systems together with electronic warfare, combat systems and C4I solutions [1]. The research development in Additive Manufacturing (AM) is a fascinating area and the development is moving at a fast pace. As part of their continuous improvement work in their radar systems, they now want to investigate the possibilities to integrate the new manufacturing technology into the formation of their future electromechanical components.

In general AM offers various of benefits in terms of reduced lead-time, optimised resource utilisation and flexibility which the current state-of-the art deficiencies in. Traditionally AM has been used to print complex homogeneous non-functional structures, but as a result of major achievements in recent years the possibility to print functional structures has paved the way [2]. AM has the potential to enable manufacturing of different components with different materials in one single building sequence which could reduce the manufacturing supply chain significantly. Mechanical products containing functional electrical elements like integrated conductors, smart materials and different types of sensors offers unprecedented possibilities. Furthermore, a lot research have been done regarding the integration of electrical elements in polymeric AM, but little has been done in metallic AM. The reason for this is the operating temperatures jeopardising the electrical elements survivability.

In addition, the integration of electric elements in metallic structures allows the user to detect, locate and quantify the addressed damage and/or degradation inside of the structure. Traditionally the structural integrity has been ensured through external inspection and/or the use of traditional non-destructive testing technologies. But as AM parts increase in complexity their through-life performance has become increasingly difficult to ensure due to the difficult accessibility. Therefore, this master thesis will explore the possibilities, advantages and limitations of integrating functional electrical elements into metal AM products [3].

1.2 Aim

This master thesis aims at studying and examining how functional electrical elements can be integrated within mechanical products using AM production technologies. The research aims to identify the requirements, limitations and needs of AM to enhance the knowledge and understanding of manufacturing of electromechanical components with AM.

The possibilities of creating mechanical products with both integrated conductors and contacts, smart materials or different sensors will be explored. The objective is to investigate one case regarding the integration of electrical elements with the aim to explore the value, knowledge- and solution space of the AM technologies for the particular chosen case. Different AM production technologies will be examined with respect to their possibilities and limitations, as well as compared to the traditional manufacturing technologies that is utilised today for integration of electrical elements.

In addition, another objective is to propose and develop a methodology with guidelines, solutions, considerations and necessary actors for implementing AM regarding electromechanical products in the company's development process and production.

1.3 Delimitations

Delimitations are necessary and are made to clarify what this master thesis will not consider and treat during the project time. Considering this master thesis's definitions and aim, the following delimitations are made.

- This is the explorative study of a research project for the company which is expected to be continued in the future.
- Due to the time constraint, only one case study regarding the integration of electrical elements in a mechanical AM component will be examined.
- Restrictions regarding the number of selections of possible integrating electrical elements to a small number that are the most interesting and relevant for the company will be made.

- Some requirements on the mechanical components that will be involved in the results for the examination might not be considered. This, to enable full exploration of the knowledge- and solution space but also the limitations.
- The study of candidate strategies will be initially constrained by the company's economical viability.

1.4 Specifications of research questions

Considering the master thesis's objectives as a basis, the following compilation of research questions to be answered throughout the thesis are made.

- RQ1: How is the feasibility of integrated electrical elements in a 3D printing procedure today?
- RQ2: What are the advantages, limitations, required activities and recommendations regarding the integration of electrical elements in a 3D printing procedure?

1.5 Ethics

As Saab is a part of the defence industry, it is important to know, understand and be acceptable with what one is developing and how and where the developed product will be used. Therefore, before accepting this research project from Saab, some important questions regarding the ethics of the project and organisation needed to be answered. For this thesis work, the answered questions have been related to the six fundamental principles which can be found in the ESCR Framework for Research Ethics [4].

For instance, the intended possible use of the research was fully informed before initiating the research project. Further, the participants confidentially and anonymity has been respected due to personal factors but also due to the high security classification of certain information. The research where conducted at Saab Surveillance which provides systems of various sort, to detect and protect the residents of a country and not to be used for the contrary.

2. Theoretical framework

2.1 Product development process

The generic product development process proposed by Ulrich and Eppinger was applied to this thesis work. However, the whole product development process was not utilised thus only some phases of the process were applied [5]. The phases of the generic product development process which were utilised, adapted and applied for this thesis work can be seen in Figure 2.1. The work started with a extensive literature studies and a number of meetings with internal and external actors. This to get a clear insight of the problem. Once a great load of relevant information was collected, a problem solving case was established and a functional analysis of the case could then be obtained. The work continued with an idea- and concept generation, evaluation and selection to obtain technically and economically feasible concepts. When the final concepts had been obtained, prototypes of these concepts were developed and manufactured. In the last phase, conclusions and recommendations could be obtained and reported. All the findings and results were continuously documented in the thesis report throughout the work [5].

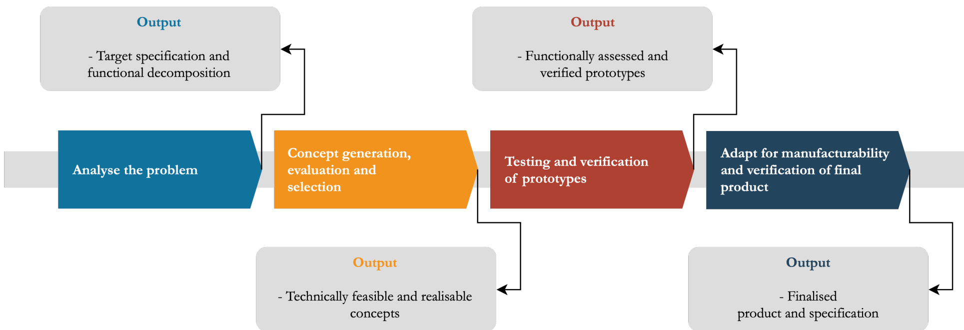


Figure 2.1: Generic product development process [5]

2.2 Additive manufacturing (AM)

The basic principles of AM were initially introduced in the late 1980's where the emphasis were on manufacturing a physical resultant part from a virtual computer-aided-design (CAD) description. In addition, data from the CAD model is used to deposit, selectively or partially melt material layer upon preceding layer. The American Society for Testing and Materials (ASTM) established a standard, which categorises additive manufacturing processes into the following seven categories

1. Vat photopolymerization
2. Powder bed fusion
3. Material extrusion
4. Material jetting
5. Binder jetting
6. Directed energy deposition
7. Sheet lamination

The report will in particular address *powder bed fusion* and *sheet lamination*. This due to the findings from the literature review, the stakeholders requirements and needs but also their respective suitability for the intended application which will be described further in the report [6].

2.2.1 Powder bed fusion (PBF)

The powder bed fusion is a term that encompasses several terms, among which Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective laser melting (SLM) and Selective laser sintering (SLS) are some. There is a wide range of different terms to describe the fusion mechanism which occurs in a powder fusion process. This has resulted in a broad terminology list with variants of *sintering* and *melting* being the most well known. There are in total four dominant powder fusion mechanisms by which fusion occurs namely chemically induced binding, solid-state sintering, liquid-phase sintering and full melting. The most utilised fusion mechanism in commercial processes is further liquid-phase sintering and full melting. This AM process is one the earliest, most rapidly growing and first commercialised process among AM manufacturing processes where selective laser sintering (SLS) is the first commercialised PBF process. The basic method of operation for all the mentioned processes is that a thermal energy fuses areas of a powder bed by inducing fusion in between powder particles. The thermal energy can either be provided by a laser or a electron beam in order to melt and fuse powder. The report will further in particular address SLM [6].

2.2.1.1 Selective laser melting (SLM)

SLM, also known to be used synonymously with SLS, is a fusion mechanism which uses a high power-density laser to melt fine powder particles. However, in some context SLS is considered to be a subcategory of SLM. The difference is, as the terms indicate, sintering versus full melting. Where with sintering, the powder is heated up to a certain temperature (≈ half of the melting temperature) where the powder particles fuses together on a molecular level rather than fully melting the powder particles. Due to that, one can sinter the powder if the AM machine is capable of melting the powder. No bigger difference between SLS and SLM will be done further on in the report and it will thus be used synonymously.

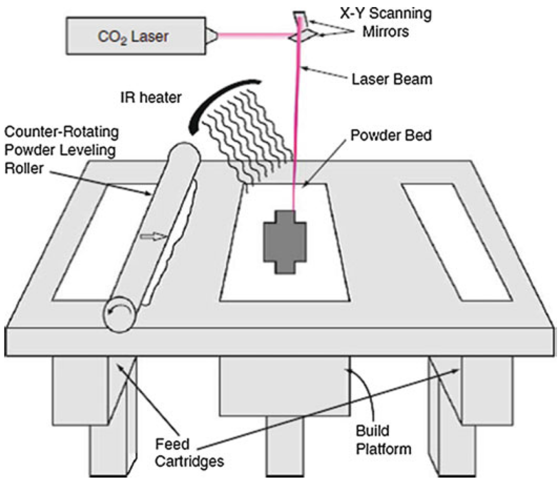


Figure 2.2: Schematic of the SLS process [6]

Mentioned process is schematically illustrated in Figure 2.2 and takes place inside an enclosed chamber filled with inert gas. The inert gas does not undergo chemical reactions under certain fixed parameters which is why it is used to prevent oxidation and degradation of the build material. There is a wide range of materials used in PBF, ranging from ceramics and composites to metals. With respect to the stakeholders product portfolio, emphasises will be on a aluminium alloy, more specific AlSi10Mg.

In short, a laser beam scans over region of the powder layer defined by the CAD-model by fusing the powder either fully or partially. Hence, the heat is generated locally and not globally to the whole build. Iteratively the build platform is lowered by the defined layer thickness (usually varies between 30 μm to 150 μm) where the recoater simultaneously distributes the powder.

There is a constant trade-off regarding the layer thickness, build quality and total print time. A thicker iterative layer result in a higher surface roughness and thus a staircase effect. Further, it is also possible to use more than one laser simultaneously based on the application. The thermal energy obtained from the laser has a wavelength tuned to the absorptivity of metal powders with a power ranging from 50-1000 W.

2.2.1.2 Laser-based system: EOS M290 Metal

There is a wide variety of different laser-based system that is used for melting and sintering of metal powder, among which the laser-based system EOS M290 Metal is one. This laser-based system will be further be used in this project. See Table 2.1 for basic specifications.

Table 2.1: Specifications for EOS M290 Metal

Technical data	
Build volume	250 x 250 x 325 mm
Laser type	Yb fibre laser 400 W
Scan speed	up to 7.0 m/s
Focus diameter	100 μm
Inert gas supply	7000 hPa, 20 m^3/h

In addition to the listed it is also worth mentioning that the power consumption is at the maximum level 8.5 kW and at average 2.4 kW with the platform heating up to 3.2 kW. This mentioning due to that the process is intented to be paused at a specific layer and then continued after insertion of the electrical component. The ambient temperature inside the chamber is slightly above room temperature ($\approx$ 30°C) due to the heat from the laser beam. Furthermore, for AlSi10Mg the local temperature from the laser beam is approximately 600°C [7].

2.2.1.3 Electron beam melting (EBM)

In contrast to SLM, EBM uses a high-energy electron beam in order for the fusion mechanism to occur between the metal powder particles. Other characteristics that differs from SLM is that the process is performed under vacuum and used solely for metals and alloys. There is also a difference in the build-up speed which is thus higher for EBM due to the speed being limited by galvanometer inertia for SLM. However, some argue that the manufacturing time sequence is lower for EBM than SLM, but the extra steps such as post-processing steps in EBM result in the process total build-up being actual higher than for SLM [6].

2.2.1.4 Properties of PBF manufactured products

There are a variety of parameters and trade-offs when printing with SLM. The fusion related process parameters influence the printed structures' microstructures, porosity level, surface roughness and heat buildup among many other. Listed below are some process parameters that are important to keep in mind when manufacturing additively with SLM [6].

- Laser-related parameters such as pulse frequency, spot size and laser power.
- Scan-related parameters such as scan speed and scan spacing.
- Powder-related parameters such as particle shape, particle size and layer thickness.
- Temperature-related parameters such as operating temperature and temperature uniformity.

For example, the laser power, operating temperature, scan speed and spacing must be balanced in order to achieve the optimal trade-off between for instance melt pool size, dimensional accuracy, surface roughness and final mechanical properties. In addition to properties of the powder produced structure, issues with the actual powder feeding can be problematic. Small powder particles can migrate and become airborne. This can result in deterioration of integrated fiber optic sensors or derogation of integrated sensors due to the clouding of the actual electrical element which in turn affects the sensitivity of it [6].

Furthermore, there is a wide variety of different models derived from physics, thermodynamics and heat transfer principals that are relevant to describe properties of PBF manufactured products among which the model of applied energy density E_A is one. The absorbed energy density affects both the melt pool size and melt pool depth of the product. The equation is defined as followed.

$$E_A = \frac{P}{U \cdot SP} \tag{2.1}$$

where P is the power of the laser and U the scanning velocity. Lastly SP can be described as the scan spacing in between the parallel scan lines [6].

2.2.2 Sheet lamination

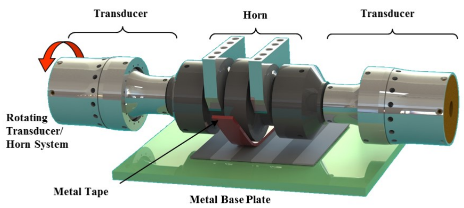
The sheet lamination is a process in which sheets or ribbons of material are joined upon each other to form an object. The mechanism in which the sheets or ribbons of material are bonded can be employed in the following four type of ways.

1. gluing or adhesive bonding
2. thermal bonding
3. clamping
4. ultrasonic welding

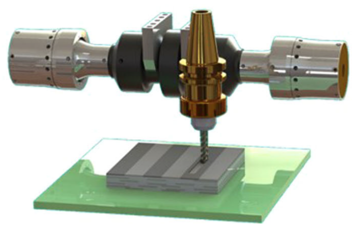
The report will further in particular address ultrasonic welding, more particularly the process is termed ultrasonic additive manufacturing [6].

2.2.2.1 Ultrasonic additive manufacturing (UAM)

Also known as Ultrasonic Consolidation (UC), is a hybrid solid-state manufacturing process that uses additive joining of thin metal foil (100-150 μm thick). The additive joining is used interchangeably with subtractive computer numerical control (CNC) milling operations, see Figure 2.3. This in order to produce metallic structures built from bottom to top with temperature ranging from room temperature to 200°C.



(a) Ultrasonic metal seam welding



(b) CNC milling

Figure 2.3: Ultrasonic Additive Manufacturing [8]

The basic method of operation, as seen in Figure 2.3a could be described by a rotating sonotrode oscillating transversely along the length of the metal foil. The thin metal foils are laid and held densely by a normal force from the rotating sonotrode to the build plate initially and with the previous layer later. As mentioned this is an additive-subtractive process where the thin metal foils are trimmed interchangeably with CNC milling, usually after four deposited layers [6].

2.2.2.2 Properties of sheet laminated products

There are three types of defects that mostly occurs during UAM. The first type of defects are voids along the layer interface that is a result of the metal foil surface roughness. It can also occur in combination with insufficient input energy or solely by insufficient input energy while bonding the layers together. In contrast to the last mentioned, excess energy input can also result in damaged areas at the layer interface which lead us to the second type of defect. Damaged areas occur due to breaking of previously formed bonds. Lastly gaps can occur in between adjacent foils which can result in weakness of the structure in question [6].

2.3 Findings from literature review

In this chapter, findings from the literature studies are presented. Once a great load of relevant information from the literature studies was collected, the information could be classified into two domains. The first field of findings is regarding current trends with regard to integration of sensors in products through AM. The second field of findings is regarding current challenges with regard to the equal subject matter.

2.3.1 Current trends in integrating sensors in products through AM

AM has developed and grown into a true manufacturing technology from prototyping but lately two new headlines within AM are now receiving attention. The headlines are *Structural Electronics* and *3D Electronics printing* and refer to the integration of a sensor or electronic system within the volume of AM products.

Sensor integration can enable monitoring applications such as "Vibration damping" where piezoelectric sensors are integrated and used to monitor and control the structural vibrations through the embedded sensors. Another application is "Structural Health Monitoring" where fibre optical sensors are integrated and used to detect or locate damage and thereby predict remaining lifetime in e.g. aerospace applications. By linking AM and sensor integration, the possibilities to manufacture smarter products with functionality opens up. This since AM allows full control of manufacturing of internal volume structures e.g. a pocket inside a component's body which is used as a space for the sensor to be integrated [9].

Dirk Lehmus et al. emphasize the benefits of a relationship between AM and sensor integration by demostrating a metallic AM part with a RFID volume integration for the RFID tag to be integrated. The integration represent a complex electronic system which would not be possible to integrate in an AM metallic part via in situ processes [9]. In another article, Philipp Stoll et al. mentions the rising importance of sensor integration by explaining that sensor integration in combination with AM is today a key enabler of the evolving industry 4.0. This approach related to the integration of sensors during an AM process is of massive interest of different industrial sectors. By utilising the core of AM which is its layer by layer manufacturing process, facilitates the integration of functional elements into different components. This allows monitoring of critical locations of components as sensors can be placed in those vicinity of critical locations [10]. Gausemeier et al. also show in their road-map that a field of research that is getting increased attention is precisely the integration of external components into AM parts. They also emphasise that the compelling importance of integration of functional elements will keep rising in the next years and that the trend has just started. An example that supports this statement from Gausemeier et al. is the conducted experiments. The experiments are conducted by several research groups regarding embodiment of external functional elements into SLM parts during the manufacturing process [11].

Alexander Dijkshoorn et al. writes about the recent developments in multi-material 3D printing which has resulted in a number of researches into 3D printing of functional structures. Combining AM and integration of sensors seems like a promising next step for increased functionality in products as there are opportunities for reduced costs regarding fully integrated manufacturing, since no assembly will be required [12]. Hessel H. H. Maalderink et al. agree that combining AM and electronic integration is an emerging field since this combination enable freedom of manufacturing. By combining AM with electronics to manufacture complex structural components with integrated electronics, there is no need for product-specific tooling as compared to traditionally manufacturing methods. This combination has the potential to unlock different cost-effective application domains e.g. antenna structures, in comparison with conventional manufacturing technologies which are not as cost-effective [13].

A presentation at the university of Cincinnati was held by Richad Dunst and Otis Mills where it was presented that Hai-Lung Tsai et al. investigated AM of smart parts with embedded sensors for in situ monitoring in advanced energy systems. The research was conducted due to an increasing need of embedded sensors in advanced system as the sensors need to survive and operate in high temperatures, high pressures and in harsh environments. This need is especially essential in civil engineering for structural health monitoring considering the traditional approach how sensors are installed onto components today. Poor survivability and reliability of the sensors are some characteristics when sensors are integrated onto the part after fabrication. Additionally, the costly and complicated sensor packaging which are required before the sensor integration are as a result of today's current traditional approach for sensor integration [14].

Adam Hehr et al. writes about Nasa's developed Digital Twin paradigm which is a long-term vision and can be defined as a physical-virtual monitoring concept. The Digital Twin paradigm provide reduction for overdesign, enhancement of reliability, support during decision making, improvement of maintenance and revolutionises safety. A key factor of the paradigm is its integrated sensors and sensor system. According to Adam Hehr et al., usage of these sensors for real-time monitoring of engineering systems is becoming a field which is getting increased attention in the industry as it can be used to provide improvement for operational decision making [15]. Maria Strantza et al. state how attractive the aerospace and automotive industries are of structural health monitoring (SHM) systems. The attraction is due to the SHM systems' ability to provide feedback regarding the structural integrity of an engineering structure during real operation conditions. Usage of integrated sensors in a SHM system entails improvement of life-safety and reduction of the operational cost as it is related to the maintenance cost [16].

In another article, Ellen Cesewski et al. discuss the opportunities and advantages that will emerge for the future when embedding non-printed components e.g. sensors within the volume of 3D printed parts. The embodiment will provide advantages such as 3D printed systems with enhanced functionality and performance. The embodiment will also provide opportunities for manufacturing of novel electronic devices e.g. 3D printed flux sensor and electrode-integrated microfluidic [17].

Based on the literature findings, it can be concluded that an emerging trend regarding integration of sensors is getting increased attention in various industrial sectors today. A trend regarding integration of sensors is emerging since integrated sensors will open up a field with new possibilities and opportunities e.g. novel monitoring applications which is desired. This as reliability and life-safety of a structure are two parameters that are in need for enhancement. Integrated sensors are notably desired in products which will be used in harsh environments. By embedding the sensors within the product's volume will ensure the survival of the functional sensors during harsh operations. Sensor integration within products also has the potential to unlock improvement of functionality and performance of the targeted products. The trend can be associated with AM since AM brings various advantages compared to conventional manufacturing technologies when sensor integration is involved. A combination of sensor integration and AM will provide enhancement for the survivability and reliability of the sensors and be more cost-effective in comparison with a combination of sensor integration and conventional manufacturing technologies.

2.3.2 Challenges of integrating sensors in metal products through AM

Integration of electronic components, specifically sensors, is as mentioned getting increased attention and many industrial sectors have begun to realise its potential and opportunities for new smart electronic applications in combination with AM. But mass production of 3D printed products with integrated sensors have not been applied to the market yet. This is due to the various challenges that need to be resolved before mass production of these smart products can be applicable in the industry.

One of the biggest challenges when integrating sensors within metal AM products is the local heat from the laser beam during the AM process. With that being said, the major issue is to ensure the sensors' survivability and functionality during the printing process since electrical components and specifically sensors are temperature sensitive components. Adam Hehr et al. emphasizes about how challenging it is to integrate sensors into metal components through melt-based 3D metal printing. The high temperature due to the AM technology can have a big negative impact on the functionality of the sensors as residual thermal stresses and interfacial voiding can occur [15]. Maier also agrees that sensors are very temperature sensitive components and thereby emphasised the recommendation to focus on developing the sensor type optical fibre sensors. This, since optical fibre sensors have the properties to survive the thermal loads during the AM embedding process. However if optical fibre sensors would be embedded within a metallic AM part, the fibres would be limited to be embedded as straight, horizontal lines. A result of this limitation off-the-shelf sensors e.g. PT100 much more interesting for the industry since they are relatively cheap, standardised and highly available [18]. In addition, a specific orientation as compared to fibre optic sensors is not required.

Chang et al. mention other challenges that are faced when embedding sensors into metallic AM parts. One issue is the compatibility of the involved materials, specifically between the host material and the material of the electrical component. The materials must be compatible with each other to ensure the properties of the functional and structural materials. Another issue is the potential of negative impact on the inter-layer connectivity and strength when stopping the AM building process to integrate the functional component onto the part and afterwards continuing the building process [19].

Dirk Lehmhus et al. reported another issue regarding embedded volume-integrated sensors within metallic components and the specified issue is the readout data. Complications regarding the readout data will occur because conductive paths need to be integrated and lead out of the part but the challenge is the attachment of the integrated sensors and conductive paths. The sensor must be physically attached to the part or it can result in a negative impact to the actual measurement. E.g., if temperature sensors would be integrated within a metallic part for temperature measurements, the response times would be slower due to insufficient thermal contact [9].

Except for challenges that are directly related to integration of sensors, other challenges that are indirectly related to sensor integration must be overcome e.g. challenges related to the AM technology to be used in coherence with sensor integration for manufacturing of smart applications. Bailey et al. have looked into strategies for 3D printed electronic manufacturing and reported a number of challenges that needs to be overcome before 3D-printing of electronic applications becomes conventional in the industry. One of the reported challenges is the material limitations for 3D printing, current inks and materials are not sufficient enough to provide the required electrical performance and reliability with regard to the industry's requirements. Another challenge is the dimensions and tolerances, very small dimensions and tolerances requirements can have difficulties to be met with current AM technologies. Lastly, 3D-printing of smart parts creates a need for integrating electronic CAD with mechanical CAD tools including analysis tools for thermal, electrical, mechanical and physical design [20].

It can be concluded from the literature findings that a number of challenges need to be overcome before integration of electronic devices e.g. sensors within 3D-printed metallic parts can become a conventional manufacturing strategy for manufacturing of smart products. The major challenges are to assure the sensors' survival and functionality from the heat during the 3D-printing process and to establish high product quality by assuring that the involved materials of the fabricated product are compatible with each other and by assuring the electronic system are physically attached to the product and not movable. Lastly, if it can be assumed that a successful integration of sensors onto a metallic part take place, a big problem and challenge that will arise is finding novel strategy solutions for how to replace the embedded sensors with new ones during maintenance. Replacement of the embedded sensors would bring a lot of difficulties or may be impossible since the embodiment of the sensors within the metallic part are not reachable unless the part is opened or split in half.

2.4 Design for AM (DfAM)

Manufacturing additively offers unprecedented design and material freedom. However, it is important to understand the AM process limitations as there is a variety of trade-offs taking place regarding manufacturability, reliability and cost of the end product. As earlier mentioned AM processes can be categorised into seven categories with unique design rules and principles applied respectively. With respect to the intended application the main focus will be on powder bed fusion process for metallic parts. Furthermore, the design guidelines are also unique when considering SLM and EBM due to the two processes' characteristics. The main focus will in particular be SLM and the material aluminium alloy, AlSi10Mg.

In addition to the unique guidelines for the sub AM process one should also take the actual laser-based system capability in consideration. This due to that the system capabilities is unique. The importance of manufacturability with regard to additive manufacturing and the machine capability (in some instances also the powder) lies within the actual concept generation phase. When generating concepts one should take geometrical features in considerations, below are some that has been taken into consideration.

2.4.1 Part orientation

The orientation of the part on the build platform affects the cost, quality and buildability of the part. The buildability factor that is of value is the angle to recoater. The part should be orientated in a manner so that the recoater do not hit the part or integrated electrical element while adding a new layer of powder when it approaches at a 0 degree angle. It is recommended to orient the part at an angle of 30 degrees or more and/or orient the thinnest part perpendicular to the recoater [21].

The cost is affected by the build time, nesting of parts and the used amount of support structures. They are all dependent on the orientation of the part. In this context the orientation and thus the nesting need to be fixed in order to generate concepts for the different cavity configuration. For example in some configuration it considers the cavity concealing the laser beam from the electrical element. Lastly, the quality of the part is defined as the surface roughness, dimensional accuracy and removability of support structures. In this context the main support will be the powder itself and is thus removed by either brushing it off, abrasive blasting it and/or usage of tools [21].

The surface roughness is also important due to the thermal paste attachment on the surface in the cavity which depends on the actual surface roughness of the cavity. During the integration process when pausing and continuing the process, the dimensional accuracy is of importance in order to prevent a mismatch of the continued part build [21].

2.4.2 Channel length and diameter

Initially holes and internal channels must be open from one end in order to clean away excess powder. It has been seen that irregularities in roundness occurs when the channel diameter exceeds 10 mm and the hole in question is built in the XY-direction. Thus the need for support structures in the centre is crucial to maintain roundness. However, diameters ranging from 1 - 10 mm can be produced with minimal deviations in roundness and manufactured without support structures in XY-direction. If one decides to produce holes exceeding 10 mm support structures can be avoided by redesigning the holes into raindrop formations instead of circular ones [21].

In the Z-direction holes ranging in diameter from 0.5 mm to 12 mm has been manufactured with good quality relatively to sizes printed in XY-direction [21]. In addition, Renishaw, a global leading British engineering company in metal additive manufacturing asserts that the minimum hole diameter on most laser-based metal systems is sensible to build diameter as small as 0.4 mm. However, they also claim that holes between 1 to 10 mm may be produced without support structures, but they can suffer from distortion as a result from their down-skin surfaces. The down-skin surfaces can in turn be a result of the slow cooling of the weld pool on top of the overhang [22].

2.4.3 Wall thickness

The thickness of the walls in a AM part depends on a variety of factors ranging from the angle direction of the recoater towards the wall, the height-to-width ratio and the surrounding of the wall. An increase of the height results in a thicker wall in order to obtain same stability and to avoid distortion/warping. Wall thicknesses ranging from 0.5 mm to 2 mm with the same height has been additively manufactured. The walls has further been angled to hit the recoater by both 0 degrees and 90 degrees. It was shown that walls oriented to hit the recoater by 0 degrees failed while the walls oriented to hit the recoater at 90 degrees succeeded for the mentioned thickness range. The thinnest wall (0.5 mm) oriented at 90 degrees was manufactured successfully even though it was expected to fail at both the angle scenarios [21].

2.4.4 Overhang angle

Horizontal segments like overhang angles and bridges in most cases need support structures in order to prevent the part from falling apart. For aluminium, the rule of thumb is that the minimum angle without the use of support structure is 45 degrees in contrast to titanium which ranges from 20-30 degrees. It has been tested with overhang angles ranging from 10 to 80 degrees. And it can be seen that from the angle 10 to 30 the surface goes from bad to corrupt [21].

2.5 Quality control of metal AM parts

The demand for visual inspection of additive manufactured components are high. In the trading towards traditional concepts made out of e.g. welding and casting, the defects and inaccuracies of the object produced must be evaluated. There are a variety of quality detection systems that can be used for detecting consequences from effects on strength, surface conditions and dimensional inaccuracies. The emphasises will be on non-destructive testing (NDT) and computerised tomography (CT). The emphasises is initially based on that there is no interest in destroying the samples in this phase and scope of the research and thus the interest for destructive testing is small. Secondly, the demand for utilising existing resources and thus use in-house resources is of primarily interest with respect to the characteristics of the organisation. The report will thus address computerised tomography (CT) and non-destructive testing (NDT) [6].

2.5.1 Non-Destructive Testing (NDT)

As the term indicates, NDT is a technique which evaluates the object in question without affecting its material and its related properties. NDT techniques can be divided into two main branches, surface methods and volumetric methods. Surface methods encompasses the following techniques

- Magnetic Testing (MT)
- Penetrant Testing (PT)
- Eddy Current Testing (ET)

and volumetric methods the following

- Ultrasonic Testing (UT)
- Radiographic Testing (RT)

MT was excluded due to lack of compatibility with aluminium which is not a ferromagnetic material but also ET, UT and RT for the lack of availability in-house. Penetrant testing was found a suitable process in order to detect defects and discontinuities on the surface of non-magnetic materials. The penetrant testing is conducted by applying a liquid/dye penetrant to the surface of the object for a specific time. The excess applied liquid/dye is dried and removed whereby the discontinuities in the object absorbs the penetrant. The penetrant in combination with the discontinue gives a hint of the location, size and characteristic of the discontinuity [23].

2.5.2 Computerised Tomography (CT)

CT scanning is a non-destructive method which is also known as industrial X-Ray computed tomography. Worth mentioning is that a industrial CT scan is described here and hence not a medical CT. As seen in Figure 2.4 a number of pictures from different angles of a specimen is taken in order to create a 3D image of the AM part. The technology is used to acquire knowledge and visualisation regarding the structural characterisation of the internal and external volume of the examined AM part. The acquired knowledge allows one, for instance, to detect porosity, cracks and powder left inside the AM part [24].

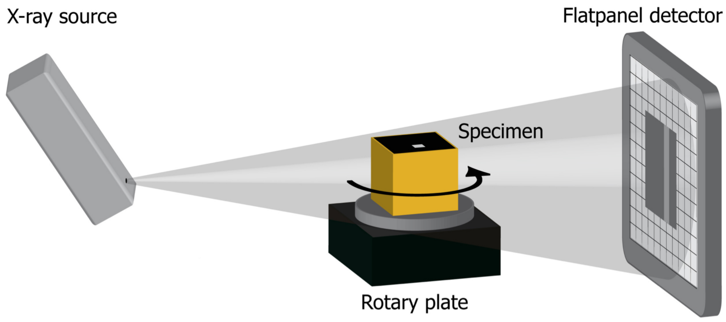


Figure 2.4: A conventional setup for CT-scanning

2.6 Classification of sensors

Sensors are devices which are used to sense and respond to an external physical quantity (input) from the physical environment. There are different types of physical quantities which sensors can detect and respond to e.g. light, speed, pressure and temperature [25]. The response (output) is commonly in form of a signal which is transformed to a human-readable display (e.g. thermometer) or to an electrical energy for further processing. An example of the latter is a temperature sensor which generates an output voltage due to changes in the temperature. There are two different types of outputs that can be generated by two different main varieties of sensors, namely analog and digital sensors [26]. Analog sensors provide analog voltages as output while digital sensors provide provide discrete values as output which require data conversion and data transmission [27].

Aside from analog and digital sensors, sensors can be further classified into two different categories, namely active and passive sensors. Active sensors require an excitation signal to operate. The excitation signal is in form of an external power supply which is required for the active sensor to produce the output signal. An example of an active sensor is the strain gauge. A strain gauge generates an output voltage in proportion to the amount of force and/or strain that is applied to the strain gauge device. Information about the generated voltage enables one to measure the strain of an object.

Unlike active sensors, passive sensors do not require an excitation signal to produce an output signal. Instead, the output signal is produced in response to some external environmental change [28]. An example of a passive sensor is the piezoelectric transducer. The piezoelectric transducer's materials generates voltage when the transducer is influenced by some type of energy which implies that piezoelectric transducers do not require an external power supply [29]. There are many different classes of sensors used for different measurements and they are all applied in various applications. These measurements can be physical properties e.g. strain, heat transfer, motion and temperature [25].

2.6.1 Temperature sensors

Temperature sensors are one of the most commonly used sensors, the function of the sensors is to measure the changes in temperature by corresponding to changes in its physical properties e.g. voltage or resistance. Temperature sensors are used in various applications e.g. mobile phone, air conditioning systems and industries. The most commonly types of temperature sensors that are used in today's electronic applications are thermocouple, resistance temperature detector (RTD), thermistor and semiconductor based integrated circuits (IC) [30].

2.6.1.1 Resistance temperature detector (RTD)

A RTD sensor is based on a simple correlation between the change in the metals' electrical resistance as a function of the metals' temperature. The resistance is measured in Ohm (Ω) and the temperature in degrees Celsius ($^{\circ}$C). Two of the most common RTD sensors that are used in various industries today are PT100 and PT1000. Their names are derived from the fact that at 100 Ω and 1000 Ω the sensors measure a temperature value of 0°C (32 $^{\circ}$F). The ratio described is defined as the relative resistance, see Figure 2.5 for the relative resistance of three different metals. The relative resistance is changed as the applied temperature is increased successively [31].

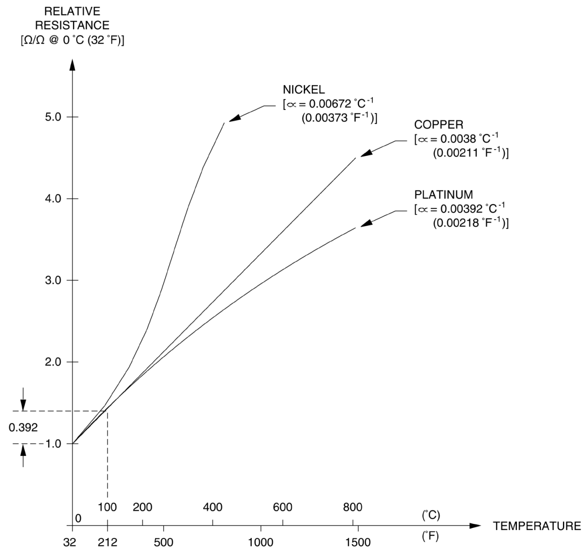


Figure 2.5: The relative resistance as a function of temperature [32]

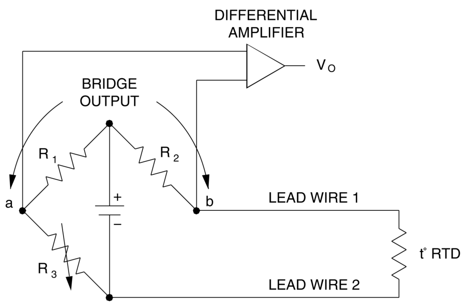
In Figure 2.5, the temperature coefficient (α) is also mapped for respectively metal. The coefficient is defined as the average change in relative resistance per degrees Celsius between the temperature range 0°C to 100°C. For example the temperature coefficient for platinum is $\alpha = 0.00392°\text{C}^{-1}$ which can be interpreted as that the relative resistance varies between 0.392 in between the mentioned temperature range.

There are two main classes of RTD sensors, namely thin film RTD sensors and wire wound RTD sensors [30], see Figure 2.6. The thin film RTD sensor configuration consist of a very thin platinum or metal glass slurry film which is deposited onto small flat substrate of ceramic while the wire wound RTD sensor configuration consist of a coil of thin platinum or metal wire on a insulator of ceramic. Both RTD sensor classes has wires attached to its configuration, the number of wires can vary between two, three and four wires and the more wires a RTD sensor has, the more accurate is the response [32].

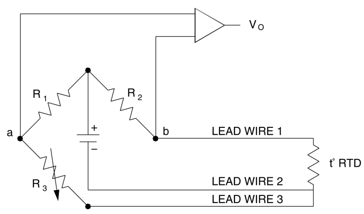
(a) Thin film RDT sensor

(b) Wire wound RDT sensor

Figure 2.6: Two different types of two-wired RDT sensors



(a) Two-wire configuration circuit



(b) Three-wire configuration circuit

Figure 2.7: Circuit with measurement of the change in resistance

3. Research methodology

3.1 Literature review

Considering the master thesis's objectives as a basis, a literature study was conducted. This was done in order to connect the customer needs to the relevant technology and in order to fund existing solutions to the main- and sub problem. The literature study was initiated at the beginning of the project, but proceeded throughout the whole development process. By searching for existing whole solutions, one can focus on finding solutions for critical subproblems that lacks fully satisfactory solutions. This can further result in the constitutions of new whole concepts with more satisfying subsolutions to the subproblems. There is a trade-off regarding the amount of keywords used and number of published articles founds to fully ensure coverage of the subject in matter.

Scopus, one of the largest citation and abstract database of peer reviewed were used as a literature source. In coherence with Saab Surveillance, keywords used in the literature search were established. The subject area, document type and year of publication were taken into consideration when screening the literature. There are two types of literature search proceedings, namely systematic literature review and systematic literature mapping. Here a literature review was preferred as the research focused on identifying open and solved challenges in order to identify research gaps [33]. The systematic literature review procedure is shown in Figure 3.1

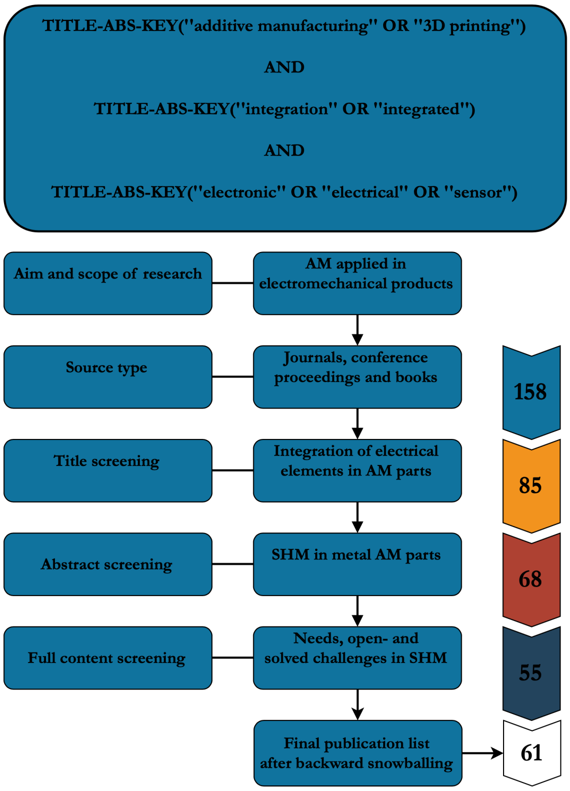


Figure 3.1: Systematic literature review process

As seen in Figure 3.1, advanced document search was used with the described queries. Boolean operators were used in order to combine different search queries. Initially, the subject area of engineering were used as a screening criteria. This followed by inclusion and exclusion criteria such as title, abstract and full content filtering. Finally, a backward snowballing were conducted in order to complement the final publication list with relevant articles from the found literature bibliography.

3.2 Empirical study

Initially company visits and semi-structured in-depth interviews with industrial experts in additive manufacturing and representatives from CAM2 (Centre for Additive Manufacture - Metal) was conducted simultaneously with the literature study. With respect to the findings from the literature review, a number of interview questions were established, see Appendix A. This was done in order to discuss the stated research questions, but also in order to discuss interconnected market trends in the integration of electrical elements in AM products. It was early concluded that the most suitable interview approach was to let the interviewee speak in a semi-structured matter. This as the topic in questions is still in its infancy and new innovative ideas is essential for future progress in the topic. Innovative ideas often occurred when the interviewee was let to divert from the questions but still discussed within the framework for the subject in matter. The established interview questions were utilised as a structuring guideline rather than a rigorous set of constrained questions [5].

In some activities visual stimuli consisting of products related to the products development and preliminary concepts was brought. This to get a different point of view on the initial approach on the stated research questions. It was concluded from the industrial experts that no inquiries from their customers and partners had been made regarding the the integration of electrical elements in their AM components. However the industrial experts provides names of companies that researched on similar topics which was utilised as an input to the literature study. In addition, the required steps for integrating electrical elements in AM components was discussed with all the parties. The case study was cautiously introduced after hearing the parties point of view for the general subject in matter in order to prevent biasing the discussion. This to avoid constraining the interviewees from diverging from the presented case study if the case study is introduced too early in the interview. After introducing the case study, the industrial experts and CAM2 representatives provided input for the continuous work and input to the concept generation phase of the project.

Furthermore, two workshops were organised in Saab Group - Defence and Security, one internal and one external. The internal workshop consisted of invited experts in the field within the organisation. This to discuss the subject in matter more specifically in order to provide input for the concept generation. The main facilitator for the workshop in question was the stated research questions where the parties shared their expertise in the facilitated brainstorming session. Innovative concepts for the case study occurred with respect to AM. The external workshop was in addition facilitated at Saab, where one of the previous industrial experts was invited to discuss the matter. Similar to previous mentioned approaches, the presented findings from the first workshop was not introduced initially due to the risk of constraining and delimiting the industrial experts creativity. The data was collected in all cases with the utilisation of field notes where keywords were documented of the interviewee statement verbatim. Subsequently after every session, the notes were processed in order to represent the actual transcript with minimal deviations and business card was requested for establishing future contact.

3.3 Concept generation

The concept generation phase was initiated with a set of needs and a related target specification from the stakeholders. It was of great importance that the customer needs were well understood and the problem identified. This in order to fully explore the solution space of different concepts and thus prevent the introduction of a superior concept later on in the process. The case study was established early into the project but with no specific computer-aided design model (CAD-model) and related dimensions. In order to analyse and demonstrate the feasibility and limitations of integrating electrical components in AM products, a cooling plate with an integrated temperature sensor was chosen to be the case study. A more detailed explanation of the case study will be described in the forthcoming chapter. The whole generic product development process as described by Ulrich and Eppinger [5] was not addressed in this thesis work. Primarily the design and manufacturing phase were the two applied phases and not necessary the marketing phase.

3.3.1 Functional analysis

In order to fully explore the solution space, the problem needs to be clarified and well understood. There are a variety of methods that can be used in order to decompose a complex problem with multi-fold functions into smaller sub-problems. In this project, a functional analysis has been used for dissecting the component that constitutes for the case study in favour of embarking a redesign. The building blocks that constitute for the functional analysis are established without implying a particular technological working principal for the sub-function in question. It was thus generated neutrally consisting of a verb and a noun. The functional analysis in combination with idea generation and morphological matrix can further generate a number of concepts [5].

3.3.2 Description of AM process with sensor integration

The overall integration process with sensor integration is schematically illustrated in Figure 3.2. After the CAD-model is converted in to a STEP file and pre-processed then transferred to the AM machine, the actual build initiates. When the build reaches a specified build height the process is interrupted and the actual integration process is initiated. The process is interrupted at the same layer for all the printed cooling plates on the build platform and is thus why concept four has a modified cooling channel.

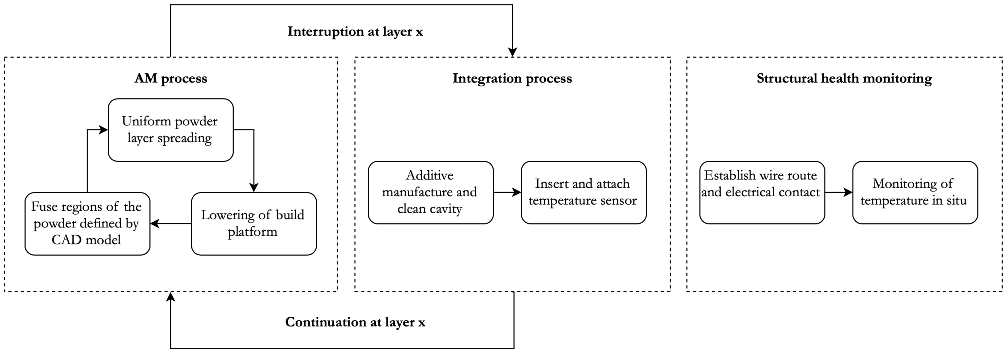


Figure 3.2: Flow chart for the enhanced AM process

The cavity configurations were further brushed and blown clean from loose powder where the temperature sensor was placed and attached in the cavity. Subsequently fast hardening resin was applied before and after the insertion in order to ensure attachment and placement when continuing the process at the layer where the interrupted layer took place. The purpose of the fast hardening resin was in addition to isolate a specific area of the sensor in order to distinguish the sensor from the metallic structure. This to prevent deceptive temperature monitoring from the metallic structure rather than the actual stimuli.

3.3.3 Brainstorming

This activity was conducted within a group where all the members possessed knowledge and creativity was used to generate innovative ideas. Internal search such as a brainstorming session is one of the most crucial phases in product development, thus it lays the foundation of the forthcoming concepts. During the sessions, it is important to encourage the generation of many distinctive ideas rather than focusing on the principal, quality over quantify. This due to the prevention of constraining the participants in eliciting their ideas. Further it is important to welcome infeasible ideas due to the possibility to further develop it into a feasible idea. It can be difficult to describe physical entities for other participants therefore it is important that sketching surfaces like cardboard and whiteboards pen are always at hand [5].

3.3.4 Morphological matrix

A morphological matrix is established and utilised in order to generate concept options by combining sub-solutions from each sub-function with each other. The sub-solutions in the matrix are derived from the the brainstorming session, thus it makes up for the input to the morphological matrix. By combining different sub-solutions in various means, both randomly and intentionally, composition of whole concepts are established. A morphological matrix is structured with the sub-functions in the first column below each other followed by the their sub-solutions in a row wise manner [5].

3.4 Concept evaluation and screening

The next step after generating a number of whole concepts by utilising the above mentioned methodology is to investigate them systematically. In most cases, it is an impossible task to investigate all of the combined fragments with respect to a project given resources and time constraints. However, this is not a necessary task to do since many generated concept are infeasible. There is a wide variety of different tools to evaluate and screen out generated concepts. In this project a combination of external decision, intuition and decision matrices were used. This was found suitable in order to maintain a high degree of objectivity during the concept evaluation and screening phase of the product development process. The benefits of a systematically concept evaluation and screening is an accurate customer-focused product considering on the actual customer need and the problem identified, but also a more traceable documentation of the product development [5].

3.4.1 Elimination matrix

An elimination matrix was the first utilised decision matrix for the evaluation and screening of the generated concepts. The decision matrix was utilised to screen out the obviously insufficient concepts which could not fulfil the most basic critical criteria. A number of selected criteria are established and the whole generated concepts are entered in a matrix. In order to quickly remember the concepts, a written description of each concept is established together with a simple 2D sketch which illustrates the key features of the fragmented sub-solution. Further, the selected criteria are established with respect to the findings and gained knowledge from the literature study and meetings with both internal and external actors. The criteria is thus a representative established criteria based on the customer needs [5].

3.4.2 Screening of temperature sensors

As mentioned in the beginning of the chapter a simplified cooling plate with a integrated temperature sensor was chosen to be the case study. A selection regarding different types of temperature sensors had to be made. The selection of temperature sensor was based on environmental requirements which had been established with the industrial supervisor at Saab. The emphasis was on the classified sensors defined in the theoretical framework.

3.5 Metal prototyping

In order to continue developing the concepts further, physical prototypes are manufactured. This to subsequently test it for various factors, among which ensuring the reliability in field and in addition a successful product development process. The metal prototypes aim primarily as a proof-of-concept which is linked to the functional test in order to verify and compare the concepts to each other. Secondly, interconnected to the above, is to use it in a visual physical manner for learning regarding its feasibility and customer needs consideration. This is further linked to ease the communication with outsiders, suppliers and top management. Tertiary and lastly a prototype is used to test the subsystem interface compatibility with test platforms and its compatibility with the system in whole [5]. The generation of prototypes often combine different prototyping technologies. Primarily 3D CAD Modelling in PTC Creo 3.0 and SLM have been used in this project.

3.5.1 Functional testing

The functional testing in this project is done in liaison with the metal prototyping and thus aims to be an extension of the concept evaluation. A functional test of the prototypes will be conducted with help of an air cooling unit. The air cooling unit aims to blast in controllable pressure flow through the fluid channel of the prototypes and the temperature of the blasted pressure flow will be known and be measured by a built-in thermometer. To evaluate the functionality and response time of the sensors in the prototypes during the functional test, some preparations has to be made. Initially, the wires of the sensors will be extended through soldering. Secondly, the sensors along with its wires will be connected to an Arduino Uno board. Finally, the Arduino board will be connected to a computer in combination with an Arduino script in order to measure the pressure flows' temperature. In addition, the response time for each concept will me monitored and measured.

4. Results

4.1 Description of the product development process

Initially, the result section present an introduction of the selected case study closely followed by current state-of-the art and defined requirements. Subsequently a function decomposition of the case study in form of a functional analysis is presented followed by the results of the concept generation, evaluation and screening. Lastly the results of the metal prototyping is presented, see Figure 4.1 for a illustration of the above mentioned.

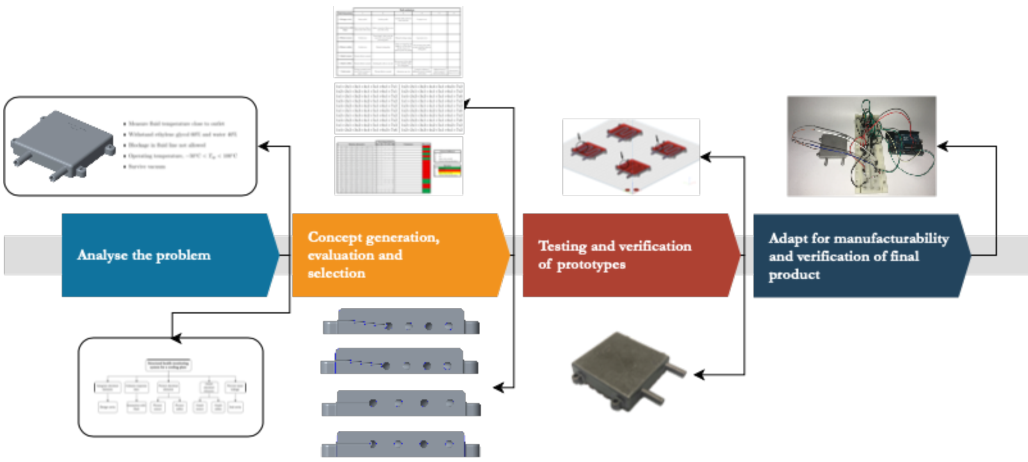


Figure 4.1: The product development process with related output

4.2 Introduction of case study: Cooling plate with an integrated temperature sensor

In order to analyse and demonstrate the feasibility and limitations of sensor integration, a case study was established in coherence with the industrial supervisors. The established case study was derived and based on a problem in the current existing cooling plate at the company. The current problem with the existing cooling plate is that there does not exist a solution of how to measure the actual temperature of the fluid around the outlet. It was realized that it would be too difficult to try to tackle the problem with the real product. Thus, a principal product was derived, see Figure 4.2. The principal product further formed the case study. It was concluded that it still was representative with respect to the main and sub-functions and thus satisfied the criterion to form the case study.

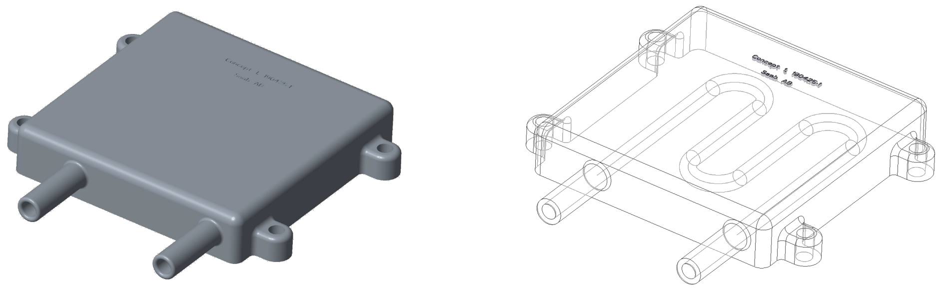
Real product ⟶ Idealized product ⟶ Principal product

Figure 4.2: Derivation process of the simplified product

The main objective of the established case study was to successfully integrate a temperature within a simplified additive manufactured cooling plate. The sensor aimed to be integrated around the outlet of the fluid channel since the functionality of the sensor is to measure the temperature of the fluid at the outlet. This, due to the temperature changes when the fluid is flowing from the inlet to the outlet and due to the developed flow profile but also due to the low stresses occurring around the outlet area.

4.2.1 Case study: Cooling plate

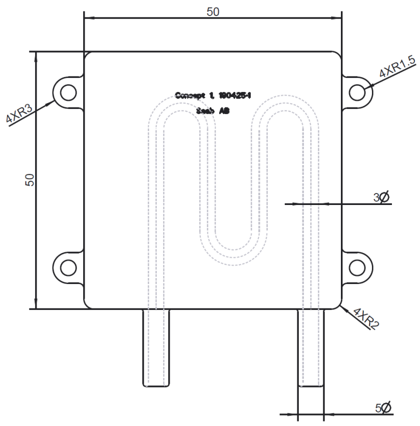
The CAD-model were modelled and drawn in Creo Parametric 3.0. The baseline dimensions for the cooling plate were derived from the temperature sensor dimensions as a basis but also considerations of designing for AM were taken, see Figure 4.4. As seen in Figure 4.3a and 4.3b the channel is not centred. The placement of the channel was adapted after the cavity configurations dimensions described later on in this chapter.



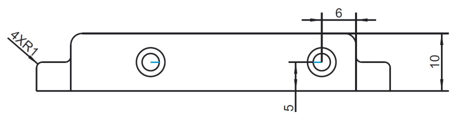
(a) ISO-view of the baseline

(b) Hidden lines view of the baseline

Figure 4.3: CAD-model of the cooling plate



(a) Top view dimensions



(b) Front view dimensions

Figure 4.4: Drawing of the cooling plate with related dimensions

4.2.2 Baseline solution

The system placement of the existing cooling plate is between a number of printed circuit boards (PCBs) where the function of the cooling plate is to cool down the PCBs. The cooling plate is additive manufactured in the aluminium alloy AlSi10Mg and has complex intricate internal features which makes it lightweight. Currently, it does not exist a solution of how to measure the temperature of the fluid around the outlet of the cooling plate. Test experiments have been conducted where tests of external temperature measurements of the fluid have been conducted where sensors are attached to or installed onto the component. The results from the test experiments have shown to not be accurate and precisely. It can thus be concluded that no current solution exist on how to measure the actual temperature of the fluid around the outlet. Thus a discrepancy between the actual temperature and measured temperature exists. The factors behind the negative results from the test experiments still remain unknown, what is known is that the measured temperature is not the fluid's temperature at that particular point and thereby the measured temperature is incorrect. Today, a safety factor is added in order to ensure the structural integrity.

4.3 Capturing requirements

4.3.1 Requirements for cooling plate with integrated sensor

The following requirements were established in liaison with the industrial supervisors and stakeholders at Saab:

- Error of the temperature measurement shall not exceed 3 %.
- Placement of the sensor in the cooling plate should not disrupt the liquid flow.
- Sensor wire route should be able to be lead out from the cooling plate.
- Sensor along with its wires should be prevented from movements after integration.
- Flowing fluid in the channel of the cooling plate should not leak out and thus be hermetically sealed.
- The cooling plate with the integrated sensor shall not diminish with respect to its mechanical properties compared to the baseline. It shall thus be kept equal or higher.

4.3.2 Requirements for temperature sensor

The following environmental requirements were established in liaison with the industrial supervisors. They were further used for the sensor screening and selection.

- Measure fluid temperature close to outlet
- Withstand liquid mixture of ethylene glycol 60% and water 40%
- Blockage in fluid line not allowed
- Operating temperature, $-50°\text{C} < T_{op} < 100°\text{C}$
- Survive vacuum
- Withstand operating temperature from the AM process ($\approx 600°\text{C}$)

4.4 Functional analysis

To be able to fully understand the main problem of the case study, a functional analysis was carried out to set a basis and ease for the next step in the development process. The functional analysis was carried out by decomposing the case into its main function with its associated sub-functions, see Figure 4.5. The sub-functions were used as basis in the upcoming brainstorming stage and morphological matrix. The following sub-functions are described and treated.

- Placement of electrical elements - Designing a cavity where the sensor along with its wires will be integrated.
- Sense fluid temperature - Integrating the sensor as near as possible to the stimuli which will further optimise the response time.
- Protect sensor - Protecting the sensor from the local heat during the AM process.
- Protect cables - Protecting the wires from the local heat during the AM process.
- Attach sensor - Preventing movements of the sensor during and after the AM process.
- Attach cables - Preventing movements of the wires during and after the AM process.
- Ensure waterproofing - Preventing the fluid to leak into the cavity.

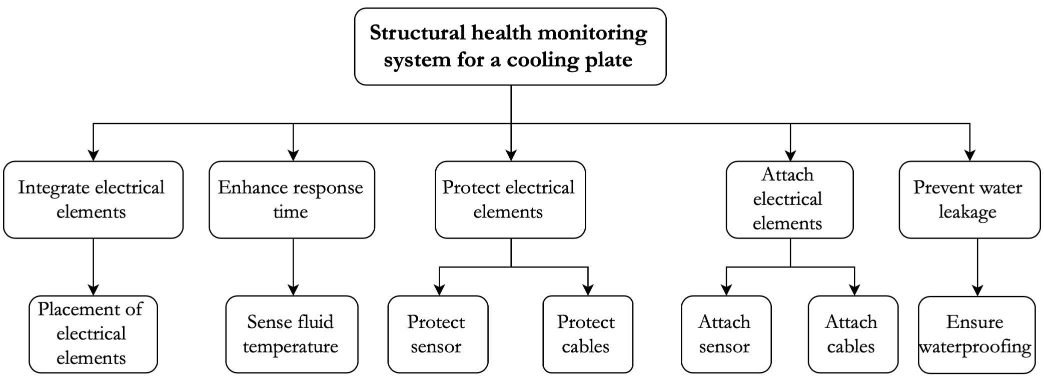


Figure 4.5: Functional decomposition

4.5 Idea- and concept generation

4.5.1 Brainstorming

The generated ideas during the brainstorming session can be seen in the morphological matrix, see Figure 4.6. The generated ideas were noted, readjusted and refined to sub-solutions to the sub-functions in the morphological matrix. In total two formal brainstorming sessions were facilitated besides the number of minor brainstorming sessions conducted within the project group and throughout the project. Together with four colleagues with different expertise, the main brainstorming session was carried out at the company. During that brainstorming session, a large number of ideas were generated as there were no limitations of how creative and unique the generated ideas could be. The objective with the brainstorming session was to generate ideas of solutions on every sub-function which were derived from the functional analysis. The generated ideas of solutions were derived through discussions and reflections within the participants of the session. The generated ideas were noted down, readjusted, refined and put in the morphological matrix. During the brainstorming session, the generation of ideas was based on the sub-functions in the functional analysis.

4.5.2 Morphological matrix

The morphological matrix unlocked the possibilities to generate a large number of unique concepts. In total, a sum of 2304 combinations of concept options could be generated from the established morphological matrix, see Figure 4.6. It was shown to be impossible to evaluate all concepts within the time frame during the concept evaluation and selection phase. This resulted in each project member individually selected ten concepts in which they found most promising. The individual evaluation and selection of the ten concepts were based on knowledge gained from the literature review including meetings with external and internal stakeholders. The individual evaluation and selection of all possible concept options from the morphological matrix resulted in 20 concepts, see Table 4.1. The concepts are written in the format sub-function x sub-solution, e.g. 2 x 2 is interpreted as sub-function two with sub-solution one.

	Sub-solution					
Sub-function	**1**	**2**	**3**	**4**	**5**	**6**
1. Placement of electrical elements (cavity design)	Elipse profile	Circular profile	Circular multi-cavities for sensor and wires	U-shaped cavity		
2. Sense fluid temperature	Direct interaction (Open in both of ends of the cavity)	Indirect interaction (Open in one end of the cavity)				
3. Protect sensor	Powder layer	Tilted cavity that conceal the sensor from the processing plane ("Smart design")	Thermal isolating coating	Cap sensor cover		
4. Protect cables	Powder layer	Thermal isolating film	Cables are wrapped up and hidden in a pocket along with the sensor to be picked up after the printing	Not necessary (if the cables are not embedded within the cooling plate)		
5. Attach sensor	Thermal adhesive material					
6. Attach cables	Thermal adhesive material	Stretching the cables in one end	Not necessary (if the cables are not embedded within the cooling plate)			
7. Ensure waterproofing	Package assembled on the sensor before insertion (o-rings or similar)	Thermal adhesive material	Aluminium cap cover	Coating by soldering of additional material assembled on the sensor	Additional material which is prepared before the insertion	Not necessary if solution 3x2 is used

Figure 4.6: Morphological matrix

Table 4.1: The 20 selected combinations

1x1+2x1+3x1+4x1+5x1+6x1+7x1	1x2+2x1+3x2+4x4+5x1+6x3+7x2
1x2+2x1+3x2+4x1+5x1+6x1+7x1	1x2+2x1+3x1+4x1+5x1+6x1+7x2
1x1+2x1+3x2+4x1+5x1+6x1+7x2	1x4+2x2+3x2+4x1+5x1+6x1+7x6
1x3+2x1+3x2+4x2+5x1+6x1+7x2	1x1+2x1+3x1+4x1+5x1+6x1+7x2
1x4+2x2+3x3+4x2+5x1+6x1+7x2	1x3+2x1+3x1+4x1+5x1+6x1+7x2
1x1+2x1+3x3+4x4+5x1+6x3+7x2	1x2+2x2+3x2+4x2+5x1+6x1+7x6
1x2+2x1+3x3+4x2+5x1+6x1+7x2	1x2+2x1+3x3+4x2+5x1+6 x1+7x2
1x4+2x2+3x3+4x1+5x1+6x1+7x2	1x2+2x2+3x1+4x1+5x1+6x1+7x6
1x1+2x1+3x2+4x2+5x1+6x1+7x3	1x2+2x1+3x3+4x2+5x1+6x2+7x2
1x4+2x2+3x3+4x4+5x1+6x3+7x6	1x2+2x1+3x3+4x4+5x1+6x1+7x2

4.5.3 The 20 selected concept descriptions

(1) Rain drop with direct interaction attached with thermal adhesive and package assembled on sensor with powder coating (1x1 + 2x1 + 3x1 + 4x1 + 5x1 + 6x1 + 7x1)

- A cooling plate with an embedded cavity for the integration of sensor with rain drop formed openings in both ends. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. After integrating the sensor along with its wires into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the electrical elements. A package will be assembled on the sensor before the integration, the package will act as a barrier to ensure prevention of water leakage. Further, powder layers will be placed above the sensor along with its cables to act as a protection from the heat of the laser during the continued printing.

(2) Tilted circular cavity with direct interaction, thermal adhesive and package assembled with powder coating (1x2 + 2x1 + 3x2 + 4x1 + 5x1 + 6x1 + 7x1)

- A cooling plate with an embedded cavity for the integration of sensor with circular formed openings in both ends. The cavity will have a horizontal geometry along with a downward geometry in one end (smart design of cavity i.e. a tilted cavity) to ensure the protection of sensor from the heat during the continued printing. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. After integrating the sensor along with its wires into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the electrical elements. A package will be assembled on the sensor before the integration. The package will act as a barrier to ensure prevention of water leakage. Further, powder layers will be placed above the cables to act as a protection from the heat of the laser during the continued printing.

(3) Tilted rain drop with direct interaction, attached with thermal adhesive and powder coating (1x1 + 2x1 + 3x2 + 4x1 + 5x1 + 6x1 + 7x2)

- A cooling plate with an embedded cavity for the integration of sensor with rain drop formed openings in both ends. The cavity will have a horizontal geometry along with a downward geometry in one end to ensure the protection of sensor from the heat during the continued printing. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. After integrating the sensor along with its wires into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the electrical elements and prevention of water leakage. Further, powder layers will be placed above the wires to act as a protection from the heat of the laser during the continued printing.

(4) Tilted multi cavities with direct interaction, attached with thermal adhesive and coated with thermal insulating film (1x3 + 2x1 + 3x2 + 4x2 + 5x1 + 6x1 + 7x2)

- A cooling plate with an embedded cavity and branched with multi-cavities for the integration of sensor along with its number of wires. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. The cavity will have a horizontal geometry along with a downward geometry in one end to ensure the protection of sensor. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. After integrating the sensor along with its wires into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the electrical elements and prevention of water leakage. Further, thin thermal insulating film will be used as cover around the wires to act as a protection from the heat of the laser during the continued printing.

(5) U-formed cavity with indirect interaction coated with thermal insulating coating, film and thermal adhesive (1x4 + 2x2 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2)

- A cooling plate with an embedded thin U-formed cavity for the integration of sensor with one opening in one end. The sensor will not be exposed and will have indirect interaction with the fluid due to the opening in only one end. During the preparation for the integration, the sensor will be covered with a thermal insulating coating. In this solution, it is assumed the wires of the sensor will not be embedded within the cooling plate. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the sensor along with its wires. Further, thin thermal insulating film will used as cover around the wires to act as a protection from the heat of the laser during the continued printing.

(6) Rain drop with direct interaction, thermal insulating coating, attached with thermal adhesive and wires not embedded (1x1 + 2x1 + 3x3 + 4x4 + 5x1 + 6x3 + 7x2)

- A cooling plate with an embedded cavity for the integration of sensor with rain drop formed openings in both ends. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. During the preparation for the integration, the sensor will be covered with a thermal insulating coating and thereby protected from the heat. In this solution, it is assumed the wires of the sensor will not be embedded within the cooling plate. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the sensor and prevention of water leakage.

(7) Circular cavity with direct interaction, coated with thermal isolating film and attached with thermal adhesive (1x2 + 2x1 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2)

- A cooling plate with an embedded cavity for the integration of sensor with circular formed openings in both ends. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. During the preparation for the integration, the sensor will be covered with a thermal isolating coating and thin thermal isolating film will enfold around the wires. This to act as a protection from the heat of the laser during the continued printing. After integrating the sensor along with its wires into the cavity, thermal adhesive material will be applied to the cavity. This to ensure the attachment of the electrical elements and prevention of water leakage.

(8) U-formed cavity with indirect interaction, coated with thermal insulating film, adhesive and powder layers (1x4 + 2x2 + 3x3 + 4x1 + 5x1 + 6x1 + 7x2)

- A cooling plate with an embedded thin U-formed cavity for the integration of sensor with only an opening in one end. The sensor will not be exposed and will have indirect interaction with the fluid due to the opening in only one end. During the preparation for the integration, the sensor will be covered with a thermal insulating coating. This to act as a protection from the heat of the laser during the continued printing. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity. This to ensure the attachment of the sensor and prevention of water leakage. Further, powder layers will be placed above the wires to act as a protection from the heat of the laser during the continued printing.

(9) Tilted rain drop with direct interaction, coated with thermal

insulating film, aluminium cap cover and thermal adhesive (1x1 + 2x1 + 3x2 + 4x2 + 5x1 + 6x1 + 7x3)

- A cooling plate with an embedded cavity for the integration of sensor with rain drop formed openings in both ends. The sensor will be exposed and have direct interaction with the fluid due to the openings in both ends. The cavity will have a horizontal geometry along with a downward geometry in one end. This to ensure the protection of sensor and thin thermal insulating film will cover the wires. This to act as a protection from the heat of the continued printing. The sensor will be assembled with an aluminium cap cover which will act as a barrier and prevent water leakage when integrated into the cavity. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity. This further to ensure the attachment of the sensor along with its wires.

(10) U-formed cavity with indirect interaction, coated with thermal insulating, adhesive and wires not embedded (1x4 + 2x2 + 3x3 + 4x4 + 5x1 + 6x3 + 7x6)

- A cooling plate with an embedded thin U-formed cavity for the integration of sensor with only one opening in one end. The sensor will not be exposed and will have indirect interaction with the fluid due to the opening in only one end. Further, the sensor will be covered with a thermal insulating coating to protect it from the local heat from the laser during the continued printing. In this solution, it is assumed the wires of the sensor will not be embedded within the cooling plate. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the sensor.

(11) Tilted circular cavity with direct interaction, thermal adhesive and wires not embedded (1x2 + 2x1 + 3x2 + 4x4 + 5x1 + 6x3 + 7x2)

- A cooling plate with a circular profiled cavity where the sensor directly interacts with the cooling water. A smart concept shall be designed so that the sensor is entirely concealed from the laser beam by a cavity tilted out of the processing plane during the continuing process. It is assumed that the wires of the sensor is not going to be embedded within the cooling plate which results in no need of protection against the direct heat source or need of being flat attached. The sensor shall be held firmly and flat using a thermal paste. The cavity seal shall also be made possible by means of a filling material in the form of a thermal adhesive paste.

(12) Circular cavity with direct interaction, coated with powder and thermal adhesive (1x2 + 2x1 + 3x1 + 4x1 + 5x1+ 6x1 + 7x2)

- Cooling plate with circular profiled cavity where the sensor shall directly interact with the cooling water. The sensor and wires shall be protected with a powder layer during the continued AM process. The sensor and wires shall be kept flat and attached using thermal adhesive paste. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal adhesive paste.

(13) Tilted u-formed cavity with indirect interaction, coated with powder and thermal adhesive (1x4 + 2x2 + 3x2 + 4x1 + 5x1+ 6x1 + 7x6)

- The cavity shall be shaped like a U-shaped pocket where the sensor does not have direct contact with the cooling water. That is a thin barrier will be present between the cooling water and the sensor for an indirect interaction. A smart concept shall be designed to avoid direct laser exposure to the sensor itself during the continued AM process. The wires shall be protected with a powder layer during the continued AM process. The sensor and wires shall be kept flat and attached using thermal paste. A water seal is not needed since there is no direct interaction with the cooling water.

(14) Rain drop with direct interaction, coated with powder and thermal adhesive (1x1 + 2x1 + 3x1 + 4x1 + 5x1+ 6x1 + 7x2)

- Cooling plate with raindrop shaped profile of cavity where the sensor shall directly interact with the cooling water. The sensor and wires shall be protected with a powder layer during the continued AM process. The sensor and wires shall be kept flat and attached using thermal paste. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal adhesive paste.

(15) Multi cavities with direct interaction, coated with powder and thermal adhesive (1x3 + 2x1 + 3x1 + 4x1 + 5x1+ 6x1 + 7x2)

- Cooling plate with multi-cavities for each cable and a pocket for the sensor itself where the sensor shall directly interact with the cooling water. The sensor and wires shall be protected with a powder layer during the continued

AM process. Sensor and wires shall be kept flat and attached using thermal paste. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal paste.

(16) Tilted circular cavity with indirect interaction, coated with thermal insulating film and adhesive (1x2 + 2x2 + 3x2 + 4x2 + 5x1+ 6x1+ 7x6)

- Cooling plate with circular profile of cavity where the sensor does not have direct contact with the cooling water i.e. a thin barrier will be present between the cooling water and the sensor for an indirect interaction. A smart concept shall be designed to avoid direct laser exposure from the AM process to the sensor itself during the continuing process. The wires shall furthermore be protected with a thin thermal insulation film. The sensor and wires shall be kept flat and attached using thermal paste. A water seal is not needed since there is no direct interaction with the cooling water.

(17) Circular cavity with direct interaction, coated with thermal insulating coating, film and adhesive (1x2 + 2x1 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2)

- Cooling plate with circular profile of cavity where the sensor shall directly interact with the cooling water. The sensor shall be protected with a thermal insulating coating/membrane and the wires with a thin thermal insulation film. Sensor and wires shall be kept flat and attached using thermal paste. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal paste.

(18) Circular cavity with indirect interaction, coated with powder layers and thermal adhesive (1x2 + 2x2 + 3x1 + 4x1 + 5x1+ 6x1 + 7x6)

- Cooling plate with circular profile of cavity where the sensor does not have direct contact with the cooling water. That is a thin barrier will be present between the cooling water and the sensor for an indirect interaction. Sensor and wires shall be protected with a powder layer during the continued AM process. The sensor and wires shall be kept flat and attached using thermal paste. A water seal is not needed since there is no direct interaction with the cooling water.

(19) Circular cavity with direct interaction, coated with thermal insulating coating, film, adhesive and stretching of wires (1x2 + 2x1 + 3x3 + 4x2 + 5x1+ 6x2 + 7x2)

- Cooling plate with circular profile of cavity where the sensor shall directly interact with the cooling water. The sensor shall be protected with a thermal insulating coating/membrane and the wires with a thin thermal insulation film. The sensor shall be fixed and held flat using thermal paste and the wires must be fixed by means of a fixture or by stretching them from one side. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal paste.

(20) Circular cavity with direct interaction, coated with thermal insulating coating, film and adhesive (1x2 + 2x1 + 3x3 + 4x4 + 5x1+ 6x1 + 7x2)

- Cooling plate with circular profile of cavity where the sensor shall directly interact with the cooling water. The sensor shall be protected with a thermal insulating coating/membrane and and the sensor shall be attached and held flat using thermal paste. It is assumed that the wires of the sensor is not going to be embedded within the cooling plate which results in no need of protection against the direct heat source or need of being attached flat. Water seal for the opening between the cooling water and the sensor must be made possible by means of filling material in the form of thermal paste.

4.6 Concept screening and evaluation

4.6.1 Selection of temperature sensor

The selection of a temperature sensor was conducted through web searches and discussions with industrial supervisor and resulted in a RTD sensor, namely a platinum resistance Pt100 wire-wound detector element. The Pt100 sensor fulfils the set environmental requirements along with advantages as it is cheap, standardised and highly available. The selected Pt100 sensor has a platinum coil wire-wound construction sealed inside a high purity alumina ceramic body. Temperature sensing range for the chosen Pt100 is $-200°C$ (min) to $+650°C$ (max), see Figure 4.7 for dimensions.

Figure 4.7: Dimensions of the selected Pt100 sensor in 3D

Furthermore, from the literature study it could be concluded that achievements had been done regarding fibre optical sensors and piezoelectric sensors. But still at this moment fibre optical sensors requires additional preparing i.e., coating of the fibres that is done manually. They are also produced on demand for research purposes mainly. When it comes to piezoelectric sensors, a wireless sensing solution is not preferred due to the environment condition with a lot of disturbances and signals. The following additional specifications of the Pt100 sensor is presented, see Table 4.2.

Table 4.2: Specifications of the chosen Pt100 sensor

Specifications	
Ice point resistance	*100 Ω*
Fundamental interval (0°C to 100°C)	*38.5 Ω (nominal)*
Self-heating	*0.02 to* 0.3°C/mW
Thermal response	$< 0.4s$
Measuring current	*1 mA*
Tolerance class	*IEC 60751*

In addition, the thermal response is seconds to 63 % of final value - in water 1m/s and the tolerance class is in accordance with IEC 60751 where

- W0.15 (Class A) −100°C to +450°C
- W0.3 (Class B) −196°C to +660°C [34]

4.6.2 Elimination matrix

An elimination matrix was established to further screen and evaluate the 20 concepts that had been selected from the morphological matrix. The evaluation was based on five critical criteria where each concept needed to fulfil all criteria in order to pass to the next development phase. When evaluating the concepts with respect to the five criteria in the matrix, each concept could either be assessed with Yes (+), No (-), More information needed (?) or Check with specification (!) for each criterion. The assessment was based on gained knowledge from literature studies and from meetings with internal and external stakeholders. The evaluation of the concepts in the elimination matrix were based on the following criteria.

(A) **Realizable**, i.e., the concept should be able to be imagined to be possible and manufacturable with today's technology.

(B) **Solving main problem**, i.e., the concept should be functional and fulfil the main function after manufacturing which is to measure the temperature of the cooling water in the outlet.

(C) **Manufacturing complexity**, i.e., the concept should not require too many steps in the whole manufacturing process including automated and manual work. A rule of thumb is that AM is supposed to manufacture complex products which may be very difficult with other manufacturing technologies and not the opposite.

(D) **Fulfil critical requirements**, i.e., the concept should fulfil all critical functional requirements from the functional analysis.

(E) **Compatible with AM process**, i.e., the concept should be able to be manufactured in the selected AM process.

Firstly, 13 concepts did not pass the elimination matrix since almost all of those concepts (12 of 13) already failed at the criterion "Manufacturing complexity, (C)" which is the reason why those concepts were not further evaluated against rest of the criteria, see Figure 4.8.

Solution alternative	Screening criteria (A)	(B)	(C)	(D)	(E)	Decision
1x1 + 2x1 + 3x1 + 4x1 + 5x1 + 6x1+ 7x1	+	+	-			-
1x2 + 2x1 + 3x2 + 4x4 + 5x1 + 6x3 + 7x2	+	+	+	+	+	+
1x2 + 2x1 + 3x2 + 4x1 + 5x1 + 6x1 + 7x1	+	+	-			-
1x2 + 2x1 + 3x1 + 4x1 + 5x1 + 6x1 + 7x2	+	+	+	+	+	+
1x1 + 2x1 + 3x2 + 4x1 + 5x1 + 6x1 + 7x2	+	+	-			-
1x4 + 2x2 + 3x2 + 4x1 + 5x1 + 6x1 + 7x6	+	+	+	+	+	+
1x3 + 2x1 + 3x2 + 4x2 + 5x1 + 6x1 + 7x2	+	+	-			-
1x1 + 2x1 + 3x1 + 4x1 + 5x1 + 6x1 + 7x2	+	+	-			-
1x4 + 2x2 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2	+	+	-			-
1x3 + 2x1 + 3x1 + 4x1 + 5x1 + 6x1 + 7x2	+	+	-			-
1x1 + 2x1 + 3x3 + 4x4 + 5x1 + 6x3 + 7x2	+	+	-			-
1x2 + 2x2 + 3x2 + 4x2 + 5x1 + 6x1 + 7x6	+	+	-			-
1x2 + 2x1 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2	+	+	-			-
1x2 + 2x1 + 3x3 + 4x2 + 5x1 + 6x1 + 7x2	+	+	-			-
1x4 + 2x2 + 3x3 + 4x1 + 5x1 + 6x1 + 7x2	+	+	+	+	+	+
1x2 + 2x2 + 3x1 + 4x1 + 5x1 + 6x1 + 7x6	+	+	+	+	+	+
1x1 + 2x1 + 3x2 + 4x2 + 5x1 + 6x1 + 7x3	+	+	-			-
1x2 + 2x1 + 3x3 + 4x2 + 5x1 + 6x2 + 7x2	-					-
1x4+ 2x2 + 3x3 + 4x4 + 5x1 + 6x3 + 7x6	+	+	+	+	+	+
1x2 + 2x1 + 3x3 + 4x4 + 5x1 + 6x1 + 7x2	+	+	+	+	+	+

Criteria fulfilment	
Yes	(+)
No	(-)
More info needed	(?)
Check with specification	(!)

Decision	
Continue	(+)
Remove	(-)
More info needed	(?)
Check with specification	(!)

Figure 4.8: Result of the elimination matrix

The reasoning why most of the concepts failed at "Manufacturing complexity" can be related to the number of required manual work steps or their inability to interact with the DfAM rules. A partition of these concepts had a cavity with a rain drop profile in their solution. The profile is not necessary and will increase the manufacturing complexity if the diameter of the cavity is not greater than 10 mm. This DfAM rule is only usable if the cavities have a circular profile with a diameter greater than 10 mm because this will result in needed support structures around the circular profile. But by using an rain drop profile instead of a circular one, eliminates the need of support structures around the profile. Due to the Pt100 sensor which only has a diameter of 0.9 mm, the cavity of prototype will be designed to have a circular diameter less than 10 mm which eliminates all concepts with a rain drop profile in their cavity.

Furthermore, concepts which had some type of packing (e.g. o-ring) assembled on the sensor before insertion to seal the cavity were eliminated due to many required manual work steps in the process. This argument also applies on concepts which had wires covered with thermal isolating film as protection from the local heat in the printing since it is assumed that the thermal isolating film are manually applied on the wires. Lastly, it was a concept which already failed at the first criterion "Realizable, (A)" since a solution where the wires are supposed to be stretched in one end to hold them flat and attached to the cavity during the printing did not seem realisable.

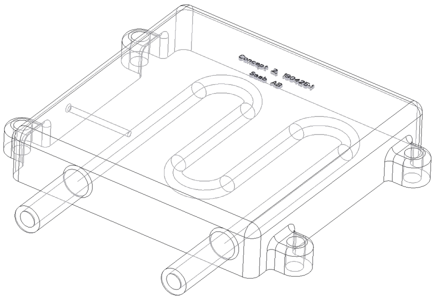
In the end, seven concepts fulfilled all the five criteria and passed the elimination matrix but since a selection of a Pt100 sensor with a thermal isolating cover had already been conducted simultaneously with the screening, it was natural to only proceed with the concepts which were involved with a sensor covered with a thermal isolating coating. This resulted in three final concepts and a fourth final interesting concept which was created by combining the first and second concept of the final ones.

4.6.3 Final concept 2

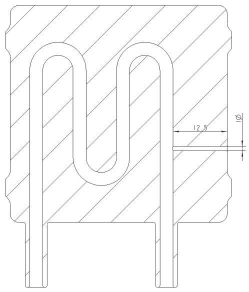
The description of concept 2 comes first since concept 1 and concept 4 will be integrated on the same cooling plate for the prototyping so the description of concept 1 will be found below in combination with the description of concept 4.

Circular cavity with direct interaction, coated with thermal insulating coating, film and adhesive (1x2 + 2x1 + 3x3 + 4x4 + 5x1+ 6x1 + 7x2)

Concept 2 is a cooling plate with circular cavity where the sensor directly interacts with the cooling water, see Figures 4.9 and 4.10. During the preparation for the integration, the sensor will be covered with a thermal insulating coating to act as a protection from the heat during the continued printing. It is assumed that the wires of the sensor is not going to be embedded within the cooling plate which results in no need of protection against the direct heat source or need of being attached flat. The sensor should be held firmly and flat using a thermal paste. The cavity seal should also be made possible by means of a filling material in the form of a thermal paste.

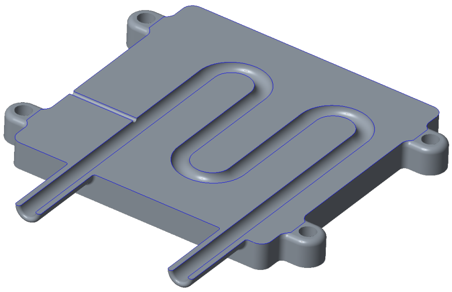


(a) ISO-view

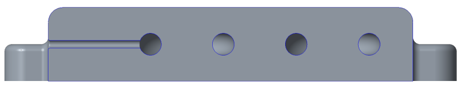


(b) Hidden lines view

Figure 4.9: CAD-model of final concept 2



(a) ISO-view



(b) Hidden lines view

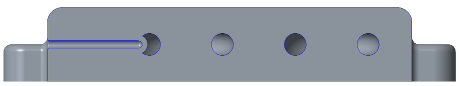
Figure 4.10: CAD-model of final concept 2

4.6.4 Final concept 3

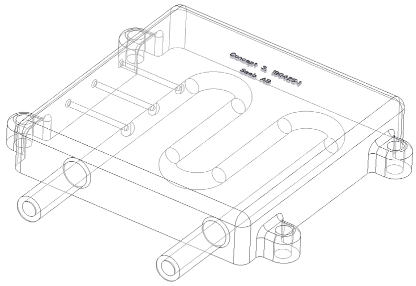
U-formed cavity with indirect interaction, coated with thermal insulating, adhesive and wires not embedded (1x4 + 2x2 + 3x3 + 4x4 + 5x1 + 6x3 + 7x6)

A cooling plate with an embedded thin U-formed cavity for the integration of sensor with only one opening in one end, see Figures 4.11 and 4.12. The sensor will not be exposed and will have indirect interaction with the fluid due to the opening in only one end. Further, the sensor will be covered with a thermal insulating coating to protect it from the local heat during the printing. In this solution, it is assumed that the wires of the sensor will not be embedded within the cooling plate. After integrating the sensor into the cavity, thermal adhesive material will be applied to the cavity to ensure the attachment of the sensor.

Instead of only one cavity, three cavities with different thicknesses on the thin barrier between the sensor and the fluid will be designed on this concept. The purposes to design three cavities on this concept for prototyping are to investigate how the response time is dependent of the barrier thickness, but also to save cost, time and powder material. The three different thicknesses are 0.5 mm, 0.75 mm and 1 mm. The selection of the thicknesses was based on an older test experiment where a thin wall barrier of 0.5 mm had survived and not been destroyed during the printing.

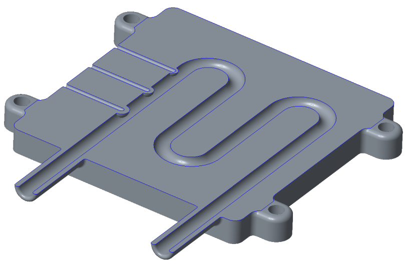


(a) ISO-view

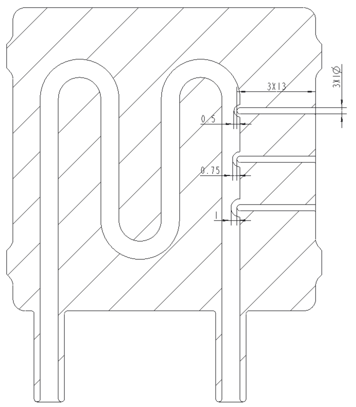


(b) Hidden lines view

Figure 4.11: CAD-model of final concept 3



(a) ISO-view



(b) Hidden lines view

Figure 4.12: CAD-model of final concept 3

4.6.5 Final concept 4

There are two cavities designed on this cooling plate, both concept 1 and concept 4 will be designed on the same cooling plate for the prototyping, see Figures 4.13 and 4.14. The purposes to design two concepts on this cooling plate for prototyping are to investigate how the response time is dependent of the direct- and indirect interaction with the fluid, but also to save cost, time and powder material. See Figure for dimensions 4.15.

Tilted circular cavity with direct interaction, thermal adhesive and wires not embedded (1x2 + 2x1 + 3x2 + 4x4 + 5x1 + 6x3 + 7x2)

Concept 1 is a cooling plate with circular cavity where the sensor directly interacts with the cooling water. A smart concept should be designed so that the sensor is entirely concealed from the laser beam by a tilted cavity, tilted out of the processing plane during the continuing process. It is assumed that the wires of the sensor are partially embedded within the cooling plate which results in the need of protection from the local heat during the printing and the need of being attached flat. The sensor should be held firmly and flat using a thermal paste. The cavity seal should also be made possible by means of a filling material in the form of a thermal paste.

Tilted circular cavity with indirect interaction, attached with thermal adhesive and wires not embedded (Combination of final concept 1 and 3)

Concept 4 is a combination of the first and the second concept. Concept 4 is a cooling plate with circular profiled cavity with only one opening in one end. The sensor will not be exposed and will have indirect interaction with the fluid due to the opening in only one end. A smart concept should be designed so that the sensor is entirely concealed from the laser beam by a tilted cavity, tilted out of the processing plane during the continuing process. It is assumed that the wires of the sensor are going to be embedded within the cooling plate which results in the need of protection against the direct heat source and the need of being attached flat. The sensor should be held firmly and flat using a thermal paste. The cavity seal should also be made possible by means of a filling material in the form of a thermal paste.

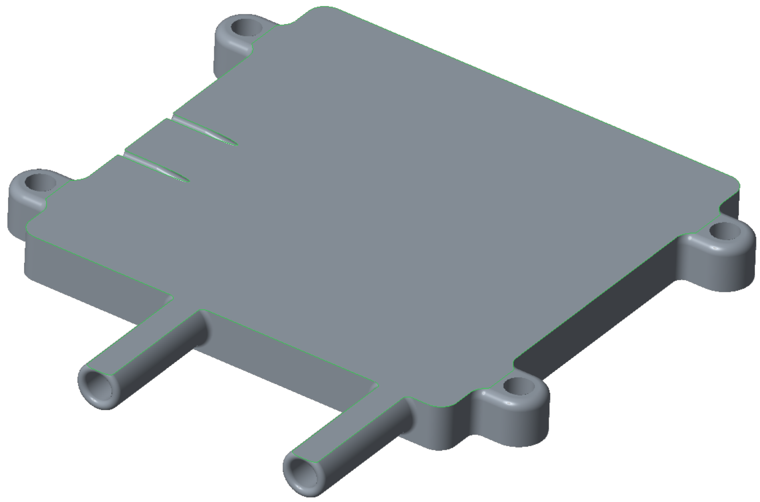
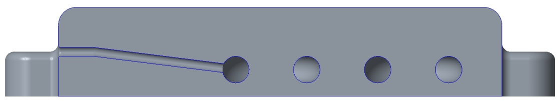
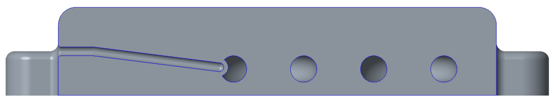


Figure 4.13: ISO-view of cooling plate with concept 1 and 4

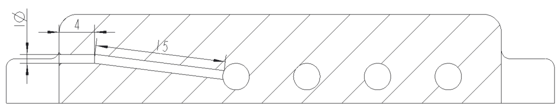


(a) Section view of final concept 1

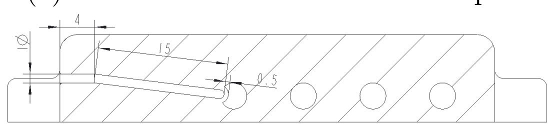


(b) Section view of final concept 4

Figure 4.14: CAD-model of final concept 1 an 4



(a) Hidden lines view of final concept 1



(b) Hidden lines view of final concept 4

Figure 4.15: CAD-model of final concept 1 an 4

4.7 Selection of thermal adhesive material

Since a thermal paste is included in all of the final concepts, a selection with regard to the most suitable thermal adhesive material was done. The screening and selection of thermal adhesive materials were based on the adhesives' resistance temperature, hardening time, bonding strength and compatibility with the SLM machine. At the end, the selection was between two adhesives, silicone and epoxy. By communicating with the suppliers of these adhesives, it was explained that silicone has a bit higher resistance temperature but much longer hardening time. In addition, silicone has poorer bonding strength and has the potential to release chemical particles during application, particles which can not prevail within a SLM machine since the particles are harmful. In the end, the evaluation of the criteria for the selection of thermal adhesive material resulted in an epoxy adhesive material, namely Loctite EA 9514 - Epoxy Adhesive. Loctite EA 9514 - Epoxy Adhesive is an epoxy adhesive with high performance and can be used for structural bonding, induction curing as well as for gap filling. The adhesive has a high temperature resistance and can operate in temperatures up to 200°C. In addition, this epoxy adhesive has a high shear, peel strength and chemical resistance [35].

4.8 Metal prototype

The metal prototypes were manufactured in an EOS M290 machine and the used material was an aluminium alloy, see Figure 4.16. In total, four cooling plates were printed at the same time on the same build platform. One of the cooling plates on the build platform is representing the baseline solution with no integrated sensor, one of the cooling plates is representing final concept 2, the third one is representing final concept 3 and the last one of the cooling plates is representing final concept 1 and 4, i.e. both final concept 1 and 4 is integrated onto the same cooling plate. The total volume for the four parts were 98218 mm^3 exclusive support structure volume. In total, the parts and the support made up of 99165 mm^3 (support 947 mm^3).

The metal prototyping process initiated with a file conversion of the CAD-models of the four cooling plates into a STL-format. The conversion to a STL-format was done for the reasoning that the surfaces of the cooling plates need to be described in triangles (polygons) which is included in the preparation of the printing. This, to ensure that the machine will understand what will be printed and how it will be printed. The STL-files of the cooling plates are then imported into the software Materalise Magics 3D Print Suite in order to prepare the last preparations e.g. set part orientation and support structures before the printing commences.

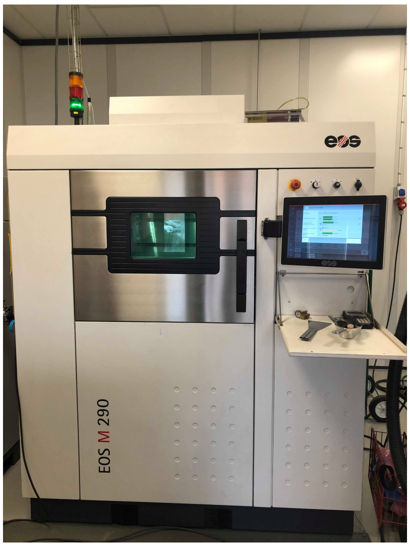
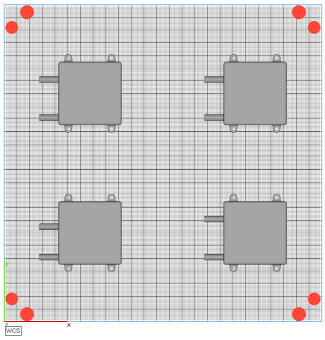


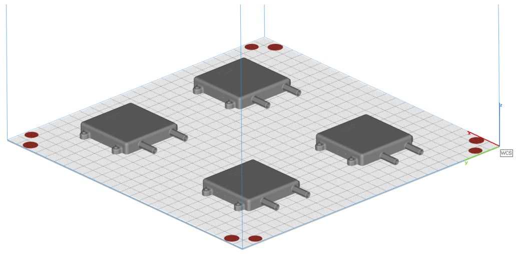
Figure 4.16: EOS M290 machine which was used for printing of the prototypes

4.8.1 Pre-processing in Materialise Magics 3D Print Suite

It can be seen in the Figures 4.17 and 4.18 how the CAD-models of the prototypes were imported and part orientated on the illustrative build platform in the software Materialise Magics. The part orientation of the CAD-models demonstrates in which direction the printing of the prototypes will be conducted during the SLM process. The support structures (red parts of the bottom of the cooling plates) can further be seen in Figures 4.19 and 4.20. The build space was shared with other components, hence the antisymmetric spacing in between the components, see Figure 4.19 and 4.20.



(a) 2D-view in Magics



(b) ISO-view in Magics

Figure 4.17: Different views of the build platform

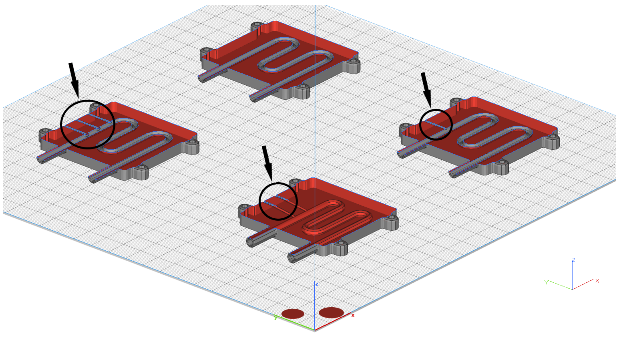
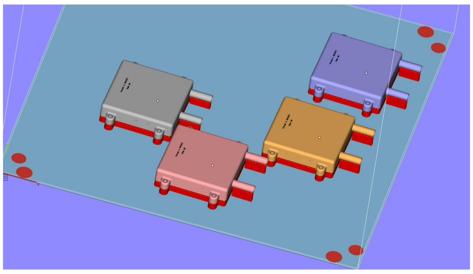
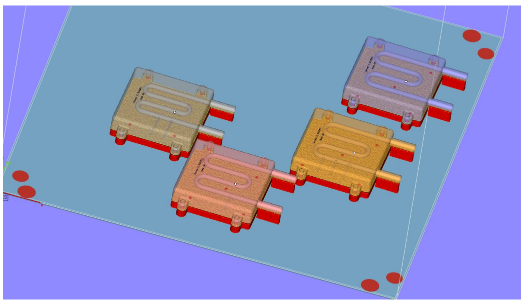


Figure 4.18: ISO-view in Magics



(a) ISO-view in Magics



(b) ISO-view in Magics

Figure 4.19: Different views of the build platform

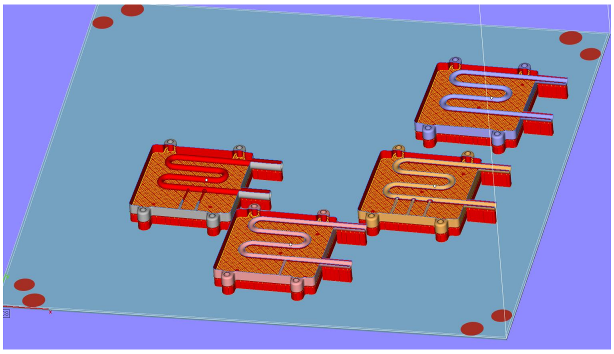


Figure 4.20: ISO-view in Magics

4.8.2 First print

Before the printing had initiated, it was determined during the pre-processing that a 5 mm thick support structure layer would be used for the printing see Figure 4.21. Next when the printing had initiated, the printing of the four cooling plates were paused approximately after 5 hours at the same building level, at 10 mm which indicates a pause when half of the cooling plates had been printed (since 5 mm is support structures and the total thickness of the cooling plate is 10 mm). Afterwards the cooling plates were taken out, a bit of the surrounding powder on the building platform was removed, see Figure 4.22b, and a small auger (0.9 mm in diameter) was used to remove powder inside the cavities but a problem occurred.

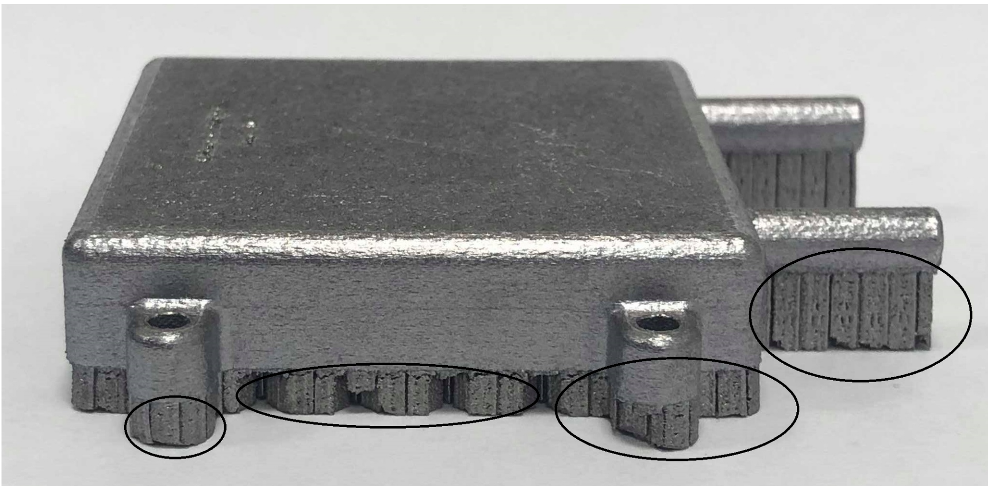
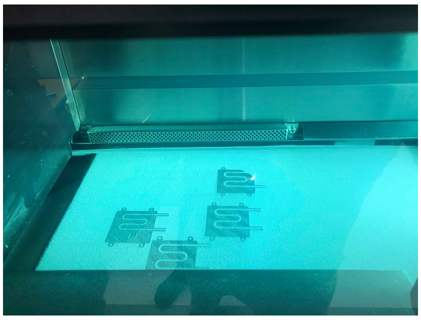


Figure 4.21: 5 mm of support structures

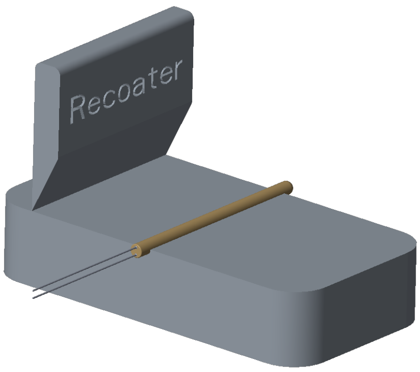


(a) Printing of the prototypes initiates

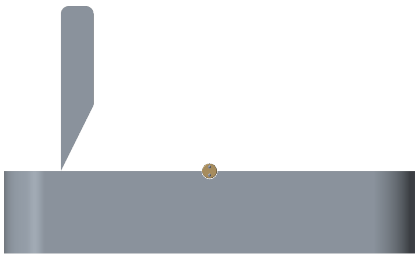
(b) A bit of the powder has been removed after stopping the printing at 10mm building level

Figure 4.22: Printing process of prototypes

Afterwards when a bit of the powder had been removed, it was realized that if the sensors would be integrated onto the cavities, approximately half of the sensors' diameter would be above the paused building level. This, since the diameter of the cavities is only 1mm and the diameter of the sensors is 0.9 mm i.e. 0.4 mm of the sensors' diameter would be above the paused building level. This turned into a problem since this would result in the recoater hitting the sensors when continuing the printing, see Figure 4.23. To solve this problem, a second pause of the printing had to be done.



(a)



(b)

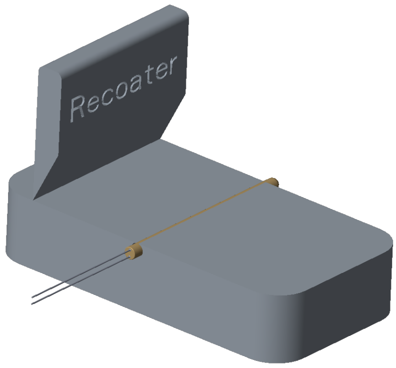
Figure 4.23: Visualisation of the continued printing after the first pause

4.8.3 Second print

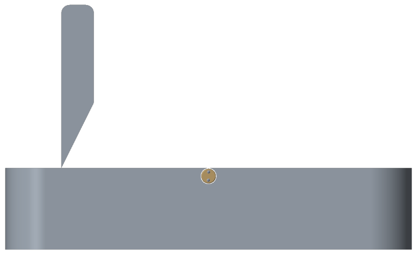
The plan to solve the recoating problem was to pause a second time. The second pause was planned to occur at a building level where the cavities had almost been printed completed. In addition 15 layers (0.030 mm layer thickness) were added to the first print in order to ensure a continous recoating. This, to ensure that the integrated sensors would not be above the paused building level and at the same time still be exposed to the heat from the laser (since the objective was to test if the sensors would survive the heat from the laser during the printing) when continuing the printing after the second pause, see Figure 4.24.

When pausing the printing the second time, as done during the first printing, a little bit of the powder was removed from the building platform and cavities. When removing the powder from the cavities with the auger, it was discovered that down-skins had emerged around the inlet's periphery, see the green ellipse in Figure 4.25. The down-skins made it impossible to integrate the sensors into the cavities.

The down-skins had a grain size which varied between 0.020 - 0.050 mm and thereby covered a lot of the space within the cavities. The auger was used for trying to remove the down-skins but the small auger was too weak and combining a drill with the auger was not a suitable solution. Melted powder grains would fall off during the drilling and be mixed with the dry surrounding powder which would cause additional problems in the machine when continuing the printing. As a result of this, no sensors could thereby be integrated during the printing process and the new plan was to integrate the sensors after finishing the printing of the prototypes.



(a)



(b)

Figure 4.24: Visualisation of the continued printing after the second pause

As seen in Figure 4.25, the red ellipse visualise the visible traction that has emerged on concept 2 after pausing the printing process for the first time. The blue ellipse visualise the visible traction after pausing the printing process the second time and the green ellipse visualise the down-skins that had emerged around the inlet's periphery of the cavity. These tractions and down-skins emerged on all of the cooling plates.

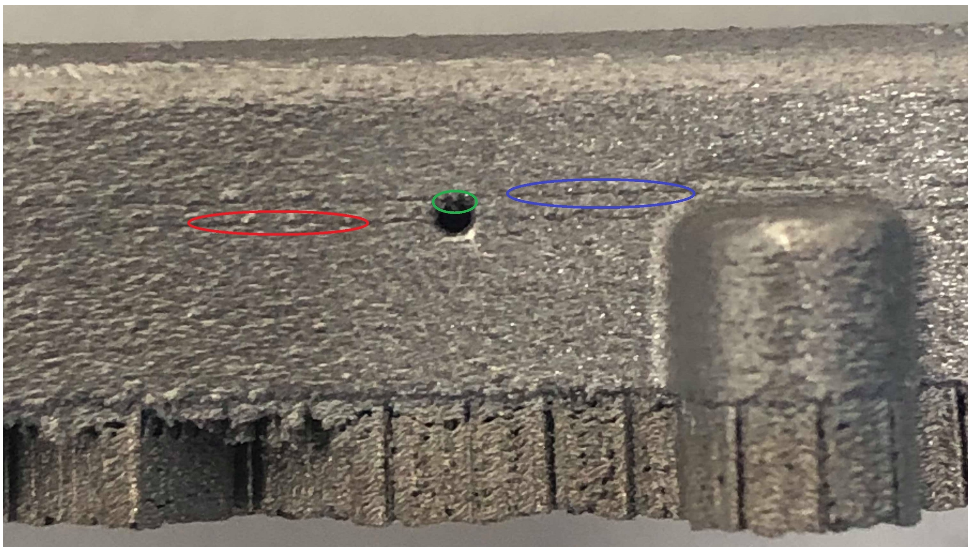
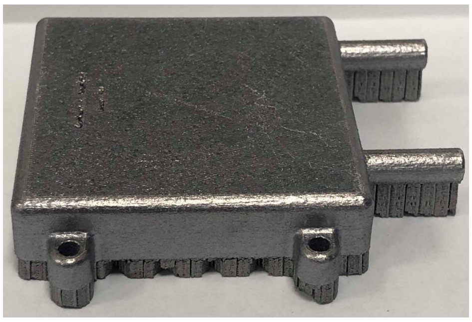


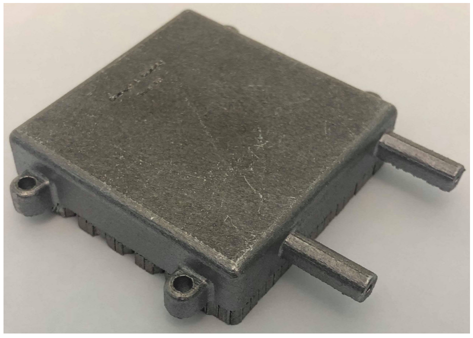
Figure 4.25: Emerged tractions on concept 2 after pausing two times and emerged down-skins around the inlet's periphery

4.8.4 Printed prototypes

In total, three cooling plates with four different integrated concept solutions were printed and the fourth cooling plate was a baseline solution used as a reference. The printed prototypes before the post-processing can be seen in Figures 4.26, 4.27 and 4.28.

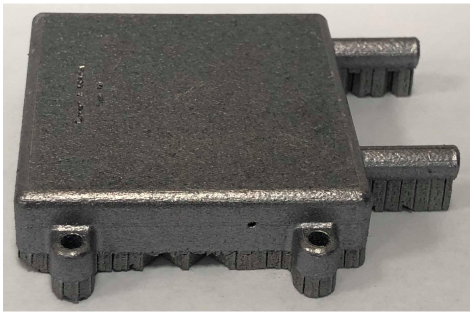


(a)

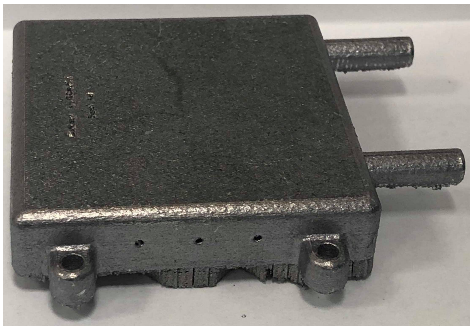


(b)

Figure 4.26: Printed prototype of the baseline solution



(a) Printed prototype of final concept 2



(b) Printed prototype of final concept 3

Figure 4.27

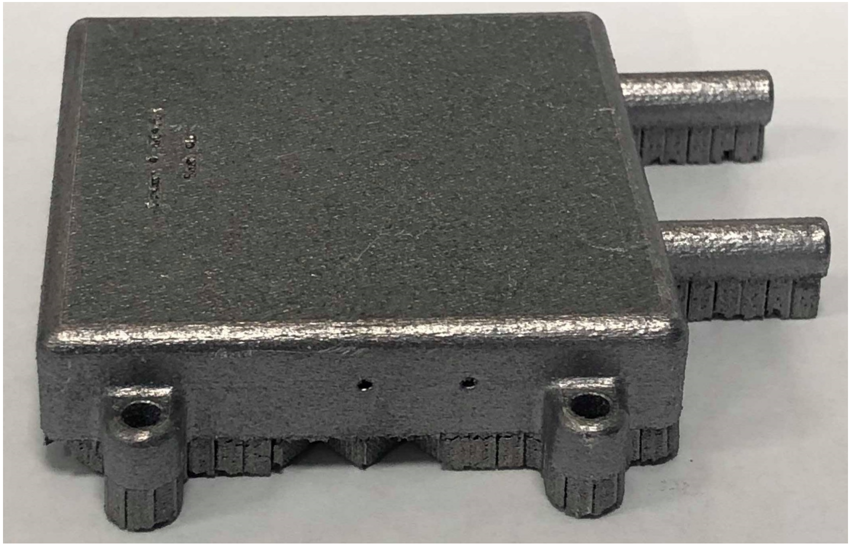


Figure 4.28: Printed prototype of final concept 4

4.8.5 Post-processing

When the prototypes were completely printed and finished, a band saw was used to cut off the 5mm thick support structures but a small layer of support structures were left on the part after the cutting. Rest of the support structures had to be manually removed with pliers. When the entire support structures had been removed from all the prototype concepts, the prototypes were polished and blasted with a mix of sand and glass. The baseline solution was the only prototype which was not post-processed. The post-processed prototypes can be seen in Figures 4.29, 4.30 and 4.31.

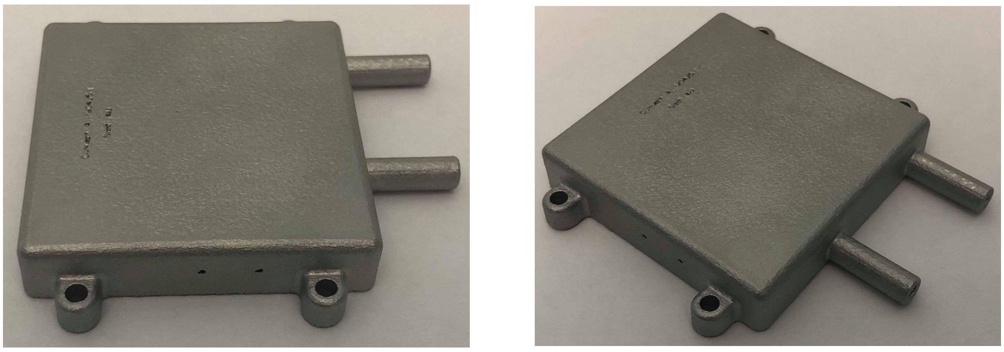
(a)

(b)

Figure 4.29: Prototype of final concept 2 after post-processing

(a) (b)

Figure 4.30: Prototype of final concept 3 after post-processing



(a) (b)

Figure 4.31: Prototype of final concept 4 after post-processing

4.8.6 Integration of sensors

To be able to integrate the sensors into the cavities of the prototypes for the upcoming functional test, the down-skins had to be removed. The down-skins were removed by drilling into the cavities with a small auger (1 mm in diameter). Afterwards, the sensors were extended by soldering the wires with 0.15 m wires in the laboratory. The extended sensors were then integrated into the cavities together with application of adhesive epoxy material. The integration of sensors into concept 4 was only possible during the pause of the printing process with regard to the tilted cavities. As a result of this, the integration of sensors into concept 4 after it had been completely printed was thereby impossible. See Figures 4.32 and 4.33 for the prototypes connected with the Arduino board.

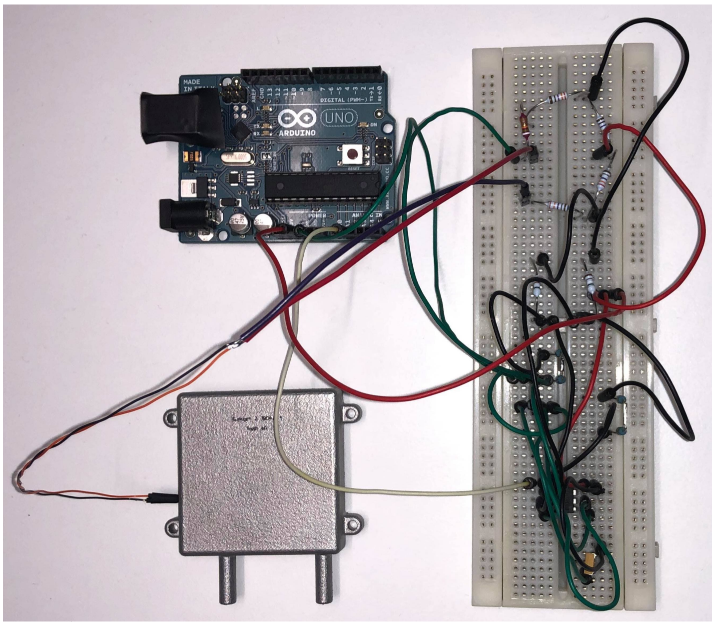


Figure 4.32: Concept 2 with the integrated sensor and connected with the Arduino board

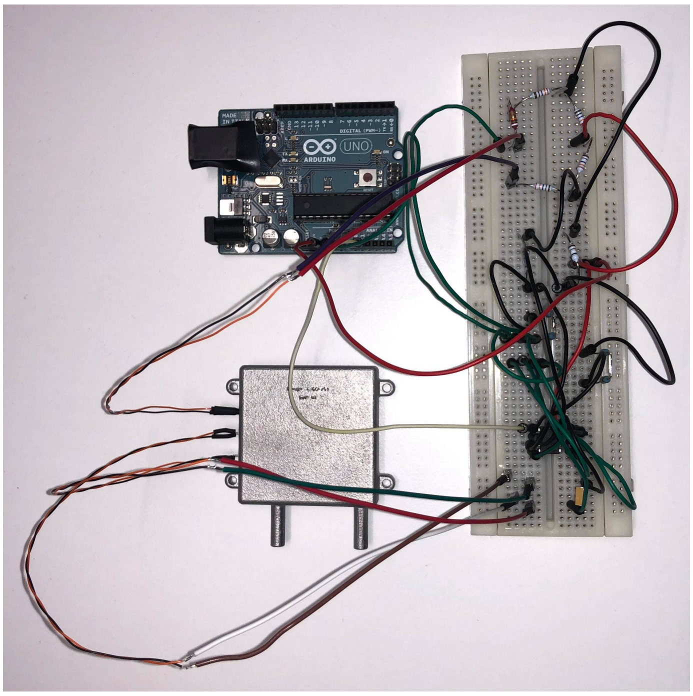
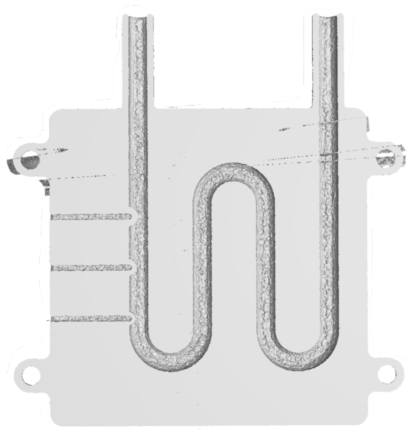


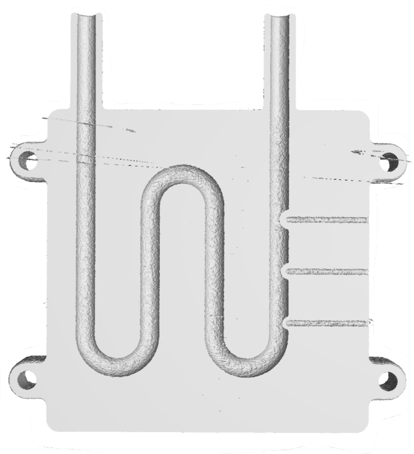
Figure 4.33: Concept 3 with the integrated sensors and connected with the Arduino board

4.9 CT-scan

The planned full CT-scan was not conducted due to the time limitation and economic viability. However, Rebecka Ericsson at Saab Bofors Test Center in Karlskoga conducted a fast 2D and 3D CT-scan of one prototype for free in order to give an insight of what a CT-scan would look like. The selected prototype for the free scanning was the printed prototype of final concept 3. A fast scan resulted in radiographs with a lot of noise, disturbances and low resolutions. As a result of this fast scan, it was difficult to detect and see defects on the prototype e.g. porosity and cracks but the down-skins (darker areas in the channel) could be seen on the radiographs, see Figure 4.36a. The radiographs of the printed final concept 3 can be seen in Figures 4.34, 4.35 and 4.36.

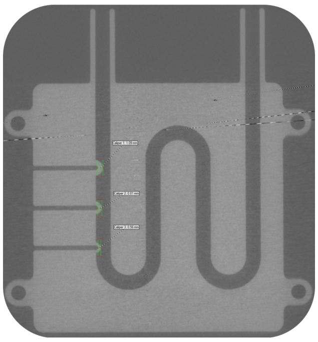


(a) 2D section from top view

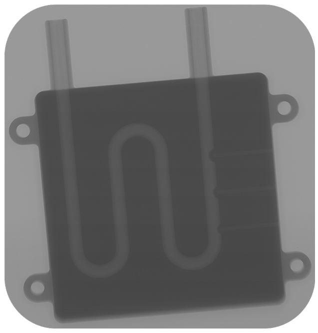


(b) 2D section from bottom view

Figure 4.34: CT 2D-view

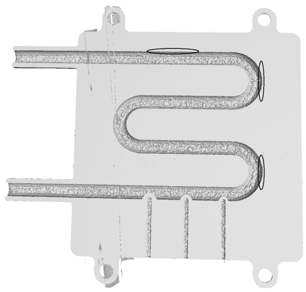


(a) Concept 3

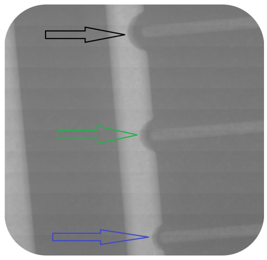


(b) Whole 2D

Figure 4.35: CT 2D-view



(a) Marked ellipses demonstrate where down-skins have appeared



(b) Zoomed radiograph of the cavities with different thickness, black arrow shows the thickest, green arrow shows the next thickest and the blue arrow shows the least thickest

Figure 4.36: CT 2D-view

4.10 Functional testing

The functional testing was only applied to the second concept, see Figure 4.37, in order to verify the precision of the integrated sensor. This due to the other concepts not surviving for various reason, among which transportation factors are one of them. A Pt100 sensor was set up and inserted in the chamber in order to work as a reference (yellow/black cable). The cooling machine was set to be heated to two different temperatures which the inserted Pt100 sensor was calibrated for, 30°C and 65°C.

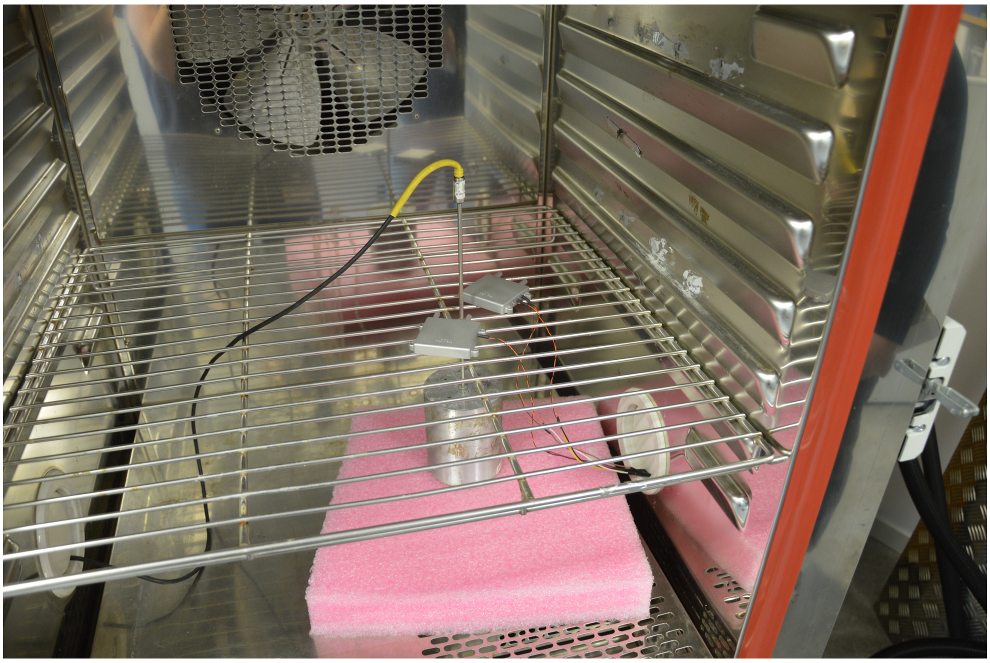


Figure 4.37: The set-up of final concept 1 and 3 in the cooling machine for the functional testing

It could be read from the integrated sensor in the second concept that a deviation of 0.4°C was obtained when the cooling machine was heated up to 30°C. Further, when the cooling machine were heated up additionally 35°C a deviation of 3°C was obtained

5. Discussion

A case study regarding integration of PT100 sensors in simplified cooling plates have been presented in this thesis work. According to the literature findings it could be concluded that sensor integration in AM products is a very research intensive area since it is stated to be a key enabler of the upcoming revolutionary industry 4.0. Although it was challenging to find relevant research articles, most of those articles were very theoretical and regarding polymer products. Many of the found articles also addressed many of the challenges related to sensor integration in AM metallic products but did not present solutions of how to overcome the challenges. The intentions for this can be related to no one wants to be first but that no one wants to be third either which is a result of why companies are conducting the researches in-house and do not want to spread their knowledge and findings regarding the discussed matter.

The generated concepts in this thesis work were derived through a product development procedure. Although, the whole generic product development procedure was not utilised. This had an impact on the explored solution space since a utilisation of the whole generic products development process would have enabled a wider exploration of the solution space. The thesis work was though delimited within a time frame which caused difficulties to utilise all the phases of a product development procedure. Another aspect which had an impact on the explored solution space was the selection of a wired sensor. A wireless sensor would have enabled a wider range of various concept solutions since a wired sensor delimits the freedom of integrating the sensor anywhere within the volume of the AM part. This, since the placement of the sensor in the generated concepts have to ensure that the wires connected to the sensor can be lead out of the part in comparison with a wireless sensor which are independent of the sensor placement.

The screening and evaluation of the concepts were only based on knowledge from the literature studies as well as meetings with internal and external stakeholders. Therefore, no calculations or simulations have been utilised for the evaluation of the generated concepts which had an impact on the feasibility of the proof of concepts. This, since it was very complicated to conduct calculations and simulations on concepts whose only objectives were to survive the printing process and be functional to measure the temperature around the outlet of the cooling plate. Instead the fundamentals of the proof of concepts were built around a build-and-error approach in order to verify the feasibility and viability of the screened and evaluated final concepts.

Furthermore, a SLM process was utilised for the printing and sensor integration by the reason of the thesis work representing as an in-house project. Since it was not preferred to outsource anything during the in-house project, the choice for selection of AM processes for prototyping was really narrow and resulted in a SLM process that had the ability to pause during its printing. It would have been interesting if a cold AM process would have been used instead for manufacturing of the prototypes in order to evaluate the feasibility of a cold AM process with respect to sensor integration. This, in order to avoid the heat problem which is a huge challenge with regard to sensor integration in AM products.

In addition, even if the prototyping of the final concepts with a SLM process was not a perfectly success, various of different learnings and conclusions were obtained for future work and recommendations. Theoretically, the protection of the sensors from the heat in the concepts should have been sufficient to survive the SLM process since the sensors were coated with ceramic but this could not be verified since the sensors could not be integrated during the pause of the printing. It was in particular learnt that the recoater is a crucial factor in the design phase that needs to be considered. This consideration is important to ensure a successful sensor integration and continued printing from a pause.

Lastly feasible set tolerances for the cavity are critical in order to manage the appearing defects (down-skins) which is another challenge regarding sensor integration. However, further evaluation regarding the tolerances need to be done due to increased play can result in entraining between the sensor and the metallic structure and in turn lead to problems in harsh environments. It was also learnt there would be a probability that post-processing technologies (e.g. band sawing and blasting) would have an impact on the embedded wired sensors and if the sensors would have been damaged, it would be too late to repair or reconstruct the discussed cooling plate. That is why one of the greatest challenges with future AM product with successfully embedded sensors will be to develop solutions of how to repair or replace damaged embedded sensors.

6. Conclusions

New learnings and knowledge have been obtained during the thesis work. The learnings are described below as conclusions which have been established through the learnings from the results, meetings and literature review. At the end of the project, a knowledge gap during the design- and prototyping phase was the main reason why the desired results were not obtained. However, due to the knowledge gap, new knowledge could be obtained which will have a contribution to Saab for their future studies.

- Integration of electrical elements e.g. sensors in AM products is a key enabler of the industry 4.0 and has the potential to enable novel important future monitoring system applications e.g. a SHM application to detect damage within a product before it breaks.
- The approach to fabricate electromechanical products through AM is a research intensive area but the approach is still too immature due to the challenges that need to be overcome before additive manufactured electromechanical products can be applied to the market.
- Research regarding integration of sensors in AM products have been conducted for polymer AM but little have been done for metal AM. This, since research on metal AM have more stringent requirements in terms of reliability and defects.
- It is possible to pause a SLM additive manufacturing process of a part to enable integration of electrical elements into the part in a EOS M290.
- The generated final concepts should in theory be feasible but currently requires too many manual work steps to be realisable for industrial production.
- Besides the challenge to ensure the survivability of the sensors from the heat of the laser, another challenge is the design of the area where the sensor is to be integrated so that the sensor will not collide with the recoater during the continued printing.
- Less freedom and more limitations with respect to design and placement of sensor need to be considered when integrating a wired sensor in comparison with a wireless sensor.

6.1 Recommendations

- Explore and evaluate cold AM technologies e.g. ultrasonic additive manufacturing which in theory should work well with the approach to integrate electrical elements into additive manufactured products.
- Explore into other cases where the objective will be to integrate smaller wireless sensors e.g. piezoelectric elements and fibre optic sensors into different components that are not in antennas.
- Explore and develop a pick-and-place machine that can be integrated in a hybrid system together with a AM machine to reduce the manual work of the concepts.
- A more representative cooling plate should be investigated for the integration of temperature sensors to verify the concepts are feasible.
- Explore into AM methods that fabricate piezoelectric sensors in AM products, AM technologies that can print piezoelectric materials in AM products to create novel monitoring system applications.
- Utilise the whole generic product development process in order to explore whole solution space for the chosen case.
- Conduct a real detailed functional test of the prototypes with the company's full available equipment in order to verify the feasibility and function of the generated concepts.
- The EOS M290 machine was not compatible to connect with the chosen Pt100 sensor. This in order to monitor the temperatures during the continued process in which the sensor is affected by. The machine was compatible with a sensor of type K in which the Pt100 is deficient in. A future recommendation is to connect a sensor of type K with the AM machine in order to monitor the precise temperature the integrated sensors are exposed to.

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A. Interview questions

The interview was initiated by describing the scope and aim of the project. This followed by the below mentioned questions in order to work as a support to get a chronological order through the semi-structured in-depth interview.

1. How long have you been working with AM?

2. What is your view on the development of AM? Which research areas do you think will be most research-intensive in the future?

3. How do you expand you knowledge regarding AM within the organisation?

4. Why do you think the development in AM is still relatively immature when it comes to AM manufactured electrical or electromechanical products in contrast to mechanical products?

5. Do you know companies working with additive manufacturing of electromechanical components and/or the integration of electrical element of AM products?

6. What 3D-printer do you use? What materials for which respective printer do you use?

7. Have you heard of UAM? If yes, what possibilities of integrating electrical elements into additively manufactured products do you see with this process? (If no, explain UAM and discuss the possibilities.)

8. There are possibilities for printing printed circuit boards (PCB) and other electrical elements. Do you think that it will be possible in the future to use a so-called all-at-once approach. Which means that you 3d-print both the mechanical and electrical in a product in the same machine?

9. Have you received inquires from customers regarding the possibility to additive manufacture electromechanical products? If yes, how did you and the customer go about producing the electromechanical products? That is how did you integrate the electrical into the mechanical? Did you use one or more AM methods? Or did you combine AM methods with conventional manufacturing methods?

10. What do you see as the major challenges when it comes to integrating electrical elements into AM manufactured products?

11. Are there often orders from customers who wish to combine different manufacturing methods, for example. laser welding and 3D printing?
12. How would a possible splitting of component occur? Any rule of thumb?
13. What possible problems can arise with a possible division of the component? For example, if a breakdown would result in porosity between the metals.
14. How would the joining plan of the divided component look like?
15. How do you compensate for shrinkage when splitting and joining components?
16. What is usually the lead time from sending a request for a 3d-print to getting it?
17. What form configurations of the cavity would cause problems?

B. Arduino PT100 Circuit and Related Script

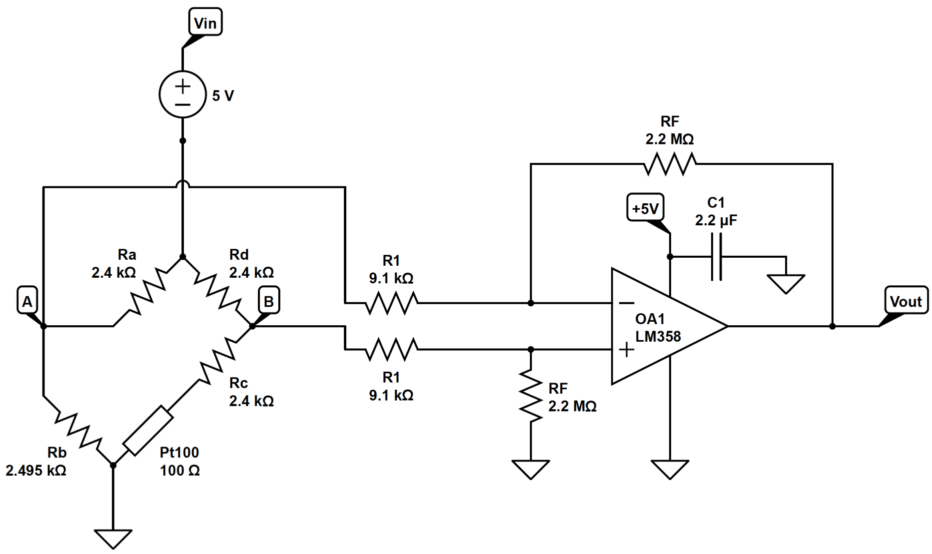

Figure B.1: Electrical bridge circuit with OP-AMP

```
void setup() {
// the setup code here, is run once:

Serial.begin(9600);

}
void loop() {
// the main code here runs repeatedly:

int pt100 = analogRead(A1);

float Vout = pt100 * (5 / 1023.0);

// the temperature equation variables includes curve fitted values:

float c = ((Vout - 0.375) / 4.5) * 100;

Serial.print("Temperature: ");
```

```
Serial.println(c);
Serial.println(" C");

delay(500);

}
```