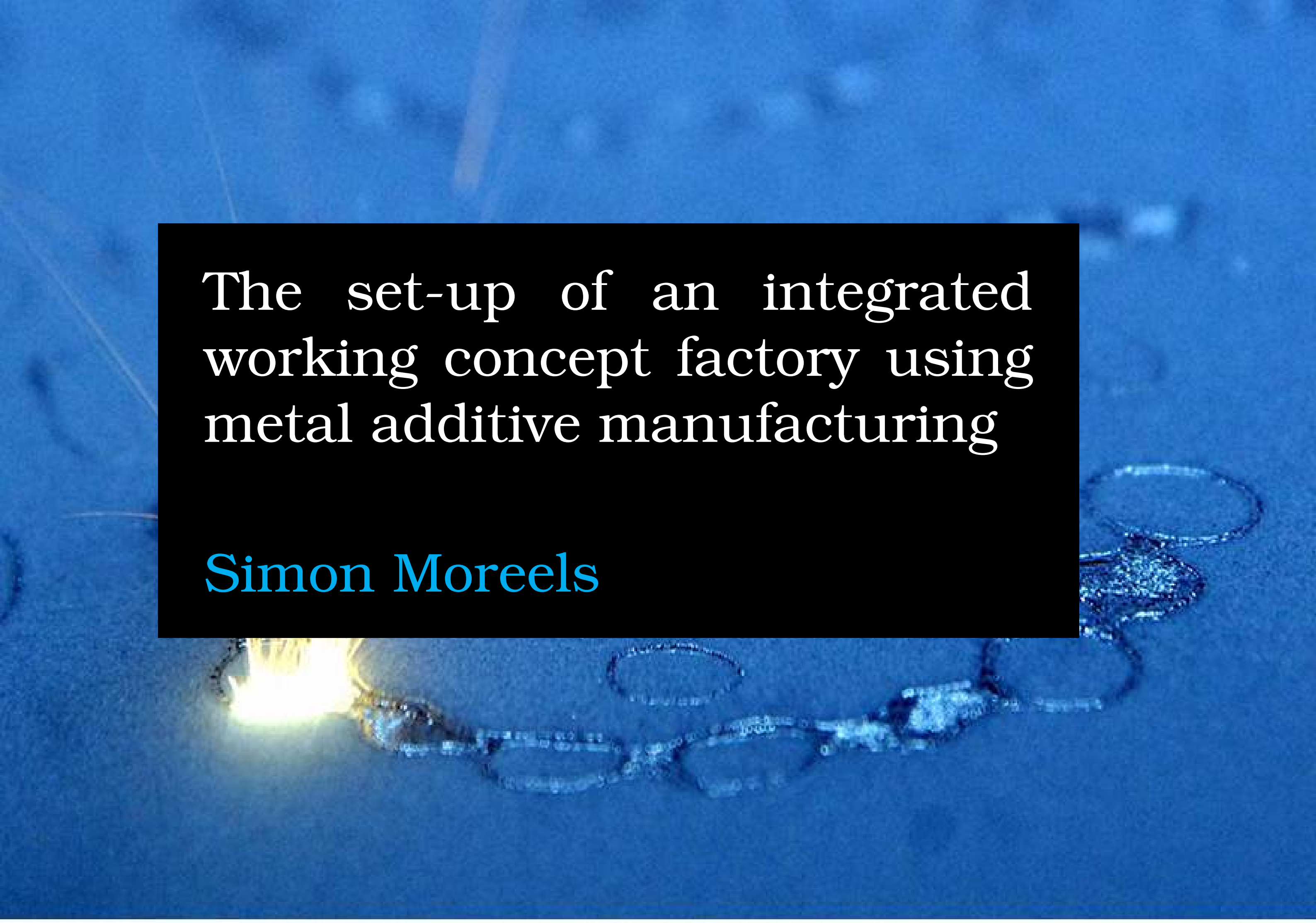
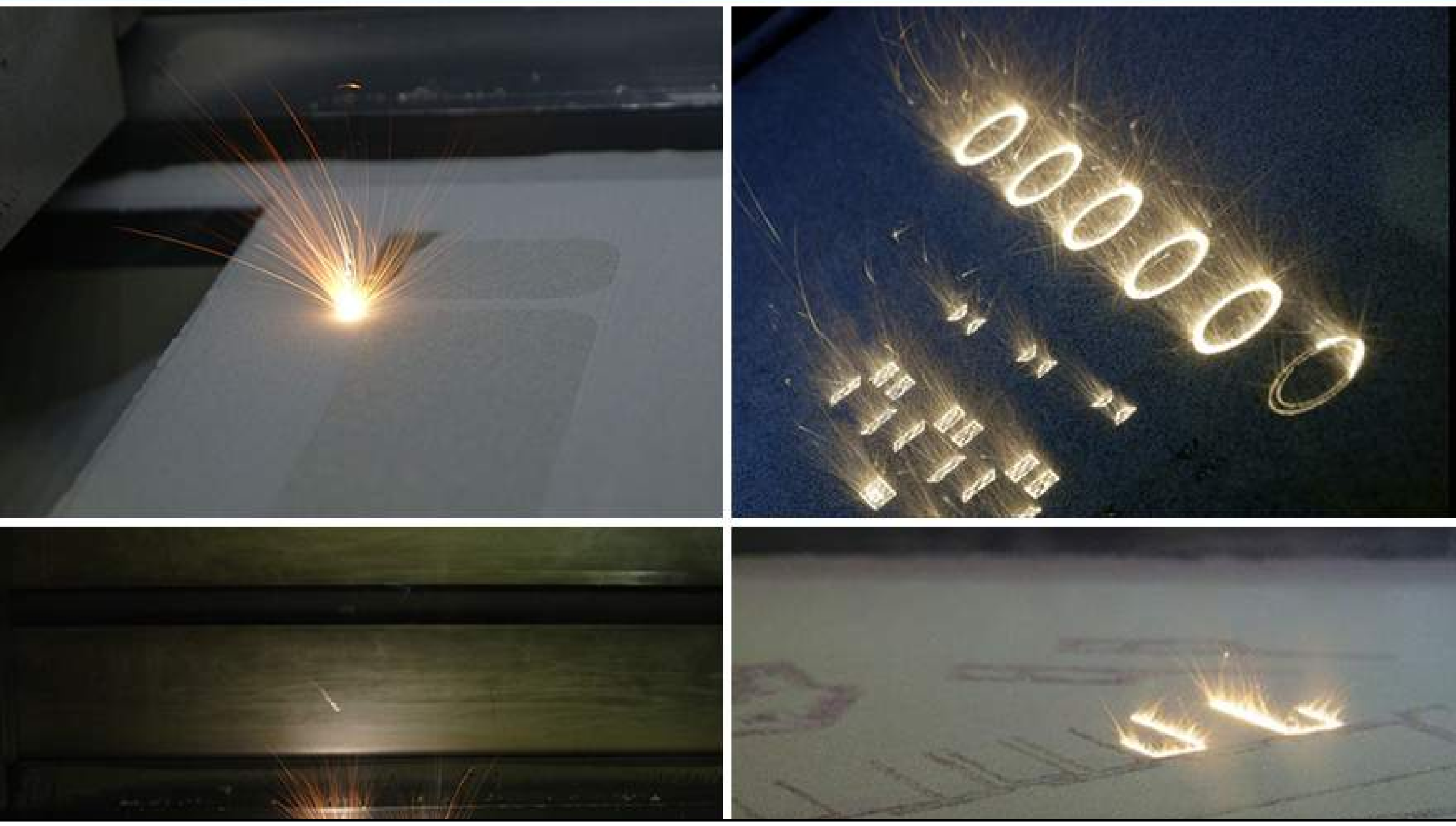


The set-up of an integrated working concept factory using metal additive manufacturing

Simon Moreels



TU Delft
Delft University of Technology

The set-up of an integrated working concept factory using metal additive manufacturing

MSc. Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

Simon Moreels

23-08-2017

Faculty of Aerospace Engineering · Delft University of Technology

The work in this thesis was supported by Sirris. Their cooperation is gratefully acknowledged.

Delft University of Technology
Faculty of Aerospace Engineering
Department of Aerospace Structures and Materials

GRADUATION COMMITTEE

Dated: 23-08-2017

Chair holder: ______________________
Prof.dr.ir. R. Benedictus

Committee members: ______________________
Ir. J. Sinke

____
Ass. Prof. S. J. Garcia

Abstract

In order to produce more complex parts, additive manufacturing is on the rise as a competitor for more conventional manufacturing methods. Unfortunately, additive manufacturing often produces products with a less desirable tolerance and surface roughness. Subtractive methods require special tooling and fixtures for each part design and typically produce parts with a better surface roughness and feature accuracy. This research focusses on the combination of both methods, in order to get a manufacturing process with a competitive advantage compared to conventional manufacturing methods and techniques.

The hypothesis of this thesis is that the combination of both additive and subtractive manufacturing can produce better results than both methods on its own. This can be done due to the production of near-net shaped parts with the additive manufacturing process and a better surface finish and accuracy due to the subtractive manufacturing process. In this research, The challenges and limitations of the combiation of both techniques are studied. This is done using the most well-known techniques used nowadays in industry, selective laser melting as additive manufacturing process and CNC machining as subtractive manufactuiring process, in order to make this research applicable in the real production evironment. Both the physical as digital integration of both techniques is researched, as well as the economic impact of the process on the manufacturing costs for low batch production of metal alloys.

Contents

List of Figures

List of Tables

Acknowledgments

This master thesis marks the final step of my Master degree in Aerospace Engineering. The work which has been done during this thesis could not have been realised without the support of many people, I want to express my gratitude towards them.

First of all, I would like to thank my supervisor Ir. J. Sinke for is guidance during this project. His high quality feedback always helped and motivated me to go the extra mile. More, I would like to thank my graduation committee members Prof. Dr. Ir. R. Benedictus and Ass. Prof. S. J. Garcia for there effort in evaluating my thesis work.

Secondly, I would like to thank my daily supervisor at Sirris, Ing. Benjamin Denayer, for his support and tutorship during this project. His positiveness and confidence have always motivated me and helped me strive towards the best results possible.

Further, I am grateful for the opportunity Ir. Walter Auwers and the whole advanced manufacturing team at Sirris gave me to perform my research in close collaboration with them. I have spent many, very enjoyable hours at all Sirris offices in Belgium. In particular, I am thankful for the support and assistance with the design, manufacturing and post-processing of my case study done by Simon Vermeir, Ing. Krist Mielnik and Ing. Olivier Rigo.

I am also thankful for my fellow master students and friends, in particular Ir. Stef Walraet and Ir. Sebastien Callens, who took the time to proofread parts of my master thesis in order to push it to a higher level. I also like to thank them for the support during my 6 years of studying.

In particular, I would like to thank my parents for the unlimited support during my studies. They give me the opportunity and flexibility to study what I wanted and pursue my dreams.

Delft, University of Technology — Simon Moreels
23-08-2017

Chapter 1

Introduction

Additive manufacturing evolved since its development in the 1980s towards a powerful technique in advanced manufacturing. In the same period, the digital revolution and the adaptation towards "Industry 4.0" contributed to the fast growing computing and communication abilities. This combination of new technologies made the evolution possible from rapid prototyping, where additive manufacturing was used only in the product development stage, mostly due to the limited strength of the materials which were used in these processes, towards the use of additive manufacturing for end-use parts in production companies.

In the past years, the range of materials which can be used has grown steadily and also metal alloys which usually processes through conventional manufacturing methods (machining, casting, forging, etc.) can be produced using additive manufacturing. The layer-based approach offers sometimes unique advantages compared to conventional methods. The design driven applications ranging from cooling channels inside the parts to lightweight lattice structures are examples of the distinctive contribution of AM to the advanced manufacturing field.

In summary, additive manufacturing possesses the capabilities to become a true competitior with conventional methods because it can produce parts with complex geometries without the additional costs of special tools, dies or fixtures for subtractive manufacturing. However, when compared to subtractive methods, current AM methods produce parts with a poorer accuracy and surface quality. It depends from application to application weather these factors are critical, but for most aerospace and other mechanical applications, part accuracy and surface quality are very important. The approaches followed in solving these issues are:

- Improving the capabilities of each AM process

- The development of an hybrid manufacturing process where AM methods work as the produciton step of a near-net shape part which can be coupled with a material removal process like machining to overcome accuracy and surface finish issues.

This master thesis focusses on the second solution. A succesfull hybrid system can accelerate the application of metal additive manufacturing inside the industry. This thesis researches the main challenges and barriers for entry associated with such a system, while providing solutions to overcome them.

The goal of 'Sirris' is the set-up of a 'Lean pilot factory' in the near future, a real life production facility where an additive manufacturing system is combined with a conventional subtractive manufacturing process to improve the accuracy and surface quality of the manufactured parts. In later years, the knowledge gathered from this combination will be put into practise in a bigger and more complex production environment where multiple additive manufacturing technologies and multiple conventional manufacturing methods will be working efficiently next to each other. It will be called a 'Flexible pilot factory'.

The goal of this master thesis is to map out the state-of-the art of the current hybrid manuacturing systems, generate a general concept of the pilot factory and define its main challenges and possible solutions to overcome the main barriers the manufacturing industry is experiencing with the integration of metal additive manufacturing into the production chain.

In Chapter 2 an overview is given of the current AM techniques and processes together with the required post-processes and a deeper understanding of metal AM systems and the AM market. Chapter 3 focusses on the definition and key learnings for hybrid manufacturing systems. Chapter 4 describes the lay-out of a pilot factory which will be set-up by Sirris and chapter 5 makes a trade-off for a decision about which AM machine to incorporate in the pilot factory. Chapter 6 and 7 focus on the digital and physical integration of all processes into one streamlined manufacturing process. In chapter 8 a case study is described where the combination of additive and subtractive manufacturing is tested, while in chapter 9 the economic implications of this hybrid system are laid out and a cost calculation of the practical case is made. In chapter 10 the main challenges and barriers for entry of a true agile pilot factory, one with multiple AM and SM processes next to each other are described. The last chapter 11 describes the main conclusions from this research and gives recommendations for future research.

Chapter 2

Overview of Additive Manufacturing

2.1 Introduction

Going back to the year 1983, some aerospace companies started experimenting with the new technology of additive manufacturing. In the early stages, the main goal of additive manufacturing was largely geared towards rapid prototyping. 4 years later, in 1987, the first commercial additive manufacturing system for polymers was introduced. The system was based on the stereolithography technology (more information in section 2.6). Around 1995, the first commercial additive manufacturing systems for metals were introduced. The following chapter gives a general overview of additive manufacturing. It's definition, advantages, limitations, techniques used nowadays and a roadmap for the future.

2.2 Definition

ASM F2792, "standard terminology for additive manufacturing technologies" defines additive manufacturing as follows [6]:

"The process of joining materials to create objects, usually in layers, from the 3D data of a model, in an opposed way to subtractive manufacturing techniques."

Underneath a few basic concepts of additive manufacturing are listed:

- Additive manufacturing is used to build physical models, prototypes, patterns, tooling components and production parts in plastic, metal, ceramic, glass and composite materials [8].

- Additive manufacturing systems use thin, horizontal cross sections from computer aided design (CAD) models, 3D-scanning systems and medical scanners to produce parts in about any shape imaginable [9] [8].
- After already more than 3 decades of research, development and use, the industry continues to expand with the introduction of new technologies, methods, materials, applications and business models [8].
- Additive manufacturing has originated from rapid prototyping, but nowadays the technique is used in many more applications than just prototyping [9].

2.3 Needs and potentials in the target sectors

Additive manufacturing offers potentials in multiple sectors, but for simplification reasons, only the target sectors of the master thesis research are researched and summarized. These include the aerospace, automotive and tooling or machinery sector.

2.3.1 Aerospace sector

Since the on of the most critical goals for the aerospace industry is the development of lightweight structures and components, additive manufacturing can provide a solution for both critical and non-critical components. Redesigning the parts with the freedom of additive manufacturing can result in significant weight saving [9]. On the other side, the aerospace industry requires a perfect quality and consistency of the parts manufactured. Certification and product consistency is still one of the main challenges additive manufacturing has to cope with. Successfully meeting this challenge would result in a more extensive use of additively manufactured parts in the industrial production of both aircraft and spacecraft. More, additive manufacturing can start a major change in the supply chain of spare parts all over the world [8] [10].

Two successful examples are the Leap engine fuel nozzle by General Electric Aviation (more information in section 2.8) and the ”Bionic Wall” by Airbus [11].The bionic wall is the part which divides passengers from crew quarters in the airbus A320 and it is made by 3D printing. This had as result a 45% lighter design for the same strength.

2.3.2 Automotive sector

In the automotive sector, the opportunity for the use of additively manufactured parts is substantial. Production runs of high end, specialty cars are relatively small, which makes them a good candidate to implement additive manufacturing in the production process. Likewise, the motorsport industry will benefit from the improved design freedom and weight saving of additively manufactured parts [8]. At the moment, usage in the mass market for cars is still too early, but if the process of additive manufacturing speeds up significantly in the future, opportunities can also be found here. Also in the second hand market and the maintenance market additive manufacturing can be used, printing the right part immediately would reduce the time a consumer has to miss his/her car [9] [12]. More, additive manufacturing is already extensively used for prototypes in the development of a new car, Ford already uses additive manufacturing extensively in order to speed up its process to manufacture a prototype [13]. Over the last few years a wider adoption of additive manufacturing is seen in the manufacturing operations of automotive companies, primarily in the jigs and fixtures and tooling applications but clearly the automotive industry is also looking at new ways and technologies to reduce cycle times tooling expenses and investments in order to bring lightweight alternatives to the market [14].

2.3.3 Tooling sector

The use of additive manufacturing to fabricate machine parts and tooling can reduce lead time and costs, but also improve functionality and customization [15]. The first two benefits, lead time and cost reduction, describe additive manufacturing as a manufacturing method which has a more favorable process than other conventional methods. The other two, improved functionality and customization, detail additive manufacturing capabilities to change and optimise the design of the product which has to be made. An example from the tooling sector: The automotive company Opel already developed multiple assemblage tools in order to reduce its production costs [8] [16].

2.4 Overall advantages and limitations of Additive Manufacturing

The main obstacles to the wider adoption of additive manufacturing technologies are the cost of machines, materials and maintenance. The perceived risk and expected economical return to replace an existing manufacturing process by additive manufacturing varies widely from company to company [9]. Another important factor that influences the adoption of an entirely new process besides costs is time to market. Companies and clients are willing to pay a premium if manufacturing time savings can be significant. Additive manufacturing can have the opportunity to reduce the part count in a product by combining 2 or more parts into one single design which can be printed [17]. Also, less time might be needed to produce and assemble complex parts. Using additive manufacturing has a significant impact on time and eventually cost savings, as well as inventory, supply chain management, assembly, weight and required maintenance [9] [18]. Also the fact that the manufacturing process can start from an adjusted CAD model makes the processes done before the actual manufacturing more simplified and so faster and less costly.

2.4.1 Benefits

The main benefits of Additive Manufacturing methods are listed below [8] [9] [19]:

- **CAD-to-Part:** additive manufacturing allows a 3D CAD drawing of a component or shape to be converted directly into a physical part. With 3D technologies, engineers have the freedom to recognise a problem and design, manufacture and test a simple solution in a matter of days [20]. This results in significantly shorter R&D iterations and a shorter development time.
- **Design for Customisation:** additive manufacturing allows producers to generate parts with greater customisation to lower costs because no extra tooling costs are required [21]. This cost advantage is biggest for small lot sizes [22].
- **Design for Function:** additive manufacturing allows the user to design for function rather than for manufacturing technique. Examples include the integration of internal features that would be impossible to produce using conventional manufacturing techniques [12].
- **Design for Light-weighting:** novel design and flexible manufacturing enables the production of lightweight structures. Hollow or complex lattice structures can be produced while the part retains its structural strength. Topology optimization can be used to make efficient use of the material starting from the applied forces on the part [21]. The complexity of the part no longer dominates manufacturing time and costs [22].
- **Material Utilisation:** additive manufacturing techniques have the potential to approach near zero waste regarding material utilisation. With additive manufacturing techniques like SLM or EBM, hollow metal structures (less material usage then a solid one) can be produced easily [12]. Also scrap generated during the process has the potential to be recycled completely.
- **Reduced Time-to-Market:** additive manufacturing has the ability to consolidate several machining steps into a single manufacturing step which will dramatically reduce the overall manufacturing time [21]. Also the fact that there is no need for tooling may result in a faster time-to-market [22].

2.4.2 Limitations

However, additive manufacturing technology still cannot fully compete with conventional manufacturing, especially in the mass production field because of the following drawbacks [8] [9]:

- **Size limitations:** Large-sized objects require very big printing machines and are also often impractical due to the extended amount of time needed to complete the build process [23].

- **Surface roughness:** Parts produced using additive manufacturing processes often possess a rough and ribbed surface finish. This appearance is due to plastic beads or large-sized powder particles that are stacked on top of each other, giving the end product an unfinished look [23]. This effect is well known as the "staircase effect".
- **Quality control:** Up to today, it is still difficult to predict a consistent quality of the manufactured products. A lot of research and innovation focusses on following all details in the process to use that data as a quality control system [12].
- **Cost:** additive manufacturing equipment is considered an expensive investment. Entry level 3D printers which can produce small plastic parts average approximately $5,000 and can go as high as $50,000 for higher-end models, not including the cost of accessories and resins or other operational materials [23]. For industrial metal printers, the costs of a printer goes to the range of $100.000 - $1.000.000.
- **Process speed:** Looking at the pure manufacturing process, additive manufacturing stays slow compared to conventional manufacturing methods. The process speed of an SLM (Selective Laser Melting) process is about 5-20 cm^3/h depending on multiple parameters like laser power, space utilization, layer thickness etc [24].
- **Material variety:** The availability of different metal alloy powders which can be used for additive manufacturing is expanding constantly, but it should be noted that the amount of different alloys is still rather limited. The most common alloys available are: tool steels and maraging steels, stainless steel, titanium, aluminium and nickel based alloys.

2.5 Overview of Additive Manufacturing techniques

As of January 2012, ASTM International Committee F42 on Additive Manufacturing Technologies defined a list of process categories and their definitions. This list is presented underneath. [6]

- **Material extrusion:** an additive manufacturing process in which the material is selectively dispensed through a nozzle or orifice.
- **Material jetting:** an additive manufacturing process in which droplets of build material are selectively deposited.
- **Binder jetting:** an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
- **Sheet lamination:** an additive manufacturing process in which sheets of material are bonded to form an object.

- **Vat photopolymerisation:** an additive manufacturing process in which liquid photopolymer in a vessel is selectively cured by light-activated polymerization.
- **Powder bed fusion:** an additive manufacturing process in which thermal energy selectively fuses regions of a power bed.
- **Directed energy deposition:** an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as the material is being deposited.

An overview of all existing additive manufacturing techniques and the most important characteristics can be found in Table 2.1.

Table 2.1: Overview of all existing AM techniques [5] [6]

Condition	ASTM Classification	Process	Lay-out	Layer Forming	Phase Change	Materials
Liquid	Vat Photo- polymerisation	Stereolithography	Liquid resin in a vat, irradiated by UV light through a laser	Liquid layer deposition	Photo-polymerisation	Acrylates / epoxies / filled resins
		Digital Light Processing	Liquid resin irradiated by UV light through a projector	Liquid layer deposition	Photo-polymerisation	Acrylates / epoxies / filled resins
	Material Jetting	Polyjet	Droplets of photopolymer irradiated by UV light or cooling	Moving printhead	Photo-polymerisation/ cooling	Acrylates / Epoxies / Wax
	Material Extrusion	Fused deposition moddeling	Material melted in a nozzle	Extrusion and deposition	Solidifiaction by cooling	(Filled) Polymers / wax
Powder	Binder jetting	3D Printing/ Z Printing	Binder jetted on powder bed	Layer of powder. Drop on demand binder deposition	No phase change, solidification by binder	Ceramics / metals / polymers / sand
	Directed energy deposition	Lasercladding	Powder injection through nozzle in laser spot	Continuous powder injection	Powder melting by laser, solidify by cooling	Metals / composites
	Powder bed fusion	Directed metal laser sintering	Powderbed in chamber of inert gas, sintered through laser	Layer of powder	No phase change, solidification by binder	Metals (limited)
		Selective laser melting	Powderbed melted through laser	Layer of powder	Powder melting by laser	Metals (limited)
		Electron beam melting	Powderbed in chamber of inert gas, melted through electron beam	Layer of powder	Powder melting by electron beam solidify by cooling	Non-ferro metals
		Selective laser sintering	Powderbed sintered through laser	Layer of powder	Melting by laser, solidify by cooling	Polymers
		Selective heat sintering	Powderbed sintered by thermal prindhead (IR)	Layer of powder	Powder melting by heat solidify by cooling	Polymers
Solid	Sheet lamination	Laminated object manufacturing	Feeding, cutting and binding of sheets	Deposition of sheet material	Binding by phase change of solder, glue or others	Paper, polymer, metals, composites, ceramics

2.6 SLM and EBM

This research focusses on metal additive manufacturing. Therfore, looking at the different techniques and the requirements for metal end-use parts in industry, powder bed fusion techniques have the greatest potential for metal additive manufacturing of small series of end-use parts. In the following section the two most important techniques of powder bed fusion for metals are described in greater detail and the benefits and limitations are compared to each other.

2.6.1 Selective Laser Lelting (SLM)

Selective Laser Melting was developed from the selective laser sintering technique [25]. Selective laser sintering does not involve the complete melting of the powder, in contrast to selective laser melting. Using the 3D CAD file as an input, it is sliced in layers between 20-100μm [9]. The first layer is constructed by applying metal powder over a temperature controlled base plate. A high powered laser beam scans the local zones specified for the current layer. This process melts the powder locally and a solidified layer is created. Afterwards, the work plate moves down by one layer thickness and the process is repeated for the second layer [9] [25]. The process is shown in figure 2.1.

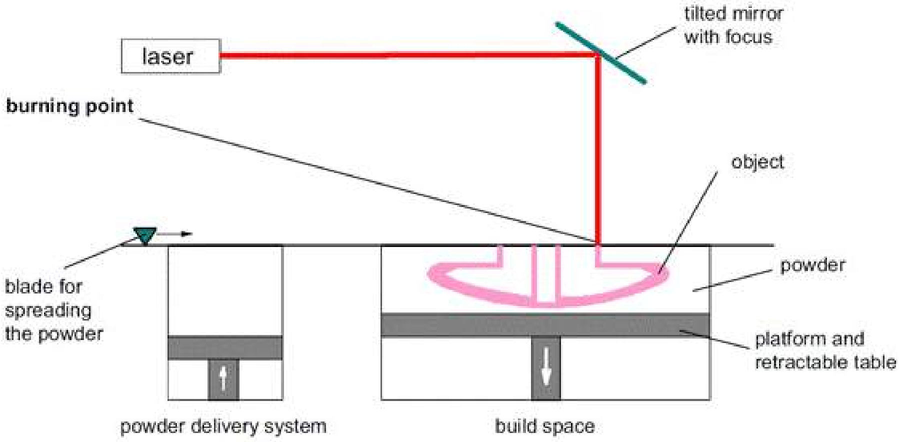


Figure 2.1: Selective Laser Melting

In order to avoid oxidation of the powder, the build space is filled with an inert gas (most of the times argon is used). This also protects the process against explosions and fire hazards related to metal powders such as titanium and aluminium [9].

After the manufacturing process the user has to wait until the temperature has dropped towards 50°C in order to prevent oxidation of the metal powder.

When constructing very large parts, the parts need to be fastened strongly to the build plate with a support structure in order to minimize the risks for warping due to thermal stresses. When the additive manufacturing process is done, everything needs to go in an oven to undergo a stress relief process [26].

Certain post-processing steps might be needed to improve the characteristics of the manufactured parts. Shot-peening to compress the surface as well as a metal polishing step to improve the surface quality and to supply corrosion prevention can be used. More information can be found in subsection 4.5.5.

Different metal powders can be used for this process, to name a few: stainless steel 316L, tool steel H13, Ti-6Al-4V , $AlSi_{12}$, $AlSi_{10}Mg$, CoCr alloy.

The main advantages of SLM are:

- High geometrical complexity, high resolution of small details and the good surface quality [9].
- The process is well suited for processing parts with internal channels, internal cavities and lightweight structure applications. This is due to the easy powder removal (parts are not embedded in a pre-sintered cake) [7].
- A short dead time between 2 productions (about 2 hours for cooling) [7].
- Easy visual inspection of the manufacturing process [7].

The main limitations of SLM are:

- Low productivity compared to EBM [9].
- The process is wall thickness dependent (not suitable for massive parts) [7].
- Support structures can be required which lowers the surface quality of overhanging structures [9].
- Internal stresses can develop inside the parts, there might be a need for additional annealing [7].
- A cutting tool is necessary in order to release the parts from the built plate [7].

2.6.2 Electron Beam Melting (EBM)

Electron beam melting (EBM) builds metal parts layer by layer from a metal powder. This is done using a powerful electron beam (usually 30 to 60KV [12]) instead of a laser as in Selective Laser Melting. Usually the layer thickness for EBM is about $50\mu m$ to $200\mu m$ [27]. A 3D CAD model defines the geometry of every melted layer. The EBM process takes place in vacuum and at high temperature which has as result first class material properties, as well as mechanical as chemical [27]. The process set-up is shown in figure 2.2.

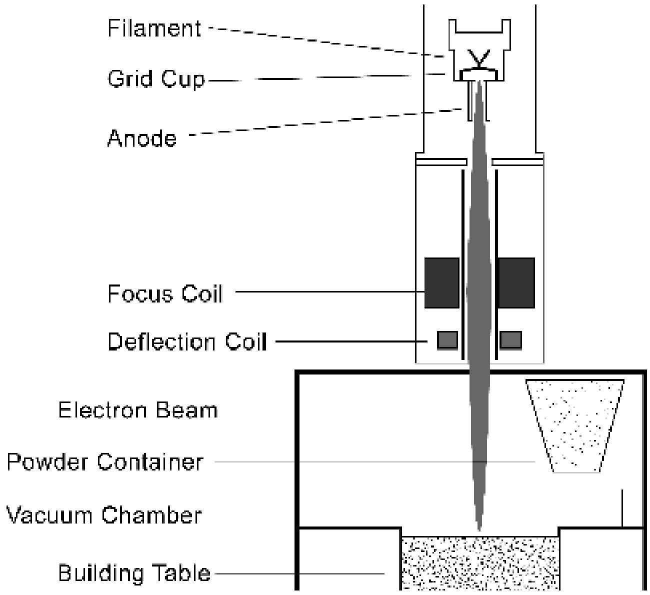


Figure 2.2: Electron Beam Melting

The materials available for EBM are [9]:

- CoCr alloys
- Titanium alloys: The most common is Ti-6Al-4V . It is important to note that the mechanical properties for EBM-processed titanium are often higher than cast titanium for yield strength, elongation and elastic modulus [27].

The main advantages of EBM compared to SLM are:

- Manufacturing process goes 2 to 4 times faster compared to SLM [9].
- If the parameters of the material are mastered, the structure can be free of cracks and unwanted porosity [9]. This makes it suitable for very massive parts [7].
- The grain size can be in the range of 10 μm to 60 μm. This results in very good mechanical and fatigue results for Ti-6Al-4V [7].
- Less supports are needed compared to SLM [7].
- Process is done under vacuum (no gas contaminations) [7].

The main limitations of EBM are:

- Only a small number of conductive materials can be used [9].

- The non-molten powder is sintered, which makes it difficult for interior channels to remove the powder afterwards [7].
- Accuracy of the process is not ideal [9].
- Surface roughness [9].
- Expensive maintenance contracts for the AM machine. [7].

At this moment, the patent for EBM machines is owned by the Swedish company Arcam AB [28] [9]. This company got acquired by GE in the end of 2016.

2.6.3 Summary SLM & EBM

Underneath the small table 2.2 summarises the main characteristics of both Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

Table 2.2: Summary SLM vs. EBM [7]

Characteristic	SLM	EBM
Layer thickness (μm)	30 - 60	50
Minimum wall thickness (mm)	0.2	0.6
Accuracy (mm)	+/- 0.1	+/- 0.3
Build rate (cm^3/h)	5-20	80
Surface roughness (μm)	5 - 15	20 - 30
Geometry limitations	Supports needed everywhere (thermal, anchorage)	Less supports but powder is sintered
Materials	Stainless steel, tool steel, titanium, aluminium, . . .	Only conductive materials (CrCo, Ti_6Al_4V, ...)

For both SLM and EBM, it is important to research the effects of the process parameters on the quality of the end part. Experience of the additive manufacturing machine operator is needed to define the right parameters regarding scanning power, scanning speed, hatching technique [1] and layer thickness. These parameters change from material to material.

2.7 Roadmap for the future of Additive Manufacturing

Altough the first materials and processes for additive manufacturing were already commercialized almost 30 years ago, new innovations are still required in order to propel

[1] hatching technique: the pattern of the laser to scan the intersection surface [29]

this growing technology further into mass commercialization and new application areas. While firstly additive manufacturing was seen as an innovative approach to product design and fabrication via rapid prototyping, AM processing technologies have become an increasingly competitive option for commercial product manufacturing of near-net shape components as well as component repair. The additive manufacturing industry is expected to grow strongly over the next years. The plastic market is leading with about 30000 machines in 2015, but the market for metal additive manufacturing machines is expected to see a double digit growth in the next years [30] [8].

The industries where additive manufacturing is growing most significantly are medical, dental, aerospace, automotive and power generation. Within these sectors, additive manufacturing has provided benefits including design freedom, reduced time to market in product development, service and increased R&D efficiency.

Focusing on productivity and manufacturing processes, the main points of attention for the coming years are [31]:

- Increase of the build-speed, possibly through scanning or new sources of energy.
- Support higher volume production: through enabling batch consistency and methodologies for consistent material supply.
- The development of new machines with for example multiple lasers.
- Development of methodologies for measurement of additive manufacturing products.
- Faster turnaround addressing material/part/component handling.
- Identification of new supply chain opportunities and establishment of existing supply chains for potential products. Because an AM machine can produce lots of different products starting from a CAD drawing, it might not be needed to wait for a product because it has to be transported from the production plant. AM manufacturing can be helpful to implement "local production".
- Reduce scrap and improve repeatability.
- Analyse stability of the additive manufacturing process in order to make improvements to additive manufacturing systems which will allow production components to be produced with required properties.
- The creation of assemblies using AM. It is sometimes possible to integrate multiple parts of one assembly into one product when it is manufactured through AM, a well-known example is the GE fuel nozzle shown in figure 2.3. When this part is made through conventional manufacturing, it is made and assembled out of 20 different parts.
- Supply chain development, from material supply, reliable additive manufacturing systems to post-processing.

2.8 Why use Additive Manufacturing for production

Before additive manufacturing can be used for production certain business drivers have to be in place. These drivers can be market related, economic, environmental or performance related. Those drivers are the result of advantages gained over traditional manufacturing techniques which require tooling. The most important drivers are listed and explained below.

1. **Customer satisfaction:** additive manufacturing can be the ideal solution for tailored products which focus on one or a limited number of individuals. This can help certain companies reach the niche market segments that are beyond the scope of mass production. Since it will be easy to make every product slightly different, the next phase of development might be mass customization. This can be a major breakthrough for products where custom features are a key component [8]. Another area where additive manufacturing can contribute to greater customer satisfaction is through improved product performance. Examples can be: more aerodynamic external forms, optimized internal structures or improved ergonomics and fit [32]. The key in all these examples is that, with the use of additive manufacturing, constraints around design for manufacturing might be closer to the optimum product [31]. It will be necessary for certain aspects of additive manufacturing production to be improved to a level more comparable with conventional processes. Examples are: surface finish, repeatability of dimensions, colours and material integrity.

2. **Reduction of tooling:** one of the biggest advantages of additive manufacturing is the reduction or even the potential elimination of tooling. Some conventional manufacturing techniques still have the constraints of molds and dies. Whereas additive manufacturing provides manufacturers the ability to produce cost effective, low production volumes [22]. It also gives the opportunity to manufacture parts at multiple locations or with multiple design iterations at little extra cost. Also, many of the restrictions of design for manufacturing are imposed by tooling. When this is eliminated, the possibilities are only limited by the design tools and the imagination of the designer. This makes additive manufacturing especially suitable for small and complicated parts [1].

3. **Part consolidation:** a big benefit of additively manufactured parts is the possibility to lower the need of assembly by making complex products in one go. This makes it more time efficient to use additive manufacturing to produce the end-products together with improvements regarding weight and durability. Successful part consolidation can be seen in the following example of a Leap Engine fuel nozzle manufactured by General Electric Aviation (abbreviated as GEA) as seen in figure 2.3. The leap fuel nozzle manufactured using additive manufacturing combines 20 different parts, into one. This caused a weight reduction of 25% and improved durability compared to the conventional part [17]. GEA identified

that the part has a 5 times life improvement of the fuel delivery system thanks to great design freedom. By 2018, GEA expects to manufacture 40000 of those parts per year [33]. However, disassembly for repair, maintenance, and recycling is an important consideration as well. A trade-off should be made to find the solution of those conflicting issues [8].

Figure 2.3: Leap engine nozzle by GE

4. **Environmental benefits:** the real environmental benefits comes from the production of end-use parts by additive manufacturing. The greatest benefit originates from the ability to make much more complex designs which are less restricted by design for manufacturing in order to reach a higher performance [8] [32]. Secondly, raw material is spared because typically, the waste from an additive manufacturing process is much less than the waste in raw material from a conventional machining process [34].

2.9 Additive manufacturing market

2.9.1 Overall market

The additive manufacturing market is currently growing as an increased number of organisations adopt additively manufactured products as well as services [8]. After a decline in 2009 the market continuously grows. The Compound Annual Growth Rate over the past 27 years for the whole market (products as well as services) is an impressive 26.2 % [1]. The CAGR between 2013 and 2015 is 31.5 % [1]. So the growth is not slowing down. AM systems manufacturers are increasingly offering solutions for end-use parts production. However, due to the higher quality standards in this market than for prototyping and modelling application, some challenges still have to be overcome and it is expected that annual revenues will drive to much higher levels in the near future [1].

The following chart 2.4 maps out reveunes for AM products and services worldwide in millions of dollars [1]. The industry has experienced significant growth over the past 20 years. In the last years, this growth is even accelerating.

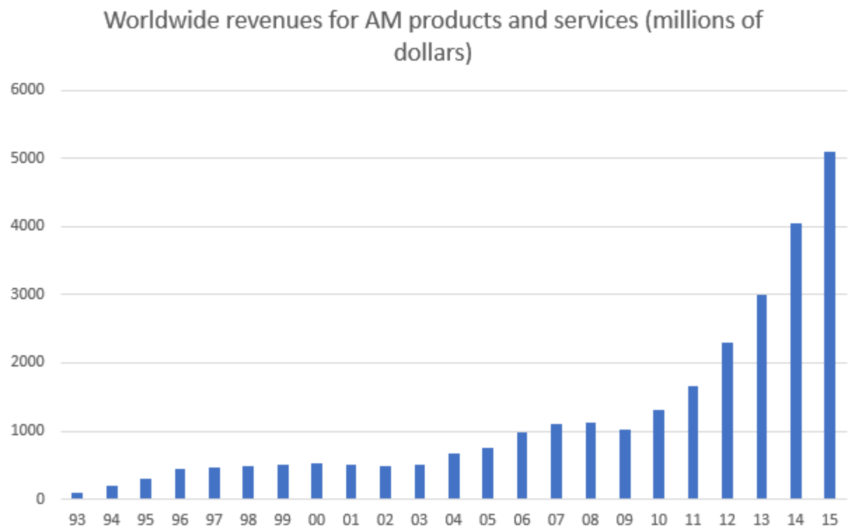


Figure 2.4: Revenues of AM products and services worldwide for the years 1993-2015. [1]

Regarding industrial systems (the ones that sell for $5000 or more), The same growth can be seen for the last two decades. Excluded are the so-called desktop printers (sale price < 5000$). The following chart 2.5 provides industrial system unit sales between 1988 and 2015 [1].

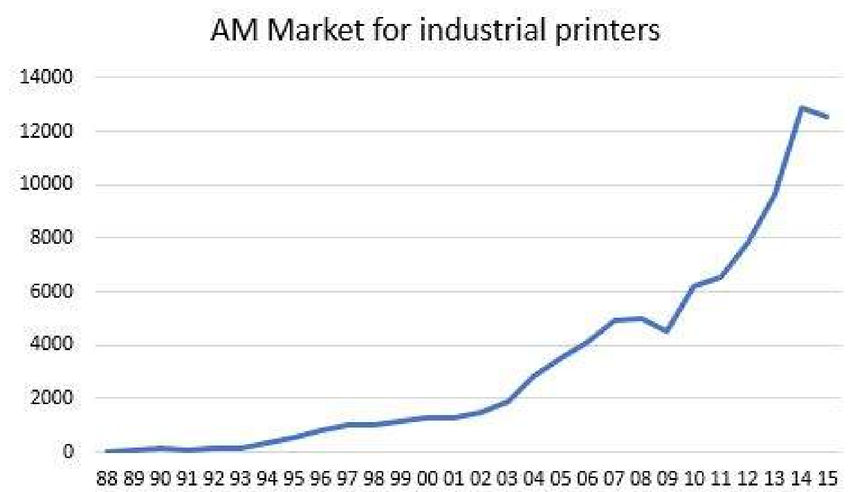


Figure 2.5: Number of sold industrial AM systems between 1988 and 2015

Focussing on the materials in scope of this master thesis, revenues from metal powder made for additive manufacturing grew significantly in the past years. Wohlers Associates began to track the sales and growth of metal powder in 2009 and the results are shown in the following graph 2.6.

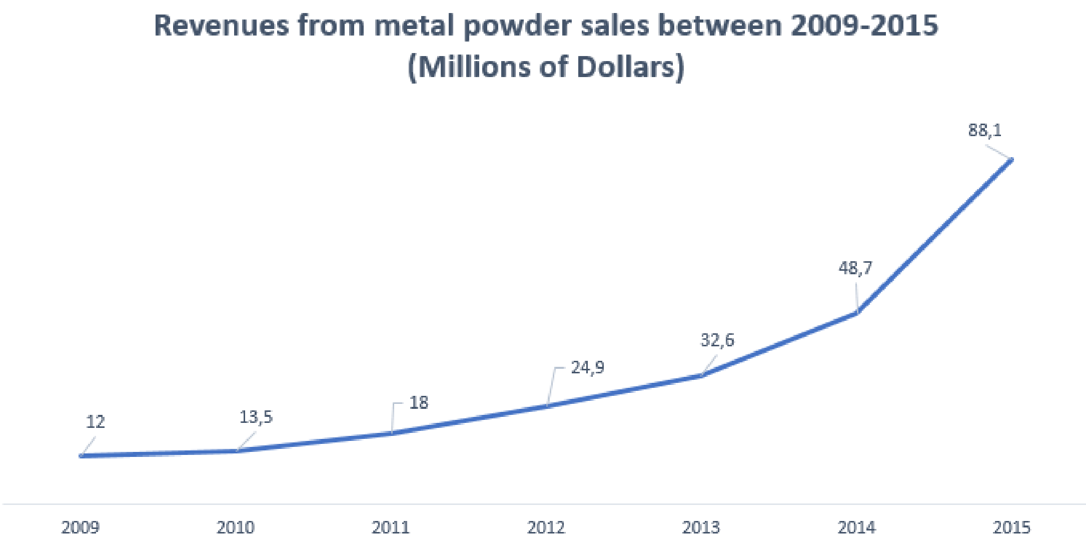


Figure 2.6: Revenues from metal powder sales for Additive manufacturing since 2009

It is expected, that in the future, the AM market will continue to grow strongly. Estimates by Wohler Associates [1] expect revenues of both AM products and services to grow exponentially in the following years, this is shown in Figure 2.7. These estimates are made with the assumption that the AM industry will not be affected by larger, macro-economic influences, like global economic recession, wars or catastrophic natural disasters.

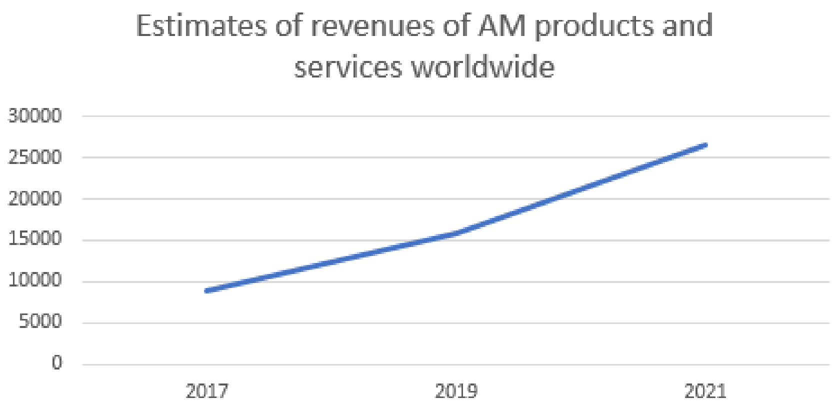


Figure 2.7: Estimates of revenues of AM products and services worldwide in the years 2017, 2019 and 2021.

AM is already mature in the prototyping market, but it is still in the innovative phase regarding the production of end-use parts. It is generally expected that new technologies need about 20 years to fully mature (going from TRL 1 to TRL 9) [35]. This research will help metal additive manufacturing moving up the TRL ladder by providing key solutions for the implementation and integration of metal additive manufacturing in the production environment for end-use parts.

2.9.2 Metal printer market in Belgium compared to the rest of the developed world

In the data which is put forward by Wohlers Associates [8], there is seen that in the last 5 years (average lifespan of a metal printer) 3405 industrial metal systems where sold to the developed world. At the moment, there are 35 industrial metal systems located in Belgium (both at companies as research centres or universities). If we compare the GDP of Belgium to the combined GDP of the advanced economies [2] [36] and the amount of installed industrial metal additive systems to the total sold in the last 5 years. It can be concluded that Belgium has about the same amount of industrial additive manufacturing machines than the rest of the developed world. Belgium takes 1.0134% of the advanced economies GDP while it accounts for 1.0279% of the metal additive systems.

[2] Australia, Austria, Belgium, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR, Iceland, Ireland, Israel, Italy, Japan, Republic of Korea, Latvia, Lithuania, Luxembourg, Macao SAR, Netherlands, New Zealand, Norway, Portugal, Puerto Rico, San Marino, Singapore, Slovak republic, Slovenia, Spain, Sweden, Switserland, United Kingdom, United States

Chapter 3

Hybrid Manufacturing

3.1 Introduction

Researchers have pursued the development of a so called make button process. A make button process can be explained as a manufactuing process where a product would be completely fabricated in a few hours starting from the CAD design without the need for moulds, fixtures or special machining stock. This is already possible with the help of different AM processes. Examples include Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Direct Metal Depositioning (DMD). Unfortunately, the high precision requirements or specifications (very important for aerospace applications) have not yet achieved these with AM processes. For metal parts, additional post-processes like machining are necessary to attain the desired functional part accuracy and surface finish [18]. Unfortunately, there has been no direct method of integrating a part from an AM process into a subtractive process to make up for the desired accuracy and surface finish without too much human intervention and lots of part programming. Hybrid processes already exist, but they are far from perfect. This chapter shows the current state-of-the-art within hybrid manufacturing combining additive and subtractive manufacturing.

The international Academy for Production Engineering-CIRP has propossed the following definition for hybrid processes [37]:

"A hybrid manufacturing process combines two or more established manufacturing processes into a new combined set-up whereby the advantages of each discrete process can be exploited synergistically"

In order to economically produce a part with the right specifications and accuracy, it is often required to use multiple manufacturing processes and techniques. Such an integrated approach helps with eliminating the main limitations of individual manufacturing processes while aggregating their advantages. For example: Normal CNC machining can not produce lightweight lattice structures and for conventional subtractive manufacturing methods the 'buy-to-fly' ratio is a lot worse compared to the same part made through additive manufacturing [38]. Researchers and companies in the past have focussed on the idea to put everything into one machine which can do everything. Both removing material as well as generation of the part produced. In general, they consist of a typical retrofitting 3-axis platform in a CNC machine centre together with a metal deposition head into the machine volume. In such set-ups, hybrid manufacturing is achieved through alternating between additive and subtractive methods after every few layers [38].

The main problem with this approach described above is that it makes use of the DMD (Direct Metal Depositioning) technique. Within the metal additive industry, powder-bed fusion techniques are more accepted due to it's better process capabilities. The process capabilities (kind of materials and eventual applications) is growing fast for these powder bed-fusion techniques and they generally outperform other metal AM processes. It is therefore necessary to develop a hybrid process that can make use of powder bed-fusion processes and use machining as post-processing step.

3.2 Characteristics of hybrid systems

As described in the introduction, hybrid systems nowadays (examples can be found in Subsection 3.3.2) typically use DMD techniques to build the part. Underneath, the major joint characteristics of hybrid systems using DMD are described:

- A fixed coordinate system which is used for all processes. This makes it possible to switch easily between additive and subtractive processes [39] [38].
- Decent process planning is required in order to cope with the risk of collision between the deposition element and the machine tool [38] [40].
- Down-time associated with constant tool changes can be seen as non-value added steps [39].
- Heat treatment is needed as a post-processing step for most metal alloys [41].
- In most working machines, the subtractive machining needs to be done without coolant due to the laser welding heads. Recently, DMG Mori developed a new system where the laser welding head is put into a closed compartment when the subractive process is used, this makes use of a coolant possible [42].
- Complex part design with varying cross sections are difficult to produce using direct energy metal deposition processes. This is due to the impossibility of integrating support structures [37].

- Post-processing of parts made by hybrid manufacturing need a protocol in order to cope with the challenges of a varying processing nature and part specific attributes [43].

Looking at these characteristics, there is need for one or more concepts around hybrid manufacturing which are able to use other types of additive manufacturing than DMD. More specifically the widely used Selective Laser Melting (SLM) process (described in 10.3.2) due to the fast growing capabilities (range of materials and applications). Because of the nature of such a process (High temperature and inert atmospheric conditions) these processes are more suited to process alloys with better metallurgical conditions. Hybrid systems need to be designed in such a way that they don't need custom fixtures and are able to work with minimal human intervention and expertise. Several key improvements can be identified:

- In-place and industry accepted AM processes can be integrated with a large variety of materials while the manufacturing processes can be established and accepted (up to full certification) in the industry.
- Process planning is simplified because there are more different processes used next to each other, which lowers the risk for one bottleneck.
- The process can cope with internal stresses before the machining operation due to the smart use of support structures.

3.3 Existing concepts

In the following section some already existing concepts of hybrid manufacturing using metals are presented. They can be seen as the current state-of-the-art in both academic research as the industry.

3.3.1 Research centres and Universities

NC State University

Research done as part of an "America Makes" research project entitled "Automatic finishing of metal additive manufacturing parts to achieve required tolerances and surface finishes" was performed by NC State university. The DASH (Digital Additive Subtractive Hybrid) approach is aimed at combining already used additive and subtractive processes by means of intelligent software and sensing technology [2]. A model of a part which includes dimensions and tolerances is created and afterwards fixturing orientation is automatically computed by analysing the part geometry. Sacrificial support structures and machine allowances are added to the part prior to additive manufacturing.

After the additive manufacturing process is performed on any metal additive manufacturing machine the part is mounted in a CNC machine, between centres. 3D scanning is performed to determine the shape and exact position of the part in a CNC machine. Using this approach, offsets are automatically computed to compensate for small additive manufacturing errors. The CNC machine generates toolpaths automatically in order to machine the part [2]. The total process is shown and summarized in figure 3.1.

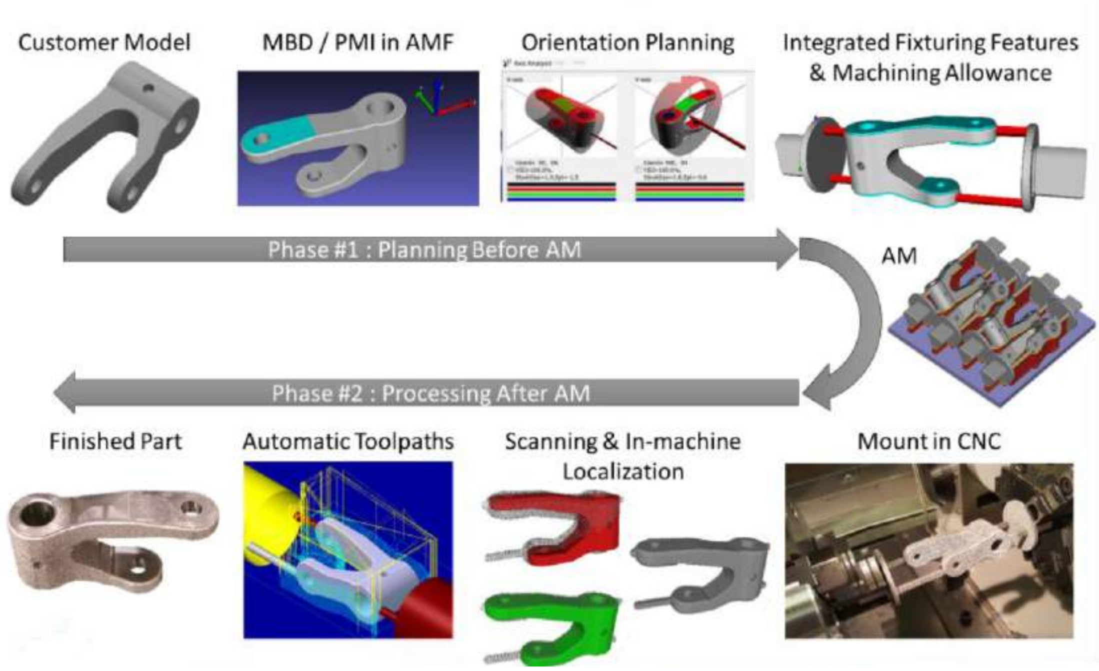


Figure 3.1: Concept by NC State University: DASH [2]

AIMS a Metal Additive-Hybrid manufacturing System: System Architecture and Attributes

A paper by Manogharan et al. [43] presents an integrated hybrid manufacturing approach to enhance and accelerate the adoption of metal Additive Manufacturing by combining both the general AM process and a direct digital subtractive process. AIMS stands for "Additive systems Integrated with subtractive MethodS" . This approach aims to be capable of improving the capabilities of critical part features. They found three main benefits of the combination of both technologies.

- Fixtures for the CNC-RP [1] process where added directly in the AM process, this eliminated the need for any additional fixtures.

[1] Rapid Prototyping Using CNC Machining (CNC-RP) Through a CAD/CAM Interface

- Employing only finishing by subtractive manufacturing reduced the total manufacturing time and costs compared to doing the whole process by CNC machining.
- The process got better results regarding buy-to-fly ratio of the parts manufactured.

They make a clear distinction between the physical needs for the integration (AM process and the CNC process) and the digital aspects (software architecture for a good process planning and operation of the combined processes). The main difference with the research performed in this MSc. thesis is the fact that AIMS uses a product handling approach instead of a pallet handling approach. Also, automatization and integration of all processes were not the objective.

LAMP Process

The hybrid process Laser-Aided Manufacturing Process (LAMP) uses a powder-fed laser deposition process in combination with a 5-axis CNC machining system [44]. A laser is used to deposit metal material where needed, while a milling tool is used to finish the layers. This is made clear in figure 3.2 [3]. Using the 5-axis capability, overhanging edges can be manufactured quite easily by rotating the base plate. This process requires complex process planning in order to define the sequence of material deposition and machining for complex parts and its features [44].

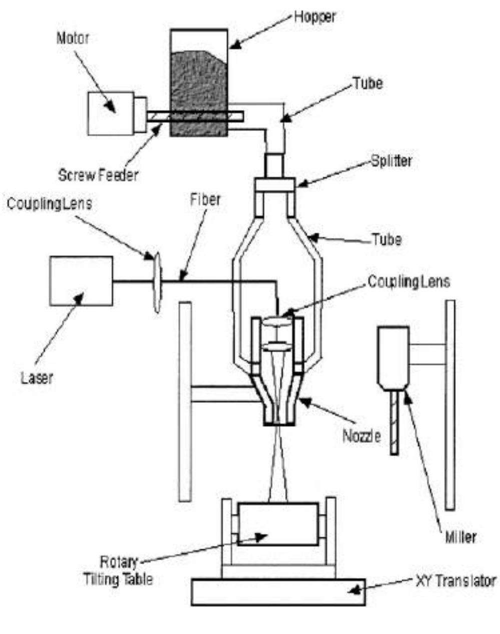


Figure 3.2: Laser-aided Manufacturing Process (LAMP) [3]

3.3.2 Industrial best practices

As an example, two companies already combined the process of additive manufacturing and milling into one machine, the Japanese ”Matsuura” and ”DMG Mori”. Matsuura presented the ”LUMEX Avance-25” [45] and DMG Mori the ”LASERTEC 65 3D” [42]. These machines use the DMD technique as additive manufacturing process, the main characteristics of these hybrid processes where described in 3.2.

LUMEX Avance-25

This machine focuses on the fabrication of mold dies. It combines DMLS with high speed machining repeatedly in order to overcome the complexity and high end specifications as mold dies require [45]. The machine is shown in figure 3.3.

Figure 3.3: Hybrid machine by Matsuura: LUMEX Avance-25

LASERTEC 65 3D

DMG MORI integrates the additive manufacturing into a 5-axis milling machine [42]. This hybrid solution combines the precision of the cutting process with the flexibility of the laser metal deposition process and allows additive manufacturing in milling quality. Surface quality is the most important winner of this combination. The company claims on it’s website [42] : " By combining both, additive manufacturing via powder nozzle and the traditional cutting method in one machine, totally new applications and geometries are possible. Especially large workpieces with high stock removal volumes are now possible to be machined in an economical way. The flexible change between laser and milling operations allows the direct milling machining of sections which are not reachable anymore at the finished part." The machine is shown in figure 3.4.

Figure 3.4: Hybrid machine by DMG Mori: LASERTEC 65 3D

Chapter 4

Pilot Factory

4.1 Introduction

In order to generate the concept and start the set-up of the 'Lean pilot factory' the following chapter describes the objective, goals, scope and main building blocks of the additive manufacturing production environment. Challenges are identified and possible solutions are listed for a working concept factory. Also, recommendations are made about possible machines to use in the pilot factory.

In the previous chapters 2 and 3 it is shown that additive manufacturing improves the capabilities and possibilities within the manufacturing industry. Unfortunately, manufacturing companies have difficulties because of certain barriers within the industry. These barriers arise due to the disruptive nature of the additive manufacturing technology. They include:

- Lack of knowledge around the opportunities and difficulties of additive manufacturing
- Lack of knowledge around the design possibilities with additive manufacturing
- Lack of process engineering capabilities

The pilot factory which will be set-up by Sirris has as main objective to provide the possibility to Belgian manufacturing companies to explore the additive manufacturing technology and get real experiences with the technology in order to evaluate if additive manufacturing would add value to their manufacturing processes in place at the moment. The pilot factory can also be used as a test environment to validate certain products and processes. In short, this can all be summarized in the objective:

'Creation of a field-lab for the Belgian manufacturing industry where additive manufacturing can be tested and evaluated.

The barriers described above can be tackled by providing different services to the companies, in which the pilot factory can play an essential role:

- Availability of machines to try and explore
- Knowledge and experience in the possibilities of additive manufacturing
- Providing 'another way of thinking' regarding the design of parts
- Definition of design and process rules for metal additive manufacturing
- Evaluation of quality control processes to help with certification of end-use products
- Providing an End to End solution, from design to fully finished product
- Solving certification issues
- Showcase applications
- etc...

These services need to help the Belgian manufacturing industry to reach higher TRL levels regarding additive manufacturing. In this way, it will be possible to have a faster integration of the additive manufacturing technology inside the industrial production environment.

4.2 Goals

The main goals of the pilot factory can be defined as follows:

1. Speed-up the integration of additive manufacturing as a state-of-the-art production method. The pilot factory can validate the production process and deliver first small series of real end-of-use parts. A crucial aspect of the pilot factory is the transfer of knowledge towards the client in order to make sure the client can realise the complete value chain from design to quality control within his own manufacturing process.
2. Act as a test environment to validate research & development projects of the industry regarding additive manufacturing (in combination with digital manufacturing) in an almost real production environment.

4.3 Scope

In the following figure 4.1 the scope of the main research topics of the pilot plant is outlined. On the bottom, in the vertical boxes, all different process steps associated with metal additive manufacturing are shown. On top, the four horizontal boxes display the main goals towards AM industrialisation and integration into the production line.

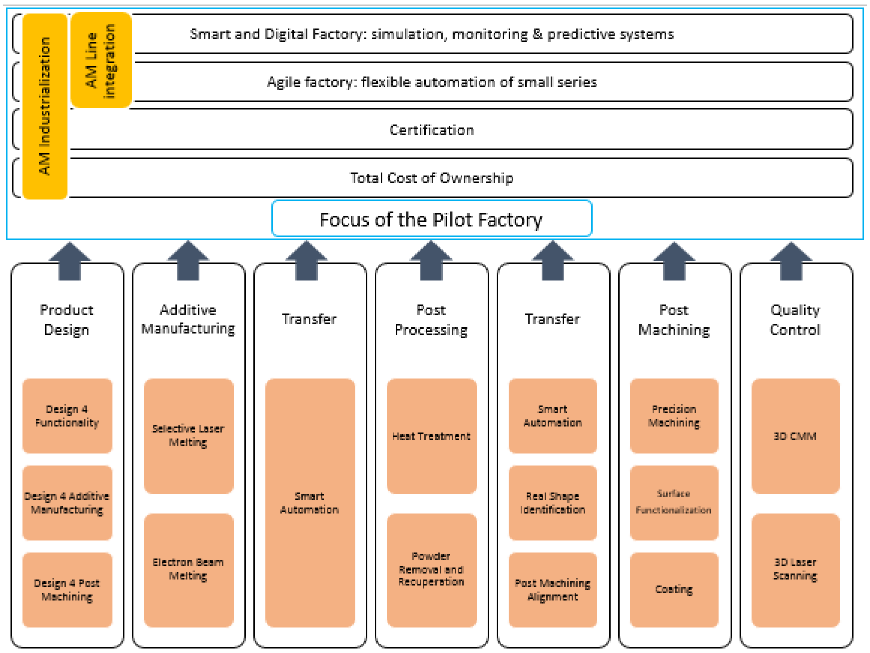


Figure 4.1: Overview pilot factory

The pilot factory focusses on the main themes: 'AM-industrialisation' and 'AM line integration'. Specifically, knowledge should be build up regarding simulation, flexible automation, certification, total cost of ownership, etc. These can be seen in the Figure 4.1 above horizontally on the top. The vertical themes regarding product design, manufacturing, transfer, post processing and quality control, will be developed somewhere else and are not in scope of the project.

4.4 Focus

The pilot factory will focus on the integration and industrialisation of metal AM techniques. Since metal additive manufacturing has the highest potential for complex products which are manufactured in small series, there are 2 main requirements of the whole process:

1. **'First time right'**:
   Since additive manufacturing has the highest benefits for complex products which are produced in small series. It is important that the manufacturing process is as reliable as possible and no mistakes are manufactured. It would be too costly and time consuming to iterate the manufacturing process for every product until it produces the right quality.

2. **'Flexible production'**:
   The pilot factory needs to be able to manufacture a large range of different products. Therefore, the process needs to be flexible and easily to adapt between 2 different products.

When choices are made regarding machines, processes etc. there will be looked back at those 2 requirements as main trade-off factors.

4.5 Concept

In the pilot factory, the whole process for the manufacturing of an end-use part is done. In the following section, all process steps are outlined. In the figure 4.2 all different steps can be seen.

Figure 4.2: Overview pilot plant

4.5.1 Material

To start the pilot factory, there is chosen to put the focus on maraging steel. This choice is made because due to the low carbon content maraging steels have quite good machinability. Also, heat treatment results in only very little dimensional change. More, maraging steel is compatible with the current materials available in the Sirris laboratories in Liege and of serious interest for the tooling industry and manufacturers of molds.

4.5.2 Additive manufacturing

The additive manufacturing will be done by an industrial selective laser melting system, The requirements and a trade-off of this system is made in Chapter 5. A Selective Laser Melting system is chosen because at the moment it is the most widely spread technique for metal additive manufacturing. This is due to its capabilities regarding materials, productivity, surface quality and level of detail it can manufacture.

4.5.3 Powder removal

After the additive manufacturing process, the residual powder around the manufactured component(s) need to be removed. This is usually done by hand and the use of air blasting. Nowadays, techniques arise where this process can be done automatically. Ideally, this process is integrated in the build chamber of the additive manufacturing machine, but it can also be done as a stand-alone process. Different companies are searching for systems to automate this process. For example: Conceptlaser came with a concept where a sort of vacuum cleaner is used to suck away the residual powder [46]. Unfortunately, only 60-80 % of the powder can be sucked away. This result greatly depends on the complexity of the part. SLM Solutions came with a concept where it would turn the whole building chamber upside down in order to remove the residual powder [47].

4.5.4 Heat-treatment

Heat treatments are used for stress relief and to improve the mechanical properties of the printed part [41]. A thermal post-processing step is used in order to increase the surface quality by closing micro cracks and to reduce residual stresses inside the part [48].A common thermal cycle for additive manufactured products made in the commonly used titanium alloy Ti-6Al-4V consists of the following 2 steps [28] [48]:

1. Stress relief inside the part, example process parameters [48]:
   - Stress relief heat treatment in a vacuum or under protective gas
   - Holding period of 60 min
   - Temperature of 675 °
2. Hot isostatic pressing in order to cure micro cracks and improve the porosity inside the part through annealing at high temperatures and pressures, fatigue properties get improved [48] [49]. Example process parameters:
   - Temperature of 900-920 °
   - Holding period of 135 min
   - Argon inert gas atmosphere
   - Pressure of 100 MPa

For SLM, the whole job (building plate and all attached parts and support structures) needs to go in the oven to undergo a stress relief process before the part can be disconnected from the plate.

Pilot factory

For the pilot factory, it will be a goal to automate the loading and unloading of the oven. This means that automatic opening and closing of the oven is an important requirement. This can be done by placing an electric opening device on the oven, or using a robotic arm outside the oven. Next to this, another requirement is the possibility to steer the oven from a central controlling system. This means the oven needs to be able to work with input data from outside software and generate output data to sent back to the central steering system. Example solutions are ovens from the Belgian company BTF Furnaces [50].

4.5.5 Post-processing

Support structure removal

For metal parts, support structures are used in order to reduce warping due to thermal stresses and to hold the part in place. Experience with the alloy and manufacturing technology used is needed in order to determine a good strategy for the placement of support structures to have a successful end product. These support structures have to be removed after the printing process. This can be done by hand tools or by use of milling, band-saws, cut-off blades and other metal cutting techniques [51]. In short: A time consuming manual process difficult to automate. CNC machining can be used to remove a part of the support structures. It should be noted that most of the time CNC machining cannot be used to remove all support structures, this is due to the fact that the part needs to be fixed in some way in the machine and enough stability needs to be in place for CNC machining. More information about this topic can be found in Chapter 8. Manual handling afterwards will be required to remove some support structures. If the support structures are not removed by CNC machining, they need to be placed where the surface quality is not critical. Generally, the surface quality of the part is worst where support structures were located.

Improvement of the surface quality

CNC machining can be used to improve the surface quality generated by additive manufacturing. The product generated by additive manufacturing is used as the starting point in the subtractive manufacturing process.

Pilot factory

In the pilot factory, the existing CNC machine located in the Sirris laboratories in Diepenbeek will be used. This is a Fehlmann Versa 825. A milling machine suited for machining of tough materials where automation can be easily retrofitted at a later date and in no way constrains the access to the working area [52]. This machine can also handle parts the size of the maximum dimensions which can be manufactured from the AM machine.

4.6 Quality control

The last years, quality control of metal components manufactured by laser- and powder bed-based additive manufacturing has been improving significantly. However, in industries which require very high quality standards, like the aerospace industry, quality control problems still arise. The main problem with additive manufacturing is the fact that it is difficult to prove that the AM process produces consistent results. Meltpool monitoring and other techniques described underneath improved the quality assurance in the past years, although it is still difficult to get structural components certified [33].

Quality control during the building process

In order to check the quality standards, 5 areas of the building process need to be checked:

1. **Powder quality:** The following data should be documented for quality research: powder particle size, flowability, moisture content, oxygen content and applied sieving. All these factors affect the end quality of the manufactured parts.

2. **Temperature:** Really important for the quality of the end-product is the temperature inside the printing machine. A common technique used is the placement of a thermal camera or sensor inside the printing machine. This device can track the temperature during the process and give an input to the temperature control system of the machine.

3. **Process gas atmosphere:** Most metal additive processes happen in an inert gas atmosphere, either argon or nitrogen, at oxygen levels below 500 parts per million [53]. This helps to prevent impurities, oxides in particular, from contaminating the metals used as parts are built [53]. The atmosphere inside the machine needs to be constantly checked during the process.

4. **Meltpool:** The dimension and homogeneity of a weld seam is influenced by various variables during the melting process like heat conduction of the material, scanning speed, laser power, surface tension of the melt, grain size, ascending smoke, plasma formation etc. A camera can be used to detect the intensity of the emitted light of the melt, which corresponds to the temperature of the melt pool by the law of Planck. Although, a technique was developed by the KU Leuven [54] to check only the melt pool instead of the whole building area with a conventional camera; this is done by assembling the camera and photodiode sensor with sufficient local

resolution directly in line with the optical path of the laser. This way, real-time documentation and control of the building process in laser-based Additive Manufacturing machines is possible in an industrial environment. Therefore the quality of this production process is better checked.

5. **Documentation of process parameters:** Some literature [55] suggest the co-production of a test specimen (for example for tensile test) with every batch, but this would add a lot of time and costs to the production process. After the building process, the final part quality and the congruence with the initial order are checked. This includes optical inspection and dimension check, surface control (roughness) and weight (density).

Quality control after the manufacturing process

1. **Dimensional quality:** 3D scanning equipment or measurement machines can be used to check the dimensional aspects of the manufactured part.
2. **Non-dimensional quality:** Numerous non-destructive testing methods can be used for quality control of metal additive manufactured parts. Methods which are described in literature [56] include:
   - Applying Archimedes' method in order to check the material porosity.
   - Ultrasonic testing of the part to determine the dimensions and depth of near-surface flaws.
   - X-ray testing to determine porosity of the part.

4.7 Transfers between different process steps

It is the goal to automate the transfer of the part between all different process steps (AM process, heat treatment, post-processing and eventual quality control). Therefore, an AGV (Automated Guided Vehicle) will be used. Because it is also the goal to perform automatic loading and unloading of the machines, robotic arms need to be in place to perform this task. Therefore, it is most efficient to use an AGV with a robotic arm mounted on it, which performs this loading and unloading and cancels the need for multiple robotic arms next to every machine. Examples of these systems are on the market, one is the Kuka KMR iiwa [57]. This robot can be seen in figure 4.3.

Figure 4.3: Kuka KMR iiwa

A system with rails (as SLM uses, see subsection 10.3.2) could be another possible solution, but looking at the currently more complex set up of all the machines, an AGV system will be economically beneficial.

4.8 Conclusion

This chapter described the concept of a 'Lean pilot plant' which will be set-up by Sirris. In order to fulfil the objective of bringing additive manufacturing to the shop floor, it will be used as a research and testing environment for Belgian industry partners. As main requirements, it is defined that 'First time right' and 'Flexible production' are most important. When there is looked at the concept generated in Section 4.5, the focus is not on the additive manufacturing process itself, but on all the processes around and mainly after it. In order to improve the accuracy and surface quality of the manufactured parts, the main challenges are found in the machining step. Therefore, a practical test was done to find the main challenges for applying subtractive manufacturing to a additively manufactured part (see Chapter 8).

Chapter 5

Additive manufacturing machine

5.1 Introduction

In the following chapter a trade-off is presented which was used to define the right industrial additive manufacturing system. Technical and non-technical requirements as well as the price of the machines are taken into consideration.

5.2 Requirements

The requirements of the AM machine which will be placed in the pilot factory, can be divided into 2 main categories: technical, and non-technical requirements. Both will be given in the following section.

5.2.1 Technical requirements

The following lists describe the technical requirements for the AM machine used in the pilot factory. The list is split up into 5 categories: Machine construction, laser source, materials, quality control and software.

1. **Machine construction**
    1.1. Building volume of at least 250 x 250 x 200 mm (x,y,z).
    1.2. The atmospheric condition of the building volume is under protection against a to high concentration of oxygen and constantly monitored.
    1.3. The building plate can be pre-heated to 200 degrees C.

1.4. There is an easy replaceable system to provide a new layer of powder, this system needs to be interchangeable.

1.5. The total machine is in agreement with the EC standards.

1.6. Class 1 machine [58] (international standard regarding the protection for electric shocks).

1.7. The following requirements are not absolutely needed, but might be good to have them for future research and development of the pilot factory:

   - The building unit can be pulled out of the machine
   - The building plate is equipped with an EROWA system [59] [1]

2. **Laser source**

2.1. Diode regulated Yb-fibre laser.

2.2. At leat 400W effective output.

2.3. Digital dynamic scansystem in 3 axis.

2.4. Minimum spot diameter: 50μ m or smaller.

2.5. Motorised x, y and z mirrors.

2.6. Scansystem reaches the whole building surface.

3. **Materials**

3.1. The machine set-up is equipped for the manufacturing of maraging steel (material 1.2709).

3.2. The machine is capable of working with reactive materials (Titanium, Aluminium, ...).

4. **Quality control**

4.1. Quality control and optimisation when a new powder layer is spread out. It is very important that the newly spread layer is perfectly flat and the whole area is filled with powder. This quality system is able to guarantee the flatness of the newly spread layer.

4.2. Filtersystem to guarantee the powder quality is in place. This filter system checks and guarantees the size of the powder particles.

4.3. The machine can optionally later be equipped with a meltpool monitoring system.

5. **Software**

[1] A Swiss company specialised in workholding systems for machining operations developed a system to fix a pallet (in this case the base plate) easily inside a manufacturing machine, this fixture is standard for all manufacturing applications.

5.1. Machine-, process- and status-parameters can be outputted through an OPC-UA protocol [2].
5.2. The machine is capable of building time calculation before the actual process.
5.3. A notification can be provided when the building job is done or interupted.
5.4. The intuitive interface in multiple languages (at least english is provided).
5.5. Real-time monitoring of the most important proces data.

5.2.2 Non-technical requirements

The non-technical requirements of the machine focus on the maintenance service and delivery of the machine:

1. The AM machine can be delivered by the machine manufacturing company in Diepenbeek within 6 months after first payment.
2. Maintenance service is available within 250 km of the machine (Diepenbeek, Belgium).
3. The machine manufacturer is willing to set-up research projects together with Sirris around the integration of AM manufacturing in the production environment.
4. The machine manufacturer is willing to share status and process data of the machine.
5. The machine manufacturer has a proven experience in delivering AM machines to industrial manufacturing companies in the aerospace, automotive and tooling industry.

5.3 Presentation of the machines in the trade-off

In the following section, an overview is given of all machines which delivered their offer in response to the tender weather they meet the requirements described in 5.2. In table 5.1 an overview is given of the used symbols.

Table 5.1: Description of the symbols used

Symbol	Description
✓	This machine meets the requirement
X	This machine does not meet the requirements
O	In the tender delivered to Sirris, no information was given regarding this requirement

[2] The OPC-UA protocol is described in 6.3

Table 5.2: List of companies which delivered their offer in response to the tender and their machines

Company	Type
SLM	280
DMG Mori	Lasertec 30 SLM
Conceptlaser	M2
EOS	M290
Renishaw	AM400

Technical requirements

Table 5.3: Comparison of the different machines regarding machine construction

Machine construction	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
1.1 Building volume	✓	✓	✓	✓	✓
1.2 Atmospheric protection	✓	✓	✓	✓	✓
1.3 Replacable recoating system	✓	✓	✓	✓	✓
1.4 Base plate pre-heating	✓	✓	✓	O	✓
1.5 EC Standards	✓	✓	✓	✓	✓
1.6 Class 1 machine	✓	✓	✓	✓	✓
1.7.1 Removable building unit	X	X	X	X	X
1.7.2 EROWA system	X	X	✓	X	X

Table 5.4: Comparison of the different machines regarding laser source

Laser source	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
2.1 Yb-fibre laser	✓	✓	✓	✓	✓
2.2 400 W effective output	✓	✓(600W)	✓	✓	✓
2.3 Digital dynamic scansystem	✓	✓	✓	✓	✓
2.4 Spot diameter [μm]	80	55	50	O	70
2.5 Motorised mirrors	✓	✓	✓	✓	✓
2.6 Scansystem reachability	✓	✓	✓	✓	✓

Table 5.5: Comparison of the different machines regarding manufacturing materials

Manufacturing materials	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
3.1 Maraging steels	✓	✓	✓	✓	✓
3.2 Reactive materials	✓	✓	✓	✓	✓

Table 5.6: Comparison of the different machines regarding quality control (QC) systems

Quality control	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
4.1 QC new powder layer	✓	X	✓	✓	X
4.2 Particle size QC	✓	✓	✓	✓	✓
4.3 Meltpool monitoring	✓	X	✓	✓	X

Table 5.7: Comparison of the different machines regarding software systems

Software	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
5.1 OPC-UA protocol	X	X	✓	X	X
5.2 Building time calculation	✓	✓	✓	✓	✓
5.3 Job status notification	✓	✓	✓	✓	✓
5.4 English interface	✓	✓	✓	✓	✓
5.5 Monitoring of data	✓	X	✓	✓	✓

Non-technical requirements

Table 5.8: Comparison of the machines regarding non-technical requirements

Non-technical requirements	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
1. Delivery time	✓	✓	✓	✓	✓
2. Maintenance	✓	✓	✓	✓	✓
3. Openness for collaboration	O	✓	✓	X	X
4. Openness for data exchange	✓	✓	✓	X	X
5. Experience	✓	X	✓	✓	X

The German company SLM still had the opportunity to collaborate on research projects under consideration, therefore there is given an O mark.

5.4 Trade-off

5.4.1 Trade-off criteria

The trade-off criteria are split into 3 main categories, Quality of the machine, the so called technical requirements described in section 5.2, price of the machine, and the non-technical requirements. Each of these categories is given a weight compared to its overall importance.

1. **Technical requirements (65%)**

   The machine satisfies or exceeds the technical requirements described in section 5.2.1.

2. **Non-technical requirements (35%)**

   These include delivery time within 6 months and maintenance availability (enough technical assistance for the machine within a short distance), also the openness for clolaboration and data exchange is included. This includes the possibility for a collaboration between Sirris and the machine builder regarding research projects, feasibility studies etc. There is also the possibility to read machine-, process- and status-parameters with an OPC-UA system or technically equivalent system. More, The suppliers were asked to deliver a reference list of relevant companies where they delivered the same machine as proposed to Sirris. This experience is also taken into account.

Trade-off technical requirements

Looking at the comparison of all machines (tables 5.3-5.7), it can be noted that for a lot of requirements all machines meet the required quality features. Therefore, a trade-off is made using all requirements with a difference between the machines. Each requirement is given a maximum score which is in relation to its importance. The total number of points which can be scored equals 65.

Table 5.9: Trade-off Technical requirements

Technical requirements	Max.	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
Base plate pre-heating	10	✓	✓	✓	O	✓
EROWA System	10	X	X	✓	X	X
Minimum spot diameter [μm]	7	80	55	50	O	70
QC of a new layer	8	✓	X	✓	✓	X
Meltpool monitoring	10	✓	X	✓	✓	X
OPC-UA	10	X	X	✓	X	X
Monitoring of status data	10	✓	X	✓	✓	✓

Looking at the requirements, both the spot diameter and the quality control of a new layer is given a slightly lower maximum score because these are not requirements which would make it impossible to do a certain AM integration project (both digital as physical integration). It are more requirements which guarantee the quality of a part. Most scores were either given the maximum points, if the requirement was met, or a 0 if the requirement was not met. Only for the spot diameter the scores were given with relation to the actual spot diameter, the smaller the better (and the more accurate manufacturing).

Table 5.10: Trade-off Technical requirements with points

Technical requirements	Max.	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
Base plate pre-heating	10	10	10	10	0	10
EROWA System	10	0	0	10	0	0
Spot diameter [μm]	7	4	6	7	0	5
QC of new layer	8	8	0	8	8	0
Meltpool monitoring	10	10	0	10	10	0
OPC-UA	10	0	0	10	0	0
Monitoring of status data	10	10	0	10	10	10
Total	**65**	**42**	**16**	**65**	**28**	**20**

Trade-off non-technical requirements

In table 5.11 a trade-off is made for the non-technical requirements of the additive manufacturing machine. These include delivery time and maintenance availability, but also the openness for collaboration and data exchange. More, the suppliers were asked to deliver a reference list of companies where they delivered the same machine as proposed to Sirris. This reference list was also given a score, together the total maximises 35 points. Looking at the requirements around delivery time and maintenance availability, it was clear that all machines and their manufacturing companies meet the requirements set. Therefore, they are not taken into account during the trade-off.

Openness for data exchange is given the highest weight for the trade-off because it would obstruct the digital integration of the pilot factory if it is impossible to read out data of the machine. The openness for collaboration and experience are given an equal weight. These requirements are not critical for the project. When the questions regarding non-technical requirements asked in the tender were not answered, a score of 0 is given.

Table 5.11: Non-technical Trade-off

	Max.	SLM	DMG Mori	Conceptlaser	EOS	Renishaw
Openness for collaboration	10	0	10	5	0	0
Openness for data exchange	15	5	5	15	0	0
Experience	10	8	2	10	0	0
Score	**35**	**13**	**17**	**30**	**0**	**0**

Looking at the scores given: openess for collaboration is rated with the maximum score if there was actually stated that the company was willing to collaborate on research projects regarding the integration of metal AM. Conceptlaser was given half of the score because the local management was willing to, but due to the recent sale of the company to GE, the future was very unsure and no confirmation could be given. The openess for data exchange is an important requirement for a digital integration of the machine in the pilot factory. Some companies do not allow (and make it impossible) to link the machine to external software. Conceptlaser was found totally open about data exchange, while both SLM and DMG Mori had some issues with it. Both EOS and Renishaw did not respond to this question. Last, the companies were asked to provide a list of past clients were they delivered the offered machine. This list was rated on extensiveness and given a score on 10.

5.4.2 Summary Trade-off

In the table 5.12 the 2 trade-offs are summarised together and the total score is calculated. A perfect score would give a result of 100.

Table 5.12: Summary Trade-off AM Machine

	Max.	**SLM**	**DMG Mori**	**Conceptlaser**	**EOS**	**Renishaw**
Technical	65	42	16	65	28	20
Non-technical	35	13	17	30	0	0
Total score	**100**	**55**	**33**	**95**	**28**	**20**

It can be seen that the Conceptlaser M2 machine is of superior quality and fit for this project, although it also comes with the highest price.

5.4.3 Price comparison

Underneath in Table 5.13 the price asked for each machine is shown. This price including hardware, assembly and delivery of the machine. It can be seen that there are 2 prices for the SLM machine shown, SLM 1 and SLM 2. This is because SLM gave the opportunity to buy an AM machine (SLM 2) which is currently used in there facilities to manufacture reference parts for prospective clients.

Table 5.13: Price comparison

Machine	**SLM 1**	**SLM 2**	**DMG mori**	**Conceptlaser**	**EOS**	**Renishaw**
Price [EUR]	445000	359000	475000	510000	441000	418751

The question which needs to be answered is if the higher price compared to the others of the Conceptlaser M2 machine is not too high for Sirris. Due to the fact that its price still falls inside Sirris' budget, and that all other machines have serious issues with meeting all requrements stated in 5.2, there is chosen for the Conceptlaser M2 machine.

5.4.4 Conclusion

This chapter makes a trade-off of the available options for the addtive manufacturing machine which will be used in the pilot factory. Using the responses on the tender which was sent out, a thorough consideration is made in order to chose the machine which suits the project. As can be seen, the Conceptlaser M2 machine scores the highest for the trade-off based on the pre-set requirements. The main aspects where the M2 machine differentiates itself from the competition are:

- The possibility to include an OPC-UA system.
- The ability to pre-heat the base plate before and during manufacturing in order to reduce thermal stresses.
- Openness for data exchange and eventual collaboration.
- The state-of-the-art software package which is included or can be included in the future.

More information can be found in the technical specifications of the Conceptlaser M2 machine [59].

Chapter 6

Digital Integration

6.1 Introduction

Digital integration is one of the objectives for the pilot factory, it is the goal to create a digital environment where all machines and processes communicate with each other. In this chapter, the main state of the art solutions, challenges and barriers for entry are described.

Digital integration in manufacturing can be defined as a future where all physical objects on the shop floor, people and systems are connected with each other through one integrated system [60]. It would require a combination and coordination between physical and computational components on the shop floor. The digital factory is a virtual model of a real factory used to design, plan and execute manufacturing operations in the production environment which should be linked to real time data and statistics [61]. One feature is the ability to create interfaces between digital and physical entities. Further, functionalities need to be implemented in order to be capable of receiving data and providing feedback to the factory again. One of the main challenges is the fact that data and physical resources are generally heterogeneous and the integrated system needs to make sure all data is used in a right and consisted way [62]. There is a need for a common language of the data in order to present and analyse it corectly.

The main benefits of a digital factory can be summarized into 3 main pillars:

- **Process optimisation:** Products and processes are networked with each other and are able to respond to both internal and external events [61]. The manufacturing can also be scaled more easily (Plug-and-produce principle).
- **Optimised resource consumption:** Processes can be simulated on beforehand in order to make smarter decisions [63].

- **Creation of complex autonomous systems:** Production units are able to organise themselves and become more self-contained [60]. This means that decision making (for example production planning) can be done by pre-defined algorithms.

6.2 Smart manufacturing

The digital transformation and new information technology techniques within the production industry allows new ways to connect multiple systems and processes and can create extra value for businesses. New data-driven strategies can support enterprises to optimize their performance by analysing the processes running on the shop floor and using the data which is generated to make smarter decisions for the future. The combination of recent advances in manufacturing technology combined with improvements in the computer sciences and information technologies has as a result the implementation of the Internet of Things [1] in the production environment. This implies the use of sensors, control systems, machine-to-machine communication, data analytics and security mechanisms. Specific focus should be given to the transformation of production systems used already at the moment into mechanisms controlled or monitored by computer-based algorithms. The main challenge is the availability of a secure communication tool capable of collecting and exchanging manufacturing data generated by different machines. This data interchange can be used to support (automatic) decision making in the production line. This can be found in the OPC-UA[2].

6.3 OPC-UA

In order to set-up integrated and networked manufacturing systems, the following requirements have to be met [65]:

- The software used is independent of the manufacturer, industry sector, operating system or programming language used for the different machines (AM machines as well as others) inside the pilot factory. This way, the production line can be adapted easily with extra machines without the need for a complete redesign of the software system(s).
- Scalability of the network is done easily.
- Complex communication content for modelling is seen as representative of real products and their production sequences.

[1] The interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send and receive data [64].

[2] OPC-UA stands for Object linking and embedding Process Control - Unified Architecture

OPC-Unified Architecture is seen as an enabler for Industry 4.0 [3]. It is the newest state-of-the-art system for interconnectivity in automation systems. It can be integrated easily in all layers of the automation system, independent of the already installed operating system or hardware. The idea is that the OPC-UA transport mechanism specifies data exchange, while at the same time the information models specifies which information is exchanged. The OPC-UA has as main responsibility the communication between cell controller, machine control and robot controller [67]. It transports raw data and pre-processed information from the smallest level (sensors) towards control systems and eventually production planning. Every type of information is available anytime and anywhere. The format of communication is independent of the respective application, enabling communication between different processes from multiple manufacturers. This results in a tremendous simplification of the whole production chain through the standardisation of data communication, making it easier to analyse real time process data, alarms and historical production data.

6.4 Pilot factory

The goal of the pilot factory is to demonstrate a digital integration between all processes within the pilot factory. These processes can be linked using a central control system which can be handled by an operator. From there, the whole process can be steered and controlled using digital data streams between the machines. This outline is shown in figure 6.1.

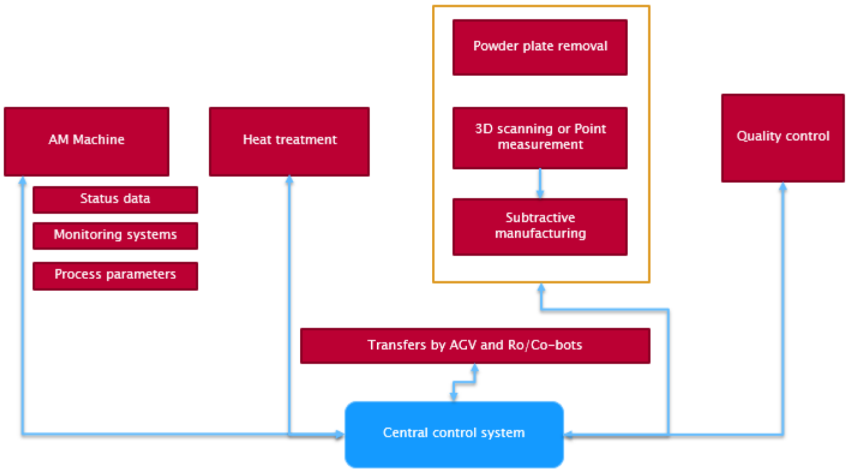


Figure 6.1: Digital outline of the pilot factory

[3]The next phase in the digitization of the manufacturing sector, driven by four disruptions: the astonishing rise in data volumes, computational power, and connectivity, especially new low-power wide-area networks; the emergence of analytics and business-intelligence capabilities; new forms of human-machine interaction such as touch interfaces and augmented-reality systems; and improvements in transferring digital instructions to the physical world, such as advanced robotics and 3-D printing [66].

The main challenges for the pilot factory regarding digital integration can be identified as follows:

- Extraction of the status data of all machines towards a general system (combination of different software systems). The main challenge is getting access to all important data from the different machine suppliers. The ultimate goal would be the use of one system, but for the near future, the use of a general system/data language on top of all manufacturing processes and its software systems would suffice.
- Extraction of monitoring systems data which can be used as an input for quality control.
- Central steering of all machines.
- Standardized communication between machines, semantic description of all devices.

The major software building blocks associated with the pilot factory are outlined underneath in figure 6.2.

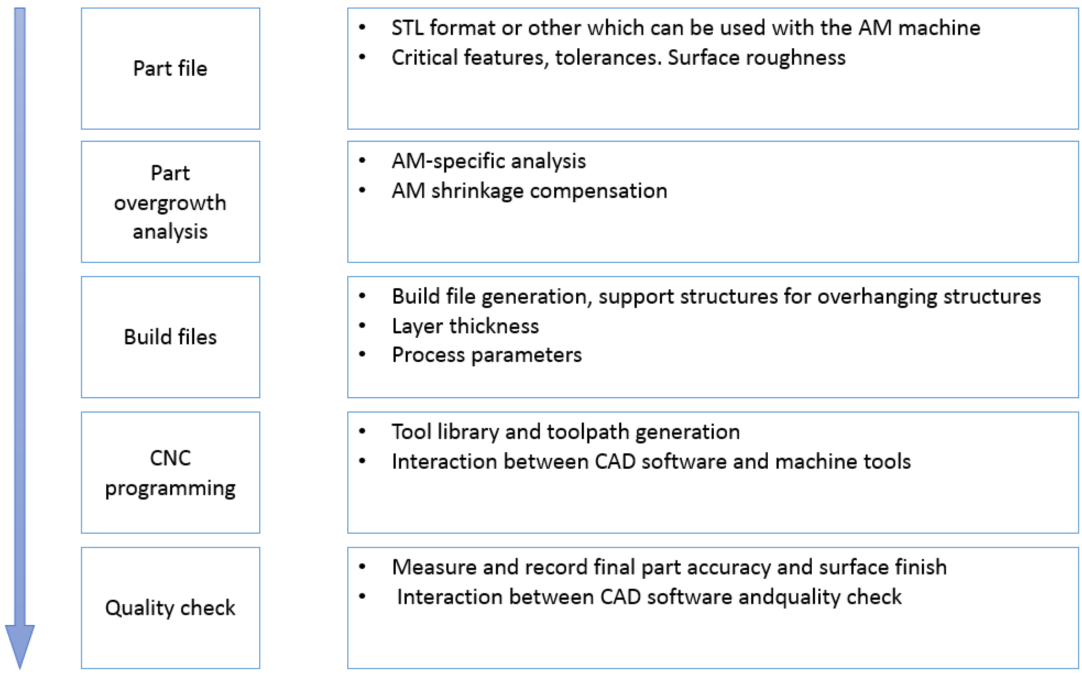


Figure 6.2: Pilot factory software components

The process flow regarding software in the pilot plant should have the capabilities to process data available in the CAD drawing, and use this input to generate the optimal toolpaths in the CNC machine taking critical features into consideration. Part overgrowth should be incorporated in order to improve the accuracy and make further CNC machining possible. Part overgrowth is adding an extra layer of material to the CAD drawing, in order to be sure the machining step can still scrape away some metal and improve the accuracy and surface quality of the part. More research on this topic can be found in section 8. Process files from both the AM process as the CNC process need to be generated and transferred through digital communication between the systems.

6.5 Conclusions and future research

This chapter maps out the main challenges regarding the digital integration of all processes in the pilot factory. It is concluded that an OPC-UA system needs to be implemented in order to create the possibility for communication and data exchange between the different machines. Also, some future research still needs to be done, examples include: the part overgrowth diameter can be optimized using software models which make use of reverse engineering in order to specify part and feature specific deviation. This would be beneficial for more efficient material utilisation. More, a laser scanner can be used in order to use image-based data system to determine the actual location of a part feature and use this as an input for the toolpath generation in order to successfully produce the part, this can also be concluded from chapter 8. Another example: Design software can be used to optimise the use of support structures not only for the AM process, but also taking the machining process into account. It is difficult to machine a critical feature if there are support structures located at that critical feature. Accessibility of the CNC-tool to the critical feature needs to be taken into account, otherwise post-processing by machining is not possible to complete. More research on this topic can be found in chapter 8.

Chapter 7

Physical Integration

7.1 Introduction

Physical integration is one of the main objectives of the pilot factory. It can be defined as the process of bringing together all sub-processes (printing process, oven, post-processing etc.) into one system and ensuring it all works together as one.

Looking at the pilot factory, it is important to make smart choices regarding the physical integration of the production process. These choices are made taking into account different criteria, although the main goal of the pilot factory 'First Time Right' stays the most important parameter, as described in chapter 4. Also production adaptability can play a role on different levels in the production. Adaptabily is used as a common term for flexibility, reconfigurability, transformability etc. Additive manufacturing is a great way to improve a production environment adaptability, although it also has it's constraints. A desktop research was done in order to increase the knowledge level regarding the physical integration of production processes. Both the current industry standards as the state-of-the art products/processes are described. The focus is put on the automatic loading and unloading of CNC machinery and conclusions are drawn for the pilot factory. This is done because it is one of the feasible steps for automation inside the pilot factory. Working concepts generated for loading and unloading of the CNC machine can also be used in an automated loading and unloading step of the oven. At the end of the chapter, in section 7.4 a decision is made about which technique(s) are used to perform automatic loading and unloading in the CNC machine in the pilot factory.

Scope:

- The focus is put on the smallest chains of the production process, known as the production cell and the production station.

- Regarding batch size this study focusses on small to medium batch sizes (5-50 parts), so no batch sizes as are seen in the automotive sector. Additive manufacturing has the highest potential for small batch sizes.

- The production activity which is taken into consideration focusses on small to mid-size products, products which can be made with conventional, industrial printers at the moment. In the range of 50 x 50 x 50 mm to 250 x 250 x 250 mm.

Challenges and complexity of automatization

Focussing on the loading and un-loading process of a CNC machine. Automating the processes does not have a one-fit-all solution. The easiest and most feasible solution will depend on the batch size, complexity of the product, size of the product and production technology which is used. Fully automated production lines will focus on speed, while prototype production will focus on flexibility of the production line. The best solution will also depend on the kind of CNC machine used, together with the method used to fix the part in the CNC machine. On top of this, it might be desirable that the robot also performs other tasks than just loading and unloading the CNC machine. Examples of these tasks can be: Changing tools of the CNC machine, post processing (polishing, measurement processes, ..) of the products etc.
All different automatization levels also have an influence on the needed level of knowledge of the operator. Although most of the times, automated production lines are designed, programmed and set-up in the beginning through external partners. Afterwards, the role of the operator is limited to controlling the line and taking care of the output of the line. So a basic understanding of the systems behind the automated production line should be sufficient to operate the line. This changes when small series are produced, now the operator has to program the robot himself with the use of a control panel or offline CAM software. Here, the operator is required to have a high level of understanding about the processes and control software of the robot.

Reasons for automatization of production cells and stations:

- Companies are confronted with an increased need for customisation and small series of their products. Both product- and technology- cycli shorten. This asks for an improved adaptability of the production process [68].

- International roadmaps talk about the need for production methods which are able to produce small series of new products without the extensive use of manpower and the ability to produce quite cost effective. This is generally referred to as the 'Smart Factory'. Only by the collaboration of intelligent sensors and classical automatization (robots) coordinated by intelligent algorithms it is possible to combine flexibility and automatisaton of the production line [68].

- Companies feel the need to automate boring and repetitive tasks in the production environment [69]. Reasons for this evolution are:

- A growing shortage of technically educated personnel. Due to this shortage, employees with the right technological knowledge need to be used as efficiently as possible by removing repetitive tasks.
- In many developed countries (USA, Western Europe, . . .) labour costs are rising. In order to stay competitive with low labour cost countries automatization is needed to keep the manufacturing processes in-house and close to the end-customer. It should be noted that a lot of manufacturing companies choose to keep the manufacturing close to te end customer or prefer developed countries because of quality concerns.

7.2 Automatic loading and unloading

7.2.1 Set-up of an automated production cell

First of all, the manufacturing cell needs to be installed and prepared in order to load and unload a specific series of products from the CNC machine. This study focusses on fast changing products and adaptability of the process in general, which is a very important point of consideration in the development of an automated production cell.

7.2.2 Robot-machine interface

Current situation in the industry:

At the moment, most of the matching between different control systems happens using simple signals between the control systems of every machine used. The programming needs to be done in the robot programming language of the production cell. These control systems are most of the time not equipped with a standard industrial PLC (programmable logic controller) or PC system, which is described in chapter 6. As a consequence, when an extra or another machine needs to be integrated in the production cell, the control system needs to be completely redesigned.

State of the art:

The current state of the art systems in the industry use interfaces to connect all control systems with each other using both software and hardware. The used interfaces are equipped with a standard set of signals which can be interchanged easily. This way, a plug and play principle is created and certain components of the production cell can exchange information in an easy way. A central system is used to program all signal exchanges and to coordinate the total production environment.

7.2.3 Simulations and programming of the CNC machine

Current situation in the industry:

CNC machines can be programmed off-line with the use of CAM software. This is done because for an operator it is really difficult to imagine movements of more than 3 axises which all happen at the same time. This way, the danger for collisions of the tooling and the part itself becomes quite big [70]. The off-line programming with CAM software supports the operator to determine the most optimal machining tracks and simulating the movements of all axises to avoid internal collisions.

If such a process is equipped with an automatic loading and unloading process, usually the possibility lacks to simulate the whole process, including the loading and unloading of the product. In order to avoid collisions between the loading and unloading tool and the CNC tooling, a simulation on beforehand is needed.

State of the art:

From one CAD software package, the CAM module in the CNC machine is generated and translated into machine control code. The same CAD software consists of a module which can generate and simulate all movements within the CNC machine, also the loading and unloading tool.

7.2.4 Lay-out of the different machines next to each other

Current situation in the industry:

A lot of times, when a CNC machine is equipped with an automatic loading and unloading device, it becomes really difficult for an operator to manually operate the machine. In between series or in special occasions it might be needed for an operator to make adjustments inside the CNC machine. Occasions like these include really small series where it is more time efficient to load and unload the cell by an operator compared to an automatic device. Really critical parts might need visual inspection by an operator during the process, which might become difficult.

State of the art:

The ideal solution is a set-up where the cell is built in a way everything is perfectly reachable for an operator. Very simple methods can be used to reach this objective. For example, a platform can be built in order to move the robot to the side with a minimum of work effort.

7.2.5 Robot grippers

Current situation in the industry:

When a robot needs to handle parts to load and unload the CNC machine, certain grippers are needed. A lot of times, these grippers are designed specifically for a certain part. This way, they are very expensive when the manufacturer wants to make small series of very diversified products.

State of the art:

Grippers are designed as universal as possible in order to cope with the increasing demand of adaptability in the production chain. Adjustable fingers in order to have a bigger scope is one of the solutions. Another solution is the use of an automatic system to change the griper on the robotic arm. For maching operations where a table fixture is used, pallet handling might be a solution. This means that not the product itself is handled by the robot, but the pallet on which these products are mounted. This way, one robotgripper is capable of handling a big amount of different parts.

7.3 Pallet handling vs Product handling

The following section describes the commercially available options regarding automatization concepts of CNC machines. There are several concepts available. The most important difference is found in either a pallet handling system, of a product handling system. The most important positive and negative points are described below:

7.3.1 Pallet handling

Positive points

- Easier control of the products
- No need for product specific robot grippers
- Pallet can be used as reference point
- Building plate used in powder bed additive manufacturing can be used as pallet
- The operator does not need to know how to program the robot used to load and unload the machine, since the pallet is always the same, there is no need for reprogramming the robot

Negative points

- Investments for pallets
- Nesting is more difficult during the AM process
- Freedom in how to fix the part in the CNC machine is restricted

7.3.2 Product handling

Positive points

- More freedom in how to fix the part in the CNC machine

Negative points

- Need for product specific robot grippers or special standard features on the product where the robot can grip the product
- Different robot programming for each different product
- Is the fixture rigid enough for the required accuracy during CNC machining?

7.3.3 Points to take into consideration when making the choice between product and pallet handling.

Below, some important factors which play a role in the choice for either a pallet handling system or a product handling system are listed.

Pallet handling is used a lot when a CNC machine is involved in the process, this has 3 main reasons:

1. The product which has to be made is quite complex. This makes it difficult to design robot grippers which are able to fix the part in an easy way. A palletsystem with integrated reference points can make it easier to load and un-load the CNC machine and perform the machining operations.
2. CNC machines most of the time use a pallet in order to fix the part in the CNC machine. This makes the fixing and eventual designing of new pallets more easy for both the machine operator as the planner.
3. Regarding a pallet system inside a CNC machine, multiple commercial solutions exist already through using a fixed reference system.

Product handling is used when the product does not require special robot grippers. This makes it sometimes cheaper because no special pallets need to be designed. Product handling required special design of certain tools for every end-user and product. This makes these solutions less flexible, which is difficult if the production line needs to cope with different products and small series.

7.4 Specific conclusions for the pilot factory

In the pilot factory it will be the goal to combine both additive as subtractive manufacturing. Looking at the fact that it is the scope to build the line for small series of different kind of products, pallet handling will be most beneficial for most products. The main reasons for this choice are:

- The pallet is already there, powder bed processes always use a base plate in the additive process.
- The base plate can be used as a reference point (0,0,0) for the CNC machining.
- Since the base plate always has the same format, it is not that difficult to automate the loading and unloading process of the CNC machine.
- With the use of support structures, most parts are stable enough for CNC machining when just the base plate is fixed. This is tested in chapter 8.
- There are already systems on the market where the base plate of the AM machine is accommodated with a workholding system which is quite common for CNC machines, an example is the EROWA system [59]. A Swiss company specialised in workholding systems for machining operations developed a system to fix a pallet easily inside a manufacturing machine, this fixture is standard for all manufacturing applications.

Possible drawbacks include:

- Nesting is difficult because the CNC machine needs to be able to reach everywhere the part needs to be post-processed. This makes the additive manufacturing process less efficient in terms of time and costs. More information in 9.6.4. An example of nesting is shown in figure 7.1.
- For some more complex products which need a lot of CNC machining, it might be impossible to access everywhere machining is needed. This is tested in chapter 8. Even state of the art CNC machines have difficulties to access everywhere machining is needed.

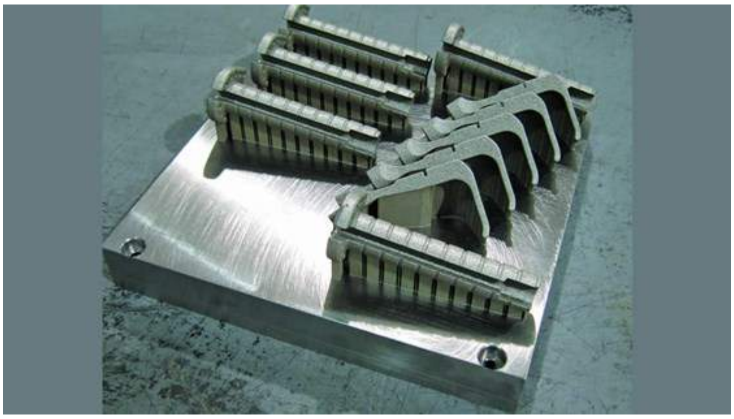


Figure 7.1: Multiple parts manufactured close to each other on one base plate

Chapter 8

Case study

8.1 Introduction

A case study was designed and performed in order to research the combination of both additive manufacturing using a powder bed process and subtractive manufacturing using a CNC milling process. This test aimed to answer the following research questions:

1. Is it possible to fix the AM part in the CNC machine, if yes, how?
2. Is the fixturing rigid enough for CNC machining (precision manufacturing)?
3. Would it be possible to fix the part in the CNC machine using the base plate? This way, the loading and unloading process can be easily automated, as described in chapter 7.
4. Can the CNC machine access all important surfaces which need to be finished? What are the consequences of nesting?

The part was printed in the aluminium alloy AlSi10Mg using an SLM machine and afterwards machined to test the concept of combining additive and subtractive manufacturing.

8.2 Approach

Below, the approach followed during the test will be outlined. This is done stepwise and certain challenges and problems are mentioned.

8.2.1 Design step

In order to test the research questions, a part was designed to print and machine certain features afterwards. A drawing of this part can be seen in figure 8.1. In order to find the problems and challenges of the combination of additive and subtractive manufacturing processes during the case study, the features added go from quite easy to machine towards really difficult to impossible to machine.

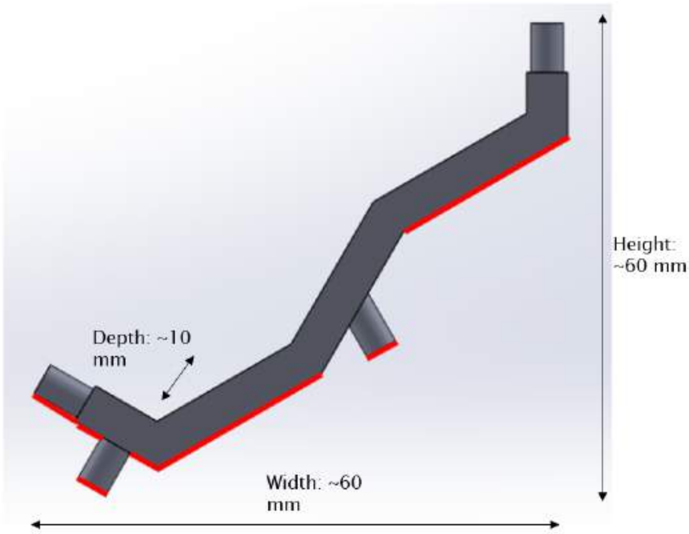


Figure 8.1: Side view from the part which will be used in the practical test

The 4 pins which can be seen on the drawing, are features where the goal will be to machine them afterwards using a CNC machine. This way, a better surface quality can be obtained in these areas. It will be tested if these features are accessible using the CNC machine and the part is stable enough to do the machining when it is fixed onto its base plate as a test of the pallet handling approach. The red lines in the figure show the places where support structures will be needed, more information is given in section 8.2.2 about the additive manufacturing process.

There was chosen for the aluminium alloy AlSi10Mg in order to keep costs for the test low. Which metal alloy is used is not important for the test and aluminium powder is a lot cheaper than titanium powder.

8.2.2 Additive manufacturing

In order to generate the support structures needed for this part, software Materialise Magics ©was used. The result can be seen underneath in figure 8.2

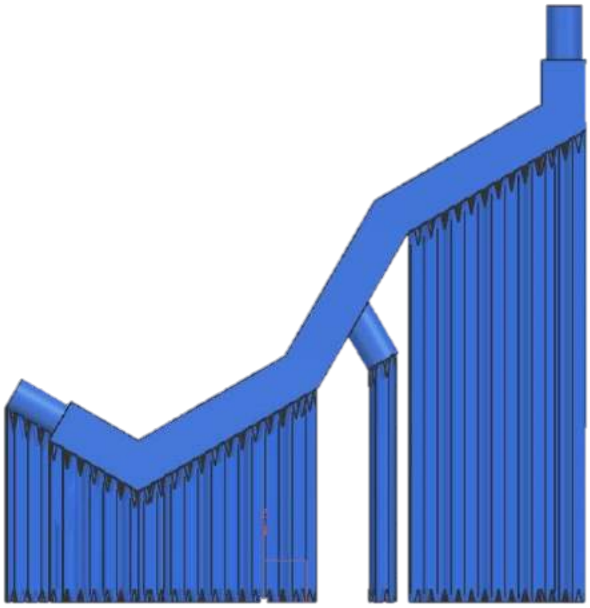


Figure 8.2: Support structures needed to manufacture the part

The part didn't had a heat treatment after the additive manufacturing process, although the build plate was heated to 150 ° C during the complete process in order to cope with the thermal stresses in the part.

8.2.3 CNC machining

Fixation in the CNC machine

First the base plate and the part had to be fixed in the CNC machine, this was done using conventional clamps on the plate as can be seen in the figure 8.3. These gave the part enough rigidity to do the subtractive manufacturing process.

Figure 8.3: Clamping of the base plate to fix the part in the CNC machine

Measurement

In order to define the location of the part in the CNC machine, some points were measured beforehand in order to make sure that machining was done at the right places. For example, the angle of the part with respect to the side of the bae plate (see figure 8.4) was an important parameter to measure.

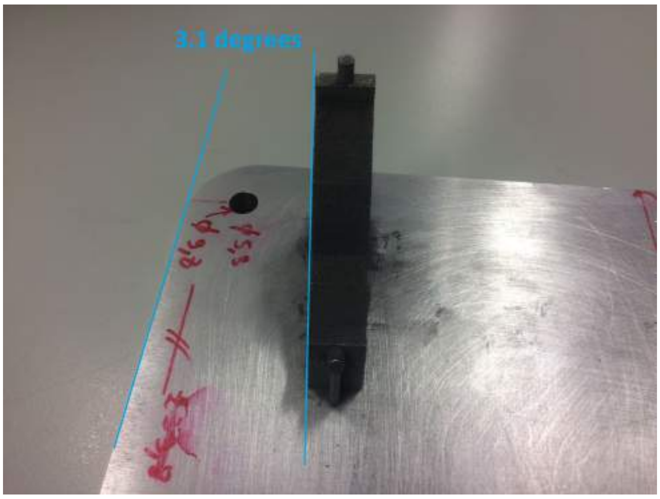


Figure 8.4: Angle between the part and the base plate

Afterwards, a reference point was defined at the first pin in order to be able to program the machining of the first pin. The reference point is defined on the centre of the pin, 0.2 mm below the current surface, in order to make sure material is removed in when machining the top side of the pin.

Background information

In this section, the milling operations are described. For clarification, all features (pins) wich were post-processed got a number, this is shown in the figure 8.5.

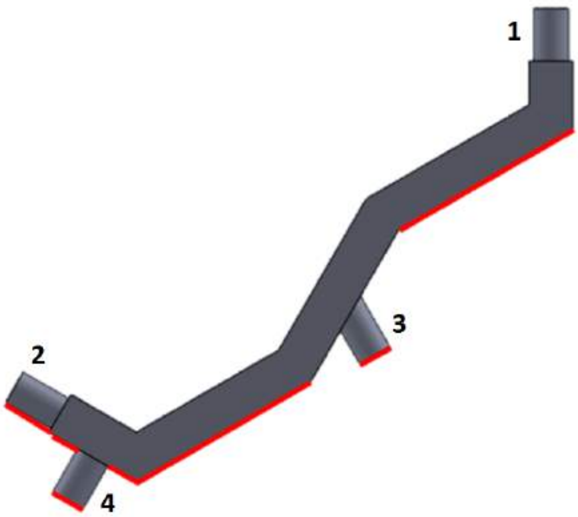


Figure 8.5: Numbered pins for clarification

Some figures in this section show the toolpaths of the milling head during the CNC operations. In these figures the following collour-code is used:

- Blue: Toolpath
- Yellow: Inflow
- White: Outflow

1. **Pin 1**

   Pin 1 had to be machined both on the top and on the side. Using the reference point defined, the machining process was programmed and performed afterwards. In the figure 8.6 the reference axises are shown, as well as the operation to machine the side of the pin (light-blue). This operation is contour milling, the milling tool does not enter the blue circle, but goes around it.

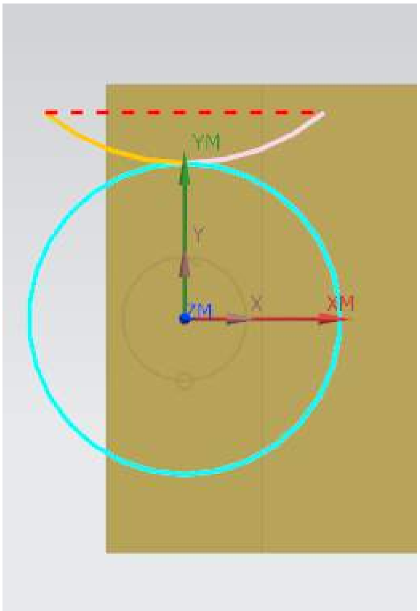
   

   Figure 8.6: Reference point and machining operation of pin 1 on the side

   For the machining of this feature of the part, there were no serious problems. Looking at the results of the machining operation, the surface quality and accuracy of the circle, the part was more than stable enough to perform the manufacturing, and the tool had no problems reaching the points which needed machining.

2. **Pin 2**

   Also pin 2 is machined on the top and on the side. The only difference with pin 1 is the location and orientation together with the fact that there are support structures below the surface which need to be machined. This was solved by first removing these support structures with the CNC machine, and afterwards performing the machining operations on the pin itself. This is shown in the figures 8.7 and 8.8 .

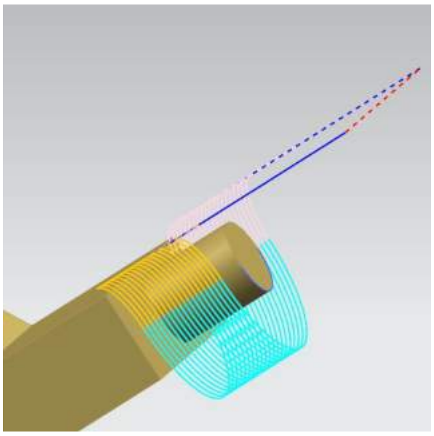


Figure 8.7: Step 1: Removal of support structures of pin 2

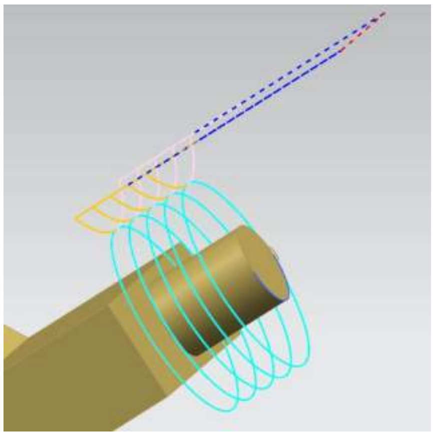


Figure 8.8: Step 2: Side machining pin 2

As a result, it is proved that it is possible to machine a feature with support structures underneath. On the other hand, the feature was really small compared to the whole part, so no stability issues arose. This might be an issue machining bigger surfaces with support structures underneath. More, it can be seen that after machining, only the lower side of the pin is done. Unfortunately, this is due to a small inaccuracy of the printing process. In order to solve this problem, it is important that enough oversize material is added at the drawing for surfaces which need to be machined afterwards.

3. **Pin 3**

   For the third pin, problems arose due to the position of the part with respect to the base plate. This positioning made it difficult to reach both the top and the side of the pin with a tool of the CNC machine. The top of the pin was post-processed by defining a zone below the pin where all material had to be removed. This is shown in the figure 8.10 in dark bleu. Another option would be to remove all the support structures at the left and make the pin accessible with a tool from the side. This would remove all support structures in the red box in figure 8.9. This operation is not performed because it would be disadvantageous for the stability of the part.

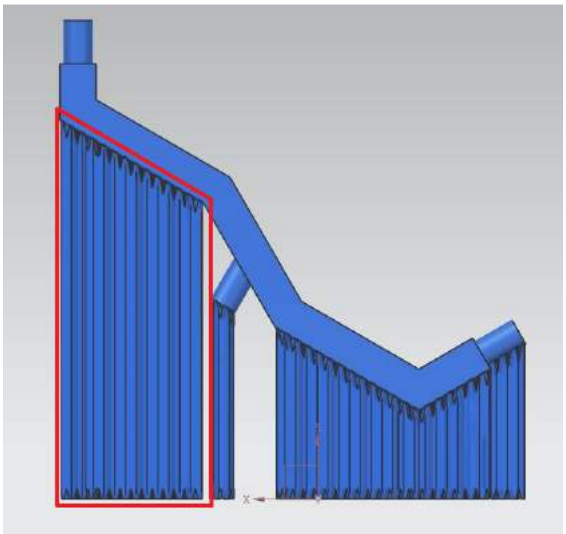


Figure 8.9: Support structures which would be removed in order to reach the pin from the left side

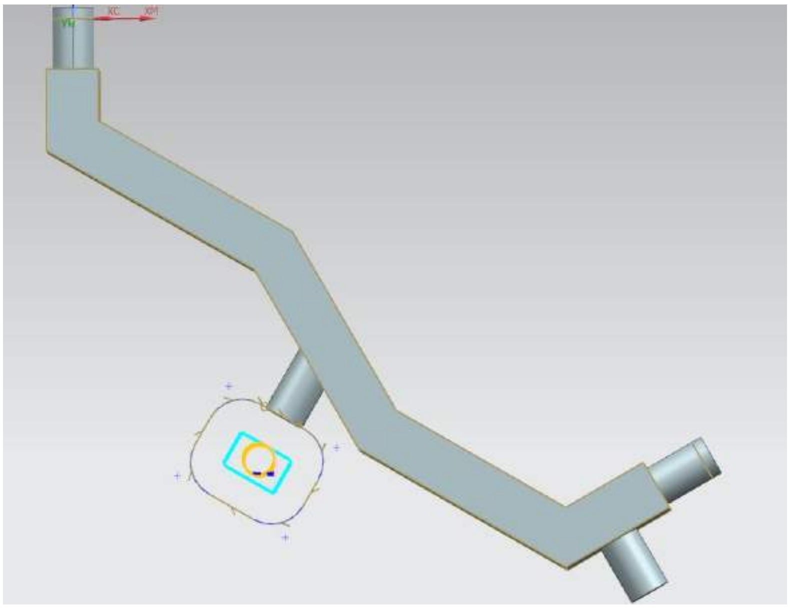


Figure 8.10: Zone where material has to be removed at pin 3

In figure 8.12 the tool path of the tool is shown. The tool removes support structures and machines the top side of the pin in one operation. Due to the position of the part on the base plate, this operation could only be done from one side (where the distance to the edge of the base plate is a lot smaller, this is shown in figure 8.11). If the machining would be done from the other side, the tool would collide with the base plate and fixturing tools during the machining operation.

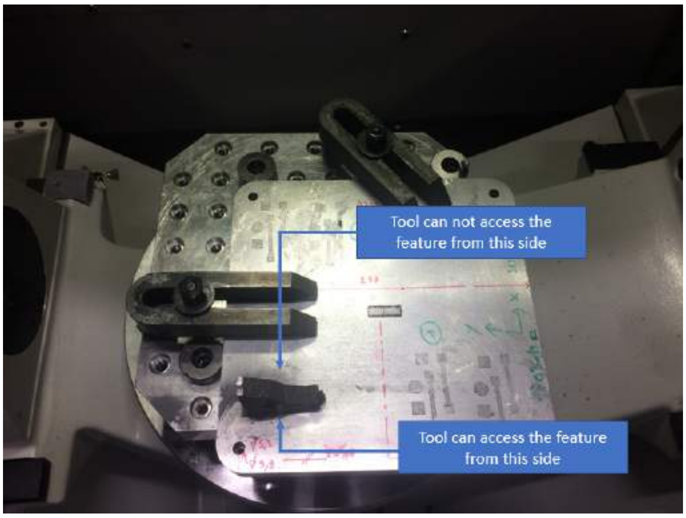


Figure 8.11: Pin 3 is only accessible from one side

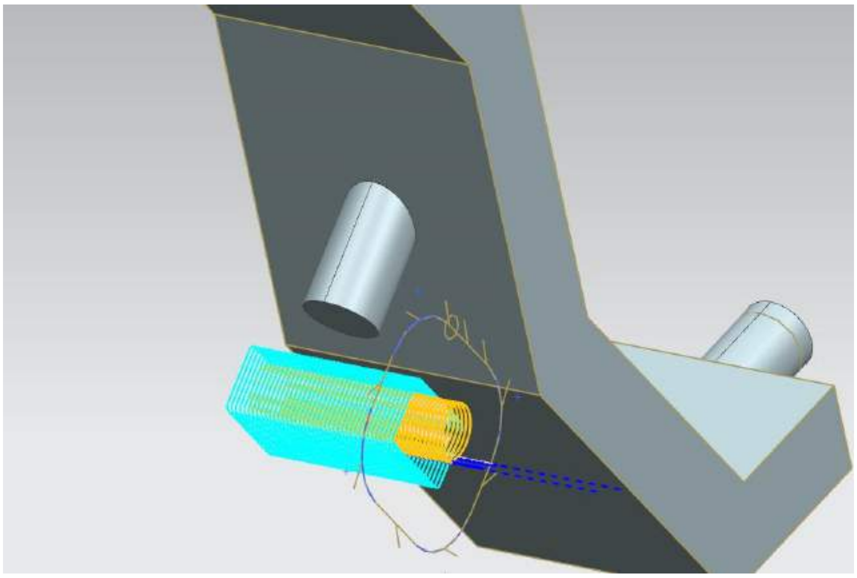


Figure 8.12: Tool paths for pin 3

Because of the angle between the pin and the surface of the part, it is not possible to access the complete side of the pin with the machining tool. Therefore the pin is to small and the tool can not make an angle to reach it from below due to the base plate.

Due to the impossibility to reach the surface of the pin from one side, it is not possible to completely machine the pin (the complete side surface). As a main conclusion, design for post-processing needs to be performed in order to make sure the tool can reach all surfaces which need to be post-processed.

4. **Pin 4**

   Pin 4 is located completely surrounded by support structures and really close to the base plate. Due to this difficult location, a tool with a small diameter has to be used to reach the pin. The same tactic as with pin 3 is used to post-process the top surface of pin 4, removal of the support structures and machining of the top side of the pin is done in one operation. In figures 8.13 and 8.14 the zone where material is removed (dark bleu) and the tool paths (light bleu) can be seen.

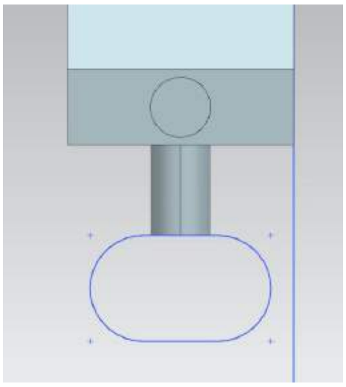


Figure 8.13: Zone where material is removed at pin 4

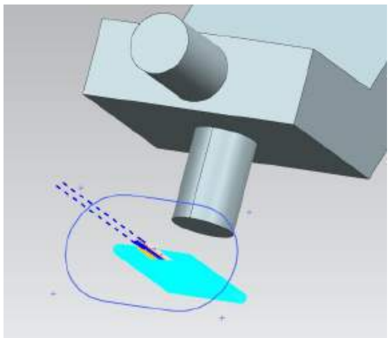


Figure 8.14: Tool paths for the post-processing of the top surface of pin 4

Afterwards, the side of the pin which is accessible with a machining tool is post processed for a better surface quality. Due to the difficult position of the pin only one side can be post-processed, while the other side is impossible to reach with the tools. This operation was done in 2 steps. First support structures are removed in order to make the pin more accessible. Afterwards the side of the tool is used to perform the improvement of the surface quality of the pin. The tool paths are shown in figure 8.16.

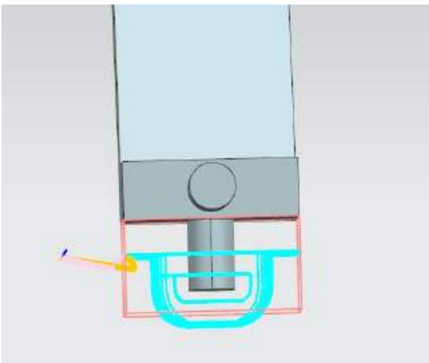


Figure 8.15: Tool paths for the removal of support structures around pin 4

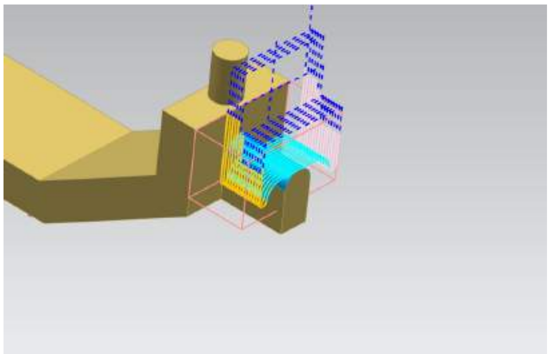


Figure 8.16: Tool paths for the post-processing of the side surface of pin 4

Looking at the results of these machining operations, it can be seen that there is a difference between the CAD model of the part and the actual manufactured part. This creates an offset which is disadvantageous for the dimensional accuracy of the part. This problem can be solved using a 3D scanner to create a model of the actual manufactured part and use this model as starting point to create the tool paths during machining.

8.3 Conclusions

In this chapter, a case study in described which answers the research questions stated in the introduction. The part is easily fixed in the CNC machine using its base plate. The fixation of the base plate and the support structures which were printed gave more than enough stability to the part in order to perform precision manufacturing. As long as not too much support structures were removed during the machining operation, no stability problems arose. Using the base plate as fixture opens opportunities for automatization of the loading and unloading of the CNC machine. Because this is a standardized plate used for all operations of the same machine, the loading and unloading can be standardized as well. The last research question, which is about accessibility of the CNC tools towards the parts is the one where the main challenges are found. In order to perform CNC machining everywhere it is needed, design for post-processing need to be performed in order to position the part on a right spot of the base plate, as well as eventually printing extra support structures in order to increase the distance between the part and the base plate. If the part was positioned in the middle of the base plate and built slightly higher, the tools of the CNC machine would have been able to reach all surfaces which needed post processing. It can be concluded that accessibility of the surfaces which need post-processing is the main challenge regarding the combination of additive and subtractive manufacturing when the base plate is used as fixture during the machining step. Also, problems arise when nesting of different products on one base plate is performed, products close to each other gives big issues regarding the accessibility for CNC tools. Secondly, another important observation is the dimensional offset between the CAD model of the part in comparison with the actual manufactured part.

Chapter 9

Cost Model

9.1 Introduction

In this chapter, the economics of the pilot factory and the combination of additive manufacturing and subtractive manufacturing in general is investigated. Specifically, the costs regarding material utilisation, production time and personnel time is studied. A cost model is developed for processing a small batch (<10 products) of metal parts using the combination of additive and subtractive manufacturing. This research uses selective laser melting as additive manufacturing method and CNC machining as subtractive manufacturing process. A cost model is developed in order to get a decent understanding of the costs associated with the combination of both manufacturing techniques.

Additive manufacturing of metal parts can have a positive impact on the total manufacturing costs of a part. Due to the softer design constraints the additive production process nearly all shapes can be created. This allows the designer to significantly improve product properties [71]. Also, customers ask for more innovative, individually tailored products with a high product quality for a reasonable price. Which results in more and more complex challenges for industrial companies [72]. In addition, the economic lifespan of products decreases which results in the need for shorter time to market and development cycles for different industrial products [73].

combined with part redesign due to the softer design constraints for AM compared to traditional methods

Additive manufacturing of metal parts can have a positive impact on the total manufacturing costs of a part [71]. The additive production process allows product designers to create parts with high geometric freedom. Nearly all shapes can be realized by AM, which allows the designer to significantly improve product properties [72]. Additive manufacturing allows the designers to concentrate on product features instead of manufacturing restrictions given by traditional production techniques [71]. Nowadays customers ask for more innovative, individually tailored products with a high product quality for a reasonable price. Which results in more and more complex challenges for industrial companies [72]. In addition, the economic lifespan of products decreases which results in the need for shorter time to market and development cycles for different industrial products [73].

9.2 Economic Aspects of Additive Manufacturing

The fast moving markets within the manufacturing industry need to rethink manufacturing completely in order to fully benefit from additive manufacturing.

9.2.1 Design for Additive Manufacturing

The main benefit regarding the design of additively manufactured parts is the complexity-for-free manufacturing. In traditional manufacturing, there is a direct relation between manufacturing costs and complexity [74]. Some literature [15] suggests that the costs per unit for additive manufacturing stays the same, although it should be taken into account that for example a CAD model needs to be designed only once. The same story for the generation of toolpaths for post-processing. Economies of scale do exist for additive manufacturing, although they are way smaller than for conventional manufacturing. Gibson et al. [5] defines the goal of design for additive manufacturing as "Maximize product performance through the synthesis of shapes, sizes, hierarchical structures and material compositions, subject to the capabilities of AM technologies" .

To pursue these items, designers should take into account the following items:

- Undercuts, variable wall thickness and deep channels can be manufactured through AM. [75]
- With AM, unlimited complexity can be manufactured. This includes twisted and consorted shapes, blind holes and products with a very high strength to weight ratio through the use of topology optimization [75] [9].
- AM can make it possible to combine multiple parts into one and remove the assembly process for certain products. This makes the assembly process easier and lowers the required handling time [75] [74]. An example is the nozzle designed and manufactured by GE shown in figure 2.3.

On the other hand, there also exist some design limitations regarding additive processes:

- Design and removal of needed support structures for metal additive manufacturing has to be done for undercuts and overhanging structures [9].

- Dimensional accuracy, tolerances, surface finish quality and minimal wall thickness need to be taken into account for every AM technique [75].
- Range of materials currently available [8].
- The building direction is important for the mechanical properties which can be achieved through AM [75].
- Component size is limited to the building volume of currently available AM machines [75].

In conclusion, designers of products which are manufactured by AM need to rethink their approach completely in order to benefit of AM techniques.

9.2.2 Economic application

Several key economic criteria in the area of AM cannot be directly expressed in euros. For example, AM helps to shorten the time-to-market-duration [76] due to the extreme variety of products one AM machine can make, therefore, chances are high there is a manufacturing machine for a specific part (definitely for spare parts) closer and transportation time and costs are lower. AM can also increase the diversity of variants, while the quantity of variants decreases [71]. Further, the introduction of new products into the market goes way faster and can be done less risky with the use of AM (No need for expensive tooling which need to be developed, which is the case for casting techniques). These examples show AM technology can have a competitive advantage over other conventional manufacturing methods for a manufacturing company [74] [77]. In fact, AM reduces both costs and time from the design phase to the production of the part(s). Mainly since there is no preliminary investment needed for special required tooling and fixtures [75]. As regards of time, once the part is designed, manufacturing can start right away and delays due to the manufacturing of tooling are eliminated [75]. More, products which are designed by topology optimisation or make use of lattice structures can significantly improve a parts strength to weight ratio, which is of great interest in the aerospace industry.

9.3 Cost calculation

9.3.1 Method

In order to project manufacturing costs, there are generally 2 methods: Qualitative and Quantitative.

Qualitative means that there will be made a process plan, where all process steps are listed. Afterwards, for every production step, there will be made a calculation in order to calculate the total costs. Also, waiting times, programming costs, and preparation as well as post production costs will be taken into account. Usually, the calculation process makes use of a few assumptions and best-guesses. In the end, all costs are added up to create a total process cost.

The quantitative method uses another approach. Here, past data is used to forecast the production costs. Which parts were made in the past and how much did those processes cost. The new product will be compared to the past products and the production costs for the new product(s) can be derived as such. Regression analysis is used to forecast the production costs of new products.

For this project, a qualitative method was developed. This method was chosen due to the fact that additive manufacturing is most of the time used for small series, and past data is to scattered for proper data analysis.

The development of the cost model consists of material and manufacturing costs (including tool costs and set-up costs). The cost model is activity-based [1].

9.3.2 Cost calculation Additive Manufacturing

The total cost for the additive part of the manufacturing process can be summarized as follows:

$$Costs_{Total} = C_{Oper} + C_{Consumables} + C_{Machine} \tag{9.1}$$

where:

C_{Oper}	Operator costs
$C_{Consumables}$	Consumables costs
$C_{Machine}$	Total costs related to the AM machine

Operator costs

The operator costs are in direct relation to the time spent by an operator for the activities he has to perform. These activities can be summarized as follows:

- Set-up of the machine
- Follow-up during the process
- Work done after the printing process

[1] Activity-based costing is a method used for assigning costs to products by adding up the cost of all activities that go in them and the resources consumed by these activities.

- Follow up during post processing [2]
- Separation of the pieces from the building plate
- Finishing the part

The total time spent on this process needs to be multiplied by the hourly rate of the operator in order to get the total operator costs of the additive manufacturing process. Note that design costs are not taken into account because the focus is put on the manufacturing costs.

Consumables

The additive manufacturing process has a set of consumables fixed per building job which need to be taken into account in the cost calculation, these include:

- **Building plate:** After each process the building plate is machined flat again, due to this process, the building plate can only be used about 20 times.
- **Powder sweeper:** The powder sweeper which is used to apply a new layer of powder is removed after every printing job.
- **Powder filter:** A filter to guarantee the powder quality in terms of size is used for about 4 printing jobs and replaced afterwards.
- **Metal powder:** The powder used has to be bought and transported to the location of the additive manufacturing machine.

Hourly costs related to the AM machine

The total costs related to the AM machine consist of:

- Depreciation costs of the machine
- Maintenance and insurance costs [3]
- Argon costs
- Electricity consumption

[2] Post processing is here defined as normal post-processing and support structure removal after the printing process, subtractive manufacturing is not included

[3] Floor space costs are not included in the model

The sum of the operators, consumables and AM machine costs result in the total cost for one AM process. It should be noted that most of the time more than one part is made during one AM process, which lowers the cost because lot of cost factors are only counted once per AM process. Also, it is assumed that the cost of overhead is 0. This can be done because when comparing AM to conventional manufacturing processes, the overhead costs would be of about the same size.

9.4 Method used for cost calculation of CNC machining

In the case of CNC, the manufacturing cost is a function of:

- Total machining time
- Tooling cost
- Operator costs

9.4.1 Total machining time

The total acquisition cost of the CNC machine itself can be calculated as the sum of the following list:

- Raw machine
- Electrical equipment
- Education personnel, when a new machine is bought the operator(s) need to be educated.
- Instalment costs
- Other attachments

In order to calculate the total cost of the machine, also recurring costs need to be taken into consideration. These costs consist of:

- Maintenance and insurance costs
- Emulsion costs

In order to find a good price per hour regarding depreciation of the machine, assumptions need to be made how much the machine will actually be working. If the factory uses a certain shift system, it largely affects the yearly amount of hours the machine will actually be working.

Yearly operator costs is the last piece of the total depreciation costs for the CNC machine. When all these costs are summed, an operating price is found for the installed CNC machine, which can be easily translated into an hourly cost for the machining cost calculation of one part.

9.4.2 Tooling costs

The second important metric in the CNC machining calculation is the costs of used tools. These tools only have a limited lifetime which make them an important cost factor.

The cost is calculated per tool life. Which is done in the following way:

Total cost per tool life = Acquisition cost of the tool + Time required to change the tool, which can be translated in operator costs

Tool life calculation

The tool life can be optimized in two ways, minimizing the costs for producing the part and minimizing the production time needed to produce the part. In the book written by Robert G. Bierley [78] both formulas are provided.

Minimizing the costs for producing the part:

$$T_c = (\frac{1}{n} - 1) * (\frac{t}{M} + TCT) \tag{9.2}$$

Minimizing the production time needed to produce the part:

$$T_p = (\frac{1}{n} - 1) * TCT \tag{9.3}$$

where:

T_c / T_p	Tool life
n	Slope of the tool-life versus cutting-speed line, also known as the Taylor exponent
t	Cost of a tool
M	Machine labour costs
TCT	tool changing time

9.4.3 Operator costs

Regarding CNC machining, an operator is needed to set-up the machine, program the toolpaths of maching tool and clean out the machine after the manufacturing process. This total time needs to be multiplied with the hourly rate of the operator.

9.5 Case study

The practical case described in Chapter 8 is filled in the model to calculate the cost required to manufacture the part and find out what the main cost drivers are in the manufacturing process. This calculation is presented in the following section 9.5. This calculation needs to be seen as an example of a part manufactured by the combination of metal additive manufacturing and subtractive manufacturing as post-process step. It is expected that other parts would give different results due to the high variation in different parts.

9.5.1 Additive manufacturing

For the cost calculation of the part the method described in subsection 9.3.2. An important point to take into account: this calculation assumes there is only one part on the building plate. In real life situation, it is always the goal to use the building plate as efficient as possible and put the maximum amount of parts in the available volume. This concept is described in more detail in 9.6.4. Increasing the amount of parts inside one building volume dramatically decreases the AM manufacturing costs per part.

Operator costs

The operator costs can be calculated as the product of the hourly rate of the operator and the following tasks the operator has to perform:

- Set-up of the machine: 1 hour
- Follow-up during the process: 1,5 hour
- Work done after the printing process: 1,2 hour. This consists of 1 hour for aspiration of the residual powder and 1 hour every 5 jobs to replacing the metal powder.
- Follow up during post processing: 0,2 hour
- Separation of the pieces from the building plate: 0,6 hour
- Finishing the part: 0 hours, finishing the part was not done during the practical case.

Multiplying the total of 4,5 hours with an hourly rate of 67 EUR/hr makes a total of 301,50 EUR operating costs.

Consumables

- **Building plate:**
  The building plate costs about 57,0 EUR, machining the plate between two building jobs has a price of 62,5 EUR. Which brings the total cost of one building plate on 1307 EUR, divided by 20 this becomes 65 EUR/buildjob.
- **Powder sweeper:**
  The powder sweeper costs 20 EUR
- **Powder filter:**
  A filter for the powder is used for about 4 printing jobs. One powder filter has a price of about 44 EUR, so 11 EUR/buildjob
- **Metal powder:**
  Aluminium powder used for the practical case costs about 65 EUR/kg. For this case, the total volume of the part is $6284mm^3$. Assuming 5% losses of metal powder, this equals 29 gram of aluminium powder. Assuming 20% extra material needed for the support structures, a total of 43 gram aluminium powder will be used, about 3 EUR.

The total consumables cost equals 105 EUR for this building job.

Hourly machine costs

- **Depreciation costs:**
  Using a linear depreciation method of 6 years and an assumed yearly usage of 3500 hours per year an hourly depreciation cost is calculated of 20 EUR/hour.
- **Maintenance costs:**
  As most additive manufacturing machines a maintenance contract is used. This costs 15000 EUR/year, or 4,3 EUR/working hour.
- **Argon consumption:**
  An Argon bottle costs about 2000 EUR and supplies about 200 hours of Argon, so 10 EUR/working hour.
- **Electricity consumption:**
  This can be assumed to be about 6 EUR per building job.

Using the additive manufacturing machine costs about 34,3 EUR/working hour.

The manufacturing time can be estimated as follows: The total volume of the part is 7855 mm3, with a height of 67 mm there is an average intersection surface of $94mm^2$. Adding a new layer of powder takes about 27 seconds, and the additive manufacturing machine can laser about 90 mm^2 in one second. Totalling 28 seconds for each layer. The height of a layer is 60 μm, so 1117 layers are needed for the part. The total estimated manufacturing time equals 8,7 hours. It should be noted that about 2 hours is needed for pre-heating and cooling down the machine before and after the manufacturing process. The total machining cost equals 366 EUR.

Total additive manufacturing costs

Table 9.1: Total costs additive manufacturing

Operator costs	301,50 EUR
Consumables costs	105,00 EUR
Machine costs	366,00 EUR
Total	**772,50 EUR**

9.5.2 Subtractive manufacturing

In the following subsection, the costs related to the subtractive manufacturing processes described in Chapter 8 are calculated. Herefore, the method described in Section 9.4 is used.

Depraciation of the CNC machine

The total cost of the CNC machine (Fehlman Versa 825) is 1.020.000 EUR[4]. This cost includes the electrical equipment needed, instalment costs, training and extra equipment costs. Using a 10 year linear depreciation gives a yearly depreciation cost of 1.020.00 EUR. Assuming 5% extra cots for maintenance and insurance of the machine, a yearly cost of 153.000 EUR is calculated. Assuming 7,6 working hours is a day and a machine which is used 90% of the time during 222 days in a year, the hourly costs of the machine equal 100,8 EUR/hr. The machine was used for a total of 1,5 hours, which equals 151,2 EUR.

Tooling costs

During the practical case a milling head was used to perform subtractive manufacturing to the part. This milling head can only be used for a limited amount of time. Afterwards it needs to be replaced with a new one. The time the milling head can be used can either

[4]The CNC machining performed in this case study is done on a machine with very high standards, and would also have been possible on a lower quality machine (in terms of flexibility and accuracy for example). Using a machine with lower standards and so a lower price, would decrease the depreciation cost of the CNC machine significantly.

be optimised towards maximum production speed, or minimising the costs associated with the tools needed for the CNC operations. This is described in subsection 9.4.2. The holder of the milling tool can be used 400 times with different tools. This holder costs 43,72 Euro, or 0,11 Euro per tool. The tool itself costs 5,21 Euro and has 3 cutting edges, so 1,74 Euro per cutting edge. Replacing the tool costs 5,26 Euro, this includes the deprection of the machine as well as the operator hourly wages for about 2 minutes time. If these three costs are summed up and formula 9.2 is applied, using a Taylor exponent of 0,25, 8.1 minutes of CNC operations costs about 7,10 Euro. During the practical case the tool was used for about 5 minutes. The total tooling costs equal 5,70 Euro. This was calculated using the formula for the economically optimised way of CNC machining instead the optimisation for production speed.

Operator costs

The hourly rate of an operator is the same as for the operator of the AM machine (67 EUR/hr), The work done by the operator can be split into three categories:

- Set-up and breaking down of the manufacturing process: About 30 minutes needed to place and remove the building plate in the CNC machine and add the right milling head as a tool.
- CNC programming: about 1 hour was spent to program all toolpaths.
- Controlling the CNC machine: about 1 hour was spent controlling the operations the CNC machine was performing.

In total, an operator worked for 2,5 hours on the case, which equals 167,5 EUR.

Total subtractive machining costs

Table 9.2: Total costs subtractive manufacturing

Depreciation costs of the machine	151,2 EUR
Tooling costs	5,7 EUR
Operator costs	167,5 EUR
Total	**324,4 EUR**

9.5.3 Cost summary

In the table 9.3 underneath a cost summary is given for the practical case.

Table 9.3: Total costs

Additive manufacturing costs	772,5 EUR
Subtractive manufacturing costs	324,4 EUR
Total costs	**1.096,9 EUR**

About 30% of the costs associated with the practical case are from the subtractive manufacturing process and 70% from the additive manufacturing process. The subtractive costs are not that high because due to the additive manufacturing process the amount of material which has to be removed in the CNC machine is very small. Because of this, actual manufacturing times are a lot shorter compared to manufacturing the part completely by additive manufacturing. it should be noted that the time needed to program the toolpaths is about the same for a near net-shaped part first made by additive manufacturing compared to using a block of material when the part is manufactured by only subtractive manufacturing.

9.6 Discussion

9.6.1 Main cost drivers

Additive manufacturing process

When there is looked at the 3 categories: operator, consumables and machine costs. It can be seen that operator and machine costs take into account the biggest part of the total costs.

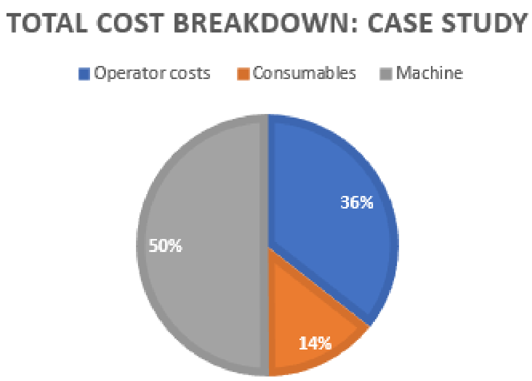


Figure 9.1: Total cost breakdown

When all consumables are put next to each other, shown in Figure 9.2, the metal powder costs seem really low. This is normal because aluminium powder is quite cheap compared to other metal alloys used in additive manufacturing. For example, Titanium powder (Ti-6Al-4V) can be bought at 320 EUR/kg. This is about 5 times more expensive than aluminium powder. As can be seen, the building plate takes into account about 66% of the consumables costs. Using this information it can be concluded that it is beneficial to put as much different parts on one building plate. More information about this concept in subsection 9.6.4.

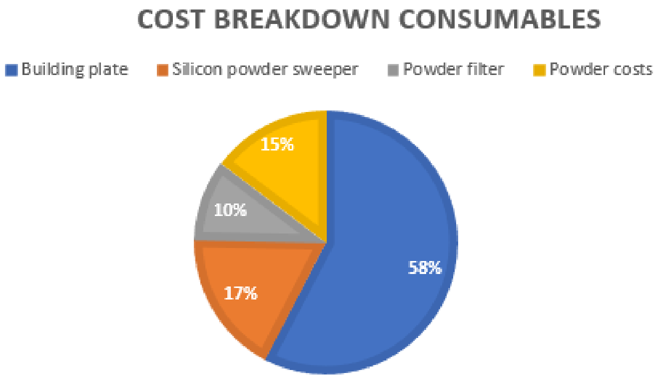


Figure 9.2: Consumables cost breakdown

Subtractive manufacturing process

In Figure 9.3 the cost breakdown is seen for the subtractive production process for the practical case. It can be concluded that the main cost drivers are the depreciation of the CNC machine and the operator costs due to the extensive programming of the toolpaths.

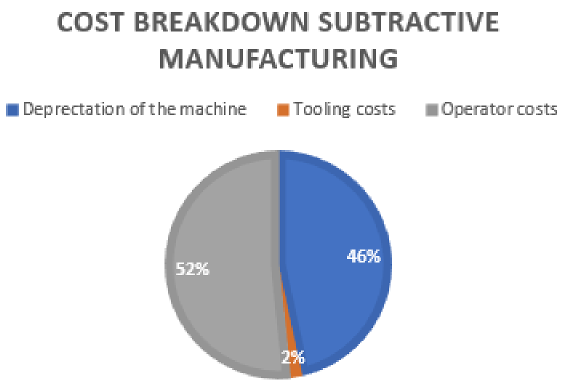


Figure 9.3: Subtractive manufacturing cost breakdown

9.6.2 Influence of cost components

The economic analysis was tested on only one single part made from an easy to machine material. One could argue that for other materials or part geometries the results would be totally different. The same argument can be made for other cost parameters. The cost of materials differ significantly for metal AM, titanium powder (Ti-6Al-4V) is about 5 times more expensive than aluminium powder, while aluminium is also a lot easier to machine. Manogharan et al. [79] assumes the cost of machining aluminium compared to titanium about 1 to 10. If the same product would have been manufactured in titanium, not only the material costs would have been higher, but also the machining time needed would have increased. More, due to the exponential increase of metal additive manufacturing in the industry, it is expected that the metal powder costs will decline in the following years. The increase in sales from metal powder made for additive manufacturing can be seen in figure 2.6. The same argument can be given for the cost of an AM machine. Due to the increase of new companies entering the market of AM machines, competition will increase and so prices will lower [80].

It can be concluded that the combination of additive and subtractive manufacturing becomes more interesting for harder materials which are more difficult to machine and therefore take more machining time. Starting with the near net shape significantly lowers the machining time needed and improves the efficiency of the material utilisation (so called buy-to-fly ratio).

Looking at figures 9.1 and 9.3, it can be concluded that the biggest cost parameters are operator time and the cost of the depreciation costs of the machines, if the cost of this hybrid manufacturing process has to be lowered, those are the two main areas where the biggest gains can be found.

9.6.3 Production speed

One of the main advantages of the concept of combining additive manufacturing and subtractive manufacturing, is the fact that subtractive manufacturing is only used as finishing step. The process is started with a near net shape of the part and only a slight amount of material is machined away from the part. This is seen at machining parameters like feed and depth of the cut employed at the CNC machine. This advantage is the strongest when the part is made of Ti-6Al-4V. The effect is smaller when relatively softer materials like aluminium are used. As can be seen in Figure 9.3 the depreciation of the CNC machine is a very important cost factor, so a short machining time is important. Also, due to the very limited amount of material which is actually scrapped away, the tooling and scrap material cost stay really low compared to normal CNC processes.

9.6.4 Nesting

As can be seen, the machine utilisation costs are an important factor in the total cost calculation. This effect is minimised through the concept of nesting. Nesting mean's as many parts as possible are build into one building volume, in order to achieve efficient machine volume utilization. This reduces the total building time and the associated costs. It is important, that not only the compactness should be maximised, but also the part's production quality should be guaranteed. If the same cost calculation method is used as in Section 9.5 with 6 parts on the building plate. It can be seen that the total cost is less than six times the cost of one manufactured part. When the same piece is put 6 times on the same building plate, the total costs rises from 772 to 843 EUR, or about 140 EUR/part. The rise in cost is mainly due to the longer needed printing time (only the laser time, applying a new powder layer stays the same) and the increased material costs. Besides a slight increase in needed operator time, all other costs are quite constant for one build job.

Chapter 10

Flexible pilot factory

10.1 Introduction

It is one of the future goals of Sirris to set up an example production facility using multiple types of metal additive manufacturing, combined with different post-process and quality check techniques. The test facility would give opportunities to Belgian companies for testing and exploring the industrial capabilities of metal additive manufacturing, while testing its process capabilities and total cost of ownership. It is the goal that this production facility acts as an enabler for metal additive manufacturing in the Belgian production environment. It should give the opportunity to Belgian companies to get real experience with the AM technology in order to increase the TRL level of Metal AM in Belgium.

The following chapter describes a concept for this production environment. It has generally the same objectives as the pilot factory described in chapter 4, besides the fact that more techniques and processes need to be integrated in one production environment, including:

- Different materials (multiple metal alloys)
- Different AM technologies (Selective Laser Melting, Electron Beam Melting, ...)
- Different processes for post-processing towards precision manufacturing
- Different finishing technologies
- Multiple quality tests

This both digital as physical integration will be done because of the fact that it helps in manufacturing products with a consistent quality.

Based on the major advantages and limitations of additive and subtractive manufacturing, a combination of both technologies solves the main issues regarding poor surface finish and high part tolerance. The flexible pilot factory has te objective to go further than only the combination of both additive and subtractive manufacturing. The goal is to start with multiple additive manufacturing machines, which are able to manufacture end-use products in multiple metal alloys and are steered from a central controlling point. Multiple techniques like the conventional selective laser melting and electron beam melting technique, but also laser deposition melting. After the additive manufacturing process, powder removal will be done either automatically, as in the SLM concept [47], or with the help of an operator, depending on the complexity of the product. Heat-treatment will be performed by multiple ovens in order to relief the thermal stresses in the part and to improve the material qualities. Hereafter, post processing is performed by either subtractive manufacturing or other manufacturing processes in order to remove the support structures or improve the surface quality and accuracy of the product. Last, quality control will be done on the manufactured parts. Both dimensional and non-dimensional (for example porosity testing) quality control will be performed, more information about quality tests can be found in 4.6. Next to physical integration, it is also one of the main goals to digitally integrate the whole production environment, this means that data is exchanged between machines so they can run more independently. Also data analysis can be performed in order to improve the planning of manufacturing operations. The following chapter describes the requirements associated with the flexible pilot factory, state of the art technologies and concepts which are now already on the market, and challenges and certain barriers to entry for a total integrated production environment.

10.2 Requirements of the flexible pilot factory

The main requirements of the flexible pilot factory are listed. The list is split up using the main manufacturing processes inside the factory.

- **Additive manufacturing systems**
  - The systems are capable of working simultaneously next to each other.
  - Multiple metal alloys can be used for manufacturing, reactive materials are included.
  - The AM machines can change between metal alloys easily and fast.
  - The building volumes are at least 250 x 250 x 250 mm big.
  - the AM machines can be loaded and unloaded automatically.

  - The building plate is equipped with a standard system so it can be used in the machining process as fixture.
  - There is a difference between all additive manufacturing machines used (building volume, laser power, minimum spot diameter etc.) in order to optimize production.

- **Post-processing capabilities**
  - Subtractive manufacturing is capable of post-processing the parts towards a dimensional accuracy of 5 μm.
  - The CNC machines are capable of performing multiple functions (tapping, drilling, milling, etc.).
  - The part can be fixed in the CNC machine in an efficient and product independent way.

- **Quality control**
  - Quality control is performed both dimensional as non-dimensional.
  - The right quality control processes are in place to ensure certification for the end products.
  - Quality control at the end of the manufacturing process is interlinked with quality control during the manufacturing process

- **Digitalization**
  - Usage of data in order to connect the different machines, predict machine failures and schedule maintenance regarding load instead of time.
  - Enterprise Resource Planning (ERP) to optimize workflow scheduling is applied.
  - Tracking system to create real time visibility to materials in the whole manufacturing chain.
  - Integration of the core system: Integrating the data obtained helps in scheduling the most optimal production run with the right set of configuration and eventual workforce.
  - Data integration enables cross-correlation of multiple data streams in order to improve quality assurance.
  - Real-time automation and process integration across the supply chain enables the necessary responsiveness.
  - The data streams are secure and protected with regards to data security.
  - A streaming analytics platform that delivers meaningful and actionable insights from processed data.

- The tracking of resources (raw materials, electricity consumption etc.) makes it possible to visualize and optimize resource consumption of the manufacturing process.
- The processes can be followed from a distance through the use of the internet in order to enable fast reaction by an operator from a different location.

10.3 State of the art technologies

Nowadays, multiple companies are generating new concepts of production facilities using metal additive manufacturing. Below, two concepts generated by well known additive manufacturing companies are described:

10.3.1 Conceptlaser

The company ”Conceptlaser” developed an new concept of an ”Additive Manufacturing Factory of Tomorrow” by decoupling the different phases of an additive manufacturing process into pre-production, production and post-processing [4]. This includes among other things flexible machine loading and physical separation of the setting up and disarming processes. The objective here was to coordinate the process components in a more targeted and centralized way and increase the flexibility of the process design to create an integrated approach. Conceptlaser found the solution thanks to a consistent modular structure of both handling stations and build and process units. This approach brings greater flexibility and availability due to combination and interlinking. It brings the time window for additive manufacturing production towards a ”24/7 level”. Also, because of the present diversity of materials, it will be easier to handle the production process. As a result, the level of efficiency and availability of the production system will be markedly increased, along with a significant reduction in the amount of floor space required. In the modules, laser sources, process gas management and filter technology are integrated. The process stations have a build envelope of 400 x 400 x 400 mm3. Still, manual handling is required for certain processes, like support structure removal and surface quality improvement. Although for example the transport of materials or entire modules can be envisaged as being done by driverless transport systems. An overview of the concept can be seen in figure 10.1.

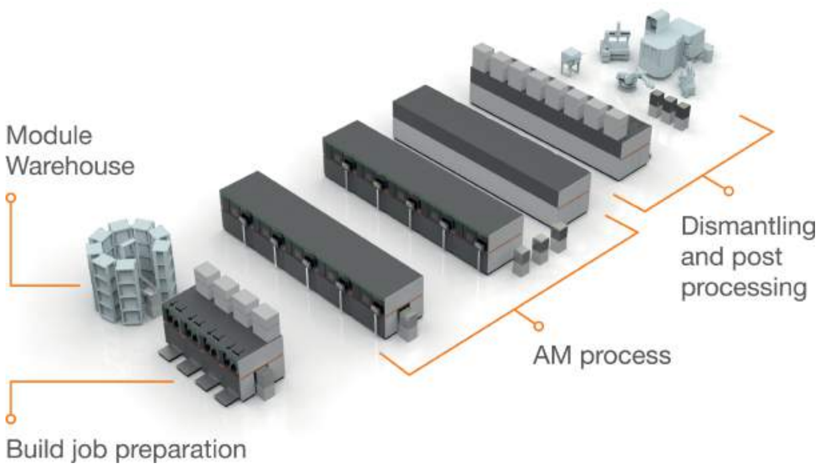


Figure 10.1: Concept by conceptlaser [4]

10.3.2 SLM Solutions

SLM solutions created a concept of a factory floor where multiple additive manufacturing machines are used next to each other. A smart powder handling system gives the ability to use multiple metal alloys. Just as in the Conceptlaser concept, the building volumes are transported to and from the additive manufacturing machines. A special system is used to remove the powder automatically after the printing process. The building volume is turned around to remove all the powder. This works quite good, although for complex products with for example cooling channels it is impossible to do the whole process automatically and human intervention of an operator with a compressor is needed, this process is described in section 4.5.3. Instead of AGV's the SLM concept uses a rail to guide the building volumes between workstations.

10.3.3 Conclusion

Both concepts described above focus on the handling of the powder and part just before and after the additive manufacturing process. They do not include the post-processing which is needed at almost every end-use part made by additive manufacturing. This is clearly a part where the industry is still lacking solutions to fully integrate both physically as digitally the manufacturing processes.

10.4 Barriers for entry

In the following section the problems and challenges for a fully integrated flexible pilot factory are described. These are split up using the different manufacturing processes, starting from the product design up to quality control and transfers between all manufacturing steps.

10.4.1 Product design

Regarding product design, the main barrier is the fact that the designer needs to take into account not only the additive manufacturing process, but also the post-processing afterwards. For example, as shown during the practical tests which are described in Chapter 8 critical features which need post machining need to be located as such that the machining tool is still capable of reaching the entire surface. Adjustments will need to be made to the design but also to the process planning (where to locate different parts on the base plate for example). An optimal solution is a computer algorithm which includes the movements of the machining tools into the topology optimization. Nesting of the parts on the base plate can also be optimized already [81], this would be improved if toolpaths of the CNC machining process can be included in these optimizations. The following list of parameters and analysis can be used as input for an algorithm generating the best solution regarding nesting and accessibility for CNC machining of the critical surfaces after additive manufacturing.

- Physical constraints: Available build volume, orientation and machining volume.
- Part information: A CAD file of the part with identification of the critical surfaces which need post-machining.
- Visibility analysis: Analysis of the accessibility of the critical surfaces.
- Tool length considerations: Maximum tool length in order to fullfill the requirements regarding accuracy of the machining process (less chattering and tool deflection).

10.4.2 Powder handling

Powder delivery

Powder delivery can be done by preparing the building boxes full of powder outside the additive manufacturing machine while AGV's (Automated Guided Vehicles) are transporting them to and back from the AM machines when the specific metal alloy in the box is needed at one of the machines. Another option is the installation of a piping system between a central powder handling station and all AM machines. For both options, the main difficulty is the fact that the AM machine needs to be completely clean from any other metal powders when it is filled with powder. An operator may be required to make sure there are no leftovers from the previous job in another material.

Powder removal

After the additive manufacturing process, the residual powder around the component(s) need to be removed. This is usually done by hand and the use of air blasting. Nowadays, techniques arise where this process can be done automatically. Ideally, this process is integrated in the build chamber, but it can also be done as a stand alone process. The powder handling concepts developed by industrial companies are described below:

Current systems in the industry

Conceptlaser:

In Conceptlaser's "AM factory of tomorrow" the handling of the new powder is done automatically. Due to the modular architecture boxes with powder can be transported automatically to the additive manufacturing machine. This integrated approach discouples the powder handling from the actual manufacturing machine, which lowers the compexity of the task significantly. Also the modules with the finished parts are handled automatically. No details are given about automated part removal, except the fact that the residual powder is sucked away using a sort of vacuum cleaner.

Renishaw:

Renishaw's 500 line machines are able to perform powder sieving and recirculation within the system automatically, reducing the need for manual handling and exposure to materials [82]. They are not capable of automatic part and powder removal. For this process, still an operator is needed due to the difficulties in automating this process.

10.4.3 Additive manufacturing

Regarding the additive manufacturing process, the main objective is to use multiple techniques inside the flexible pilot factory. These techniques include powder-bed processes like selective laser melting, but also direct metal laser sintering methods can be used for parts which tend to be bigger and don't need the accuracy which can be provided by powder-bed processes. The main problems with additive manufacturing machines for implementation in the agile pilot factory are related to software. Machine producers are not always willing to support data interchange and OPC-UA systems (described in Section 6.3) are not yet widely implemented. Regarding physical integration of the additive manufacturing machines, the main barrier is the fact that, in comparison to CNC machines, AM machines are rarely adjusted towards an automatic loading and unloading process. Solutions towards the automatic loading and unloading using robotic arms will need to be developed in order to smoothen the process and decrease the need for repetitive manual labour in the factory.

Nesting

In the chapters 8 and 9 there is concluded that nesting is beneficial for cost purposes, but gives problems when the base plate is used as fixture during the machining operation. A possible solution would be to mount multiple building plates on a base plate inside the additive manufacturing machine. The concept is made clear in the following figures 10.2 and 10.3:

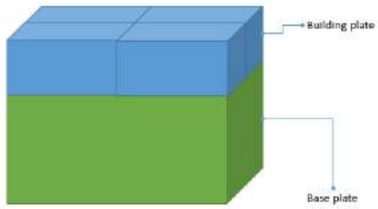


Figure 10.2: Concept to partly solve the nesting challenges

After the additive manufacturing and eventual heat treatment process, the different building plates can be separated from the base plate and used as fixture in the CNC machine.

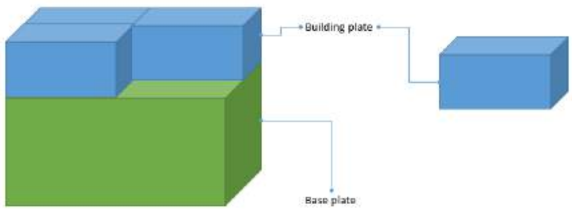


Figure 10.3: Concept to partly solve the nesting challenges with removed building plate

The following positive points are recognized when the system described above would be used:

- Accessibility of the machining tools during the CNC process would improve
- Process planning can be done more efficient due to shorter lead times in the machining operation step

The following negative points are recognized when the system described above would be used:

- The different building plates need to be aligned perfectly with each other. The main reason is the requirement for a completely flat powder layer during the printing process.

- The whole process would be more complex to automate:
  - More work which has to be performed (mounting and unmounting of the different building plates to the base plate).
  - Multiple sizes of building plates for fixturing in the CNC machine.

10.4.4 Heat treatment

For the purpose of both stress relief (lower the risk of warping) and improvement of the mechanical properties heat treatment is done directly after the Selective laser melting process. The part is removed from the residual powder and both the part, its support structures and the base plate are put in the oven for a stress relief process. Because it is the goal to have automatic loading and unloading of the oven where the heat treatment is performed, the main barrier regarding heat treatment will be the use of digital communication between the products and machines in order to make sure every product (or product batch on the same base plate) will get the right heat-treatment. The heat-treatment depends on the material used, the size of the product and the amount of support structures used, as well as the required material characteristics for the part. The central control system will need to sent the required heat treatment parameters to the oven while the oven is able to understand the data language used by the central control system.

10.4.5 Post-machining

After the stress relief process in the oven the part(s) need to be removed from the base plate and support structures have to be taken off. The base plate is usually removed using a band-saw or wire-edm machine. It is a fairly simple process to remove the base plate, completely product independent and quite easily automatable. Removing the support structures is more complex and difficult in general. Nowadays, the support structures are mainly removed by hand and with the use of small tools. Which results in a time and labour extensive process performed by an experienced operator. Possibilities to reduce the time needed for the removal of support structures are listed below:

- CNC machining can be used to remove parts of the support structures. When the original CAD drawing is used to program the CNC machine, it is possible to use the milling tools to remove the support structures in an accurate way. It should be noted that it is impossible to remove all support structures this way, because the part still needs to be fixed in some way inside the CNC machine. Work performed by an operator afterwards will still be required.
- An American start-up claims their machines automate the support removal and surface finish for advanced plastics and metals. The Hybrid Series is a fully automated post-processing machine that will both remove support materials and offer

surface finishing in an integrated system.. They claim that: "Compressed air works as a propellant for suspended solid media, within the Hybrid chamber, to deliver accurate support removal and surface finishing. The Hybrid Series has been designed to accomplish both support removal and surface finishing in one space saving footprint to maximize utilization of production floor space." [83]

10.4.6 Quality control

In metal additive manufactured parts, the most dangerous flaws are related to solidity violations (cracks, as porosity, pore clusters, etc.). Mechanical properties worsen when porosity is seen somewhere in the volume of the part, while local pore-clusters may lead to crack initiation. It is therefore very important that mechanical properties of the parts manufactured can be guaranteed, mostly for certification of the part. Regarding the surface quality there is still a lack of general understanding. Some research [84] argues that surface quality is critical towards fatigue resistance of the part, while others say the effect on the parts life cycle is insignificant [85]. It can be concluded that extensive quality testing of the manufactured parts is needed. New technologies and equipment are required in order to control and manage the quality of the whole manufacturing process. Examples include:

- The accuracy and reproducibility of the shape of the product
- Surface quality
- Eventual formation of micro- and macrocracks

Together with these quality processes, there is also a need for methods of data interpretation and integration in order to efficiently analyse the data generated by quality control processes. For example: the use of meltpool monitoring in the additive manufacturing process generates a lot of data related to the quality of the manufactured parts. These data needs to be analysed not only on part level, but it can also provide usefull information regarding the quality of the machine and its parameters.

10.4.7 Transfers between manufacturing processes

Multiple already existing techniques can be used in order to improve the transfer of products between different process steps during manufacturing. Options include:

- The use of Automated Guided Vehicles (AGV's) to transport parts or parts batches.
- Robot's or Cobot's that perform simple and repetitive tasks during the manufacturing process.

The main difficulties around these processes are the digital integration of all different machines. An example: If the Additive manufacturing machine is finished building the part, and all the residual powder is removed, a signal need to be sent to one of the AGV's to come and pick up the base plate at the right location. All processes need to be interlinked so a system of multiple AGV's and Robots can work efficiently.

10.5 Conclusion

In this chapter the lay-out of an more flexible and adaptable pilot factory is described together with its requirements. The main challenges and barriers for entry are described in more detail. It is clear that there are still multiple serious barriers which need to be overcome in order to set-up a fully working integrated manufacturing plant using additive manufacturing. This integration will be needed in order to certify all manufacturing processes so the parts made can be used in critical environments like aerospace and automotive engineering. It is only with a fully integrated manufacturing floor additive manufacturing can be used to its full potential and will be a seroiuos competitor for more conventional manufacturing methods.

Chapter 11

Conclusions

In order to help the Belgian manufacturing industry with the implementation and integration of metal additive manufacturing, Sirris will set-up a test environment to create a field-lab for the Belgian manufacturing industry where additive manufacturing can be tested and evaluated. As a first step, a lean pilot factory will be developed in order to gain knowledge around the topic. Knowledge should be built up around flexible automation, certification, total cost of ownership etc. It was the goal of this master thesis to map out the state-of-the art of the current hybrid manuacturing systems, generate a general concept of the pilot factory and define its main challenges and possible solutions to overcome the main barriers the manufacturing industry is experiencing with the integration of metal additive manufacturing into the production chain. During the research performed, the following main conclusions were found:

- The main drawback of metal additive manufacturing for end-use products is the lack of surface quality and dimensional accuracy of the part(s) manufactured. This problems can be partly solved by using a smart combination of additive manufactured, and a post-processing machining operation to improve the characteristics of the end-use part.
- Developing a hybrid system which can be implemented across multiple metal AM processes is the key to successfully developing a fast and feasible high precision hybrid process. The focus should be on the additive manufacturing process with the greatest potential regarding industrial usage: a powder bed fusion technique.
- For the additive manufacturing process inside the pilot factory, there is chosen for the Conceptlaser M2 machine because it clearly differentiates itself from the competition on 3 main points: The possibility to include an OPC-UA system which would be benificial for the digital integration of the pilot factory, the possibility to

include an EROWA system in order to physically integrate the pilot factory and the state-of-the-art software packages which are included.

- For the pilot factory there is chosen to put the focus on two main requirements: 'first time right' and 'flexible production'.
- Looking at the digital integration within the pilot factory, the main conclusion drawn is the need for a central steering system which is capable of communicating with all machines in the different manufacturing process steps. This can be solved by using machines which can be steered using the commercially available OPC-UA system.
- Regarding physical integration of the pilot factory, there in chosen for a pallet handling system during subtractive manufacturing process because of the following reasons:
  1. The base plate is already there in the additive manufacturing process and can act as a pallet and as reference point for the machining operation.
  2. The part is fixed to the base plate with its support structures.
  3. There are already commercial systems on the market which add a workholdingsystem to the additive manufacturing base plate.
- During the case study, the main challenges were discovered to be nesting of multiple parts onto one base plate and the accessibility of the machining tool when the base plate is used as fixture in the CNC machine. More, it was found that there were discrepancies between the CAD model and the actual printed part which can not be neglected.
- Clamping of the base plate in the CNC machine was done easily, while the support structures provided enough stability to the part during the machining operation.
- A cost model is developed to calculate the total costs of the combination of additive and subtractive manufacturing. It is found that the main cost drivers in the manufacturing process, are the machine depreciation costs and the operator costs, for both additive as subtractive manufacturing. More, the positive effect of the production speed on the total costs and the use of a nesting technique are proven.
- There is a possible solution for the nesting problem by using multiple building plates on one base plate. So multiple pallets can be used in one building job.

It is clear that there are still multiple serious barriers which need to be overcome in order to set-up a fully working integrated production environment using metal additive manufacturing.

Chapter 12

Recommendations

The following points identify a summary of the future research topics identified in this research:

- A 3D scanner can be used to define where the part is actually located in the CNC machine. This 3D scan can be directly linked to the toolpath generation. This 3D scan can also be linked with the part overgrowth parameter.
- Algorithms can be developed to include the toolpath generation into the topology optimisation when designing a part, this would be beneficial for the accesibility of the critical features during CNC machining. Also, the nesting of multiple parts on one base plate can be optimised keeping the toolpaths of the CNC machining in mind
- Another area of future focus should be the ability to produce thin wall features with appropriate combination of part overgrowth and machining parameters through hybrid manufacturing. The focus here would be to make sure the part stays stable enough to perform the required machining operations.
- The possibility to set-up a digitally integrated pilot factory needs to be proven. This would include the autonomous communication of all machines with each other.
- A meltpool monitoring system can be used as a first step in the quality control process. It would be better if the additive manufacturing machine can adapt itself to the results of the meltpool monitoring, creating a feedback loop. This would also be benificial for the certification of the manufactured parts.
- Research need to be done around the loading and unloading of the AM machine, as well as the automated powder removal after the AM process. These steps are not yet integrated.

Above, the main recommendations towards research projects are given. It is clear that there are still multiple seious barriers which need to be oercome in order to set-up a fully working integrated production environment using metal additive manufacturing.

Bibliography

[1] Terry Wohlers. *Wohlers Report 2016*. Wohlers associates, 2016.

[2] Dr. Richard Wysk DR. Ola Harrysson. From art to finished part, 2016. https://camal.ncsu.edu/wp-content/uploads/2016/08/From-Art-to-Finished-Part3.pdf.

[3] Jung Zhang & Frank Liou. Adaptive slicing for a multi-axis laser aided manufacturing process. *J. Mech. Des 126(2), 254-261*, May 2004.

[4] Conceptlaser. "am factory of tomorrow" opens up a great deal of potential with modular machine configurations, 2016. http://www.concept-laser.de/en/am-factory-of-tomorrow.html.

[5] Ian Gibson & David Rosen & Brent Stucker. *Additive Manufacturing Technologies: 3D printing, Rapid Prototyping, and Direct Digital Manufacturing*. Springer, 2015.

[6] Standard terminology for additive manufacturing technologies, 2015.

[7] Carsten Engel. Selective laser melting versus electron beam melting, 2014. http://www.slideshare.net/carstenengel/selective-laser-melting-versus-electron-beam-melting.

[8] Terry Wohlers. *Wohlers Report 2015*. Wohlers associates, 2015.

[9] Felip Esteve. *A guide to succesful rapid manufacturing*. Smithers Rapra, 2012.

[10] Hod Lipson and Melba Kurman. *Fabricated, the new world of 3D printing*. John Wiley and Sons, Inc., 2013.

[11] Daniel o connor. Mentoring the machines. *tct magazine volume 24 issue 3*, September 2016.

[12] Kaufui V.Wong and Aldo Hernandez. A review of additivemanufacturing. *ISRN Mechanical Engineering Volume 2012*, May 2012.

[13] FORD Motor Company. Building in the automotive sandbox, 2016. https://corporate.ford.com/innovation/building-in-the-automotive-sandbox.html.

[14] Daniel o connor. The car in front of you is 3d printed. *tct magazine volume 24 issue 4*, September 2016.

[15] Mark Cotteleer & Jim Joyce. 3d opportunity, additive manufacturing paths to performance, innovation and growth. *Deloitte Review*, Issue 14 2014.

[16] Stratasys Ltd. Stratasys 3d printing allows automotive manufacturer to reduce assembly tool production costs by up to 90%, 2015. http://investors.stratasys.com/releasedetail.cfm?releaseid=943296.

[17] Mike Titsch. Ge aviation receives award for leap engine fuel nozzle, 2015. http://www.3dprinterworld.com/article/ge-aviation-receives-award-for-leap-engine-fuel-nozzle.

[18] Kenneth Vartanian. Accelerating industrial adoption of metal additive manufacturing technology. *The Minerals, Metals and Materials Society*, January 2016.

[19] J. L. Valles. Additive manufacturing in fp7 and horizon 2020. *Report from the EC Workshop on Additive Manufacturing*, June 2014.

[20] Laura Griffiths. 3d printing manufacturing aids. *tct magazine volume 24 issue 3*, September 2016.

[21] Chris Sulavik & Michael Portney & Thomas Waller. 3d printing and the new shape of industrial manufacturing, 2014. http://www.pwc.com/us/en/industrial-products/assets/3d-printing-next_manufacturing-pwc.pdf.

[22] Christoph Klahn & Bastian Leutenecker & Mirko Meboldt. Design strategies for the process of additive manufacturing. *Procedia CIRP 36, 25th Design Conference Innovative Product Creation*, September 2015.

[23] eHOW. Disadvantages of 3d printers, 2016. http://www.ehow.com/facts_7652991_disadvantages-3d-printers.html.

[24] Dipl.-Ing. (FH) Martin Bilz M. Sc. Generative manufacturing methods: Selective laser melting. *Fraunhofer-Institut Production Systems and Design Technology*, December 2014.

[25] Lukas Lober & Cristoph Hache & Romy Petters & Uta Kuhn & Jurgen Eckert. Comparison of different post processing technologies for slm generated 316l steel parts. *Rapid Prototyping Journal, Vol. 19 Iss 3 pp. 173 - 179*, August 2013.

[26] Mustafa Megahed & Hans-Wilfried Mindt & Narcisse N & Hongzhi Duan & Olivier Desmaison. Metal additive manufacturing process and residual stress modeling. *Integrating Materials and Manufacturing Innovation*, April 2016.

[27] Dirk Herzog & Vanessa Seyda& Eric Wycisk & Claus Emmelmann. Additive manufacturing of metals. *Acta Materialia*, July 2016.

[28] W. J. Sames & F. A. List & S. Pannala & R. R. Dehoff & and S. S. Babu. The metallurgy and processing science of metal additive manufacturing. *International Materials Reviews*, March 2016.

[29] Matthias Markl & Regina Ammer & Ulrich Rude & Carolin Korner. Numerical investigations on hatching process strategies for powder-bed-based additive manufacturing using an electron beam. *Int J Adv Manuf Technol 78:239âĂŞ247*, December 2014.

[30] Dr. Paolo Aversa & Dr. Sebastiano Massaro. Driving innovation in redistributed manufacturing; a feasibility study in the motorsport industry. *3DP-RDM*, December 2016.

[31] Amanda Allison & Robert Scudamore. Additive manufacturing: Strategic research agenda. *AM SRA*, October 2014.

[32] Mary Kathryn Thompson & Giovanni Moroni & Tom Vaneker & Georges Fadel & R. Ian Campbell & Ian Gibson & Alain Bernard & Joachim Schulz & Patricia Graf & Bhrigu Ahuj & Filomeno Martin. Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology*, January 2016.

[33] Thomas Kellner. The faa cleared the first 3d printed part to fly in a commercial jet engine from ge, 2015. http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/.

[34] Samuel H. Huang & Peng Liu & Abhiram Mokasdar & Liang Hou. Additive manufacturing and its societal impact: a literature review. *Int J Adv Manuf Technol*, October 2012.

[35] Geoffrey A. Moore & Regis mcKenna. *Crossing the chasm: Marketing and selling high-tech products to mainstream customers*. Collins Business, 2006.

[36] IMF. Imf datamapper: Nominal gdp, 2017. http://www.imf.org/external/datamapper/NGDPD@WEO/OEMDC/ADVEC/WEOWORLD/NMQ.

[37] Z. Zhu & V. Dhokia & Z. Nassehi & S.T. Newman. A review of hybrid manufacturing processes - state of the art and future perspectives. *International journal of Computer integrated manufacturing*, July 2013.

[38] Bert Lauwers & Fritz Klocke & Andreas Klink & A. Erman Tekkaya & Reimund Neugebauer& Don Mcintosh. Hybrid processes in manufacturing. *CIRP Annals - Manufacturing Technology*, January 2014.

[39] Peters M. & Leyens C. Low cost integration of additive and subtractive processes for hybrid layered manufacturing. *Robotics and Computer-Integrated Manufacturing Volume 26, Issue 5, Pages 490-499*, October 2010.

[40]

[41] Bey Vrancken & Lore Thijs & Jean-Pierre Kruth & Jan Van Humbeeck. Heat treatment of ti6al4v produced by selective laser melting: Microstructure and mechanical properties. *Journal of Alloys and Compounds*, July 2012.

[42] DMG MORI. All in 1: Laser deposition welding & milling -additive manufacturing in milling quality, 2016. http://be-nl.dmgmori.com/products/lasertec/lasertec-additivemanufacturing/lasertec-65-3d.

[43] Guha Manogharan & Richard Wysk & Ola Harrysson& and Ronald Aman. Aims- a metal additive-hybrid manufacturing system: System architecture and attributes. *43rd Proceedings of the North American Manufacturing Research, Volume 1, 2015, Pages 273âĂŞ286*, September 2015.

[44] Frank Liou & K. Slattery & M. Kinsella & J. Newirk. Applications of a hybrid manufacturing process for fabrication of metallic structures. *Rapid Prototyping Journal, Vol. 13 Issue: 4*, May 2007.

[45] Matsuura. Unique one process solution: Laser sintering and milling, 2016. http://www.matsuura.co.jp/english/contents/products/lumex.html.

[46] AMazing. Concept laser once more demonstrates its role as a leading innovator in 3d metal printing, 2016. http://additivemanufacturing.com/2016/11/24/concept-laser-once-more-demonstrates-its-role-as-a-leading-innovator-in-3d-metal

[47] SLM Solutions Group AG. Slm 500/800 solution, 2016. https://www.youtube.com/watch?v=0V9d3M-qQ7k.

[48] Eckart Uhlmanna& Robert Kerstinga& Tiago Borsoi Kleina& Marcio Fernando Cruzb& Anderson Vicente Borillec. Additive manufacturing of titanium alloy for aircraft components. *15th Machining Innovations Conference for Aerospace Industry Procedia CIRP 35 55 âĂŞ 60*, November 2015.

[49] Victor Chastand & Astrid Tezenas & yannick Cadoret & Philippe Quaegebeur & Wilson Maia & Eric Charkaluk. Fatigue characterization of titanium ti-6al-4v samples produced by additive manufacturing. *21st European Conference on Fracture, ECF21, Catania, Italy: Procedia Structural Integrity 2, 3168âĂŞ3176*, June 2016.

[50] BTF Furnaces. Industriele ovens op maat, 2017. http://www.btf.be/nl/.

[51] Dr. Ian Gibson & Dr. David W. Rosen & Dr. Brent Stucker. *Additive Manufacturing Technologies; Rapid prototyping to direct digital manufacturing.* Springer, 2010.

[52] FEHLMANN. Highest productivity for precise 5-axis machining of complex work pieces., 2017. http://www.fehlmann.com/en/products/machining-centres-in-portal-design/versar-825/.

[53] TE Halterman. Industrial gases key to metal additive manufacturing – air products launches website to guide industry, 2015. https://3dprint.com/55526/industrial-gases-am-process/.

[54] Tom Craeghs & Florian Bechmann & Sebastian Berumen & Jean-Pierre Kruth. Feedback control of layerwise laser melting using optical sensors. *Physics Procedia 5*, September 2010.

[55] Manfred Schmid & Gideon Levy. Quality management and estimation of quality costs for additive manufacturing with sls. *Inspire*, October 2010.

[56] N. P. Aleshin & M. V. Grigorev & N. A. Shcipakov & m. A. prilutskii & V. V. Murahov. Applying nondestructive testing to quality control of additive manufactured parts. *Russian Journal of Nondestructive Testing, 2016, Vol. 52, No. 10, pp. 600-609*, May 2016.

[57] Kuka Aktiengesellschaft. Kmr iiwa: autonomous and extremely flexible, 2017. https://www.kuka.com/en-be/products/mobility/mobile-robots/kmr-iiwa.

[58] International Electrotechnical Commission. Protection against electric shock âĂŞ common aspects for installation and equipment, 2016. https://webstore.iec.ch/preview/info_iec61140%7Bed3.0%7Den_d.pdf.

[59] Conceptlaser. M2 cusing metal laser melting system, 2016. http://www.conceptlaserinc.com/wp-content/uploads/2016/05/M2-cusing_1015_US.pdf.

[60] Miriam Schleipen & Syed-Shiraz Gilani & Tino Bischoff & Julius Pfrommer. Opc-ua and industrie 4.0 - enabling technology with high diversity and variability. *49th Conference on Manufacturing systems*, May 2016.

[61] D. Mourtzis & E. Vlachou & N. Milas. Industrial big data as a result of iot adoption in manufacturing. *5th CIRP Global Web Conference Research and innovation for Future Production*, July 2016.

[62] Navid Shariatzadeh & Thomas Lundholm & Lars Lindberg & Gunilla Sivard. Integration of digital factory with smart factory based on internet of things. *26th CIRP Design conference*, April 2016.

[63] Syed Imran Shafiq & gorka Velez & Carlos toro & Cesar Sanin & Edward Szczerbicki. Designing intelligent factory: Conceptual framework and empirical validation. *procedia Computer Science 96*, September 2016.

[64] Li Da Xu & Wu He & Shancang Li. Internet of things in industries: A survey. *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, VOL. 10, NO. 4*, November 2014.

[65] Florian Pauker & Iman Ayatollahi & Burkhard Kittl. Opc ua for machine tending industrial robots. *Institute for Producton Engineering and Laser Technology; Conf. on Advances in Mechanical and Robotics Engineering*, October 2014.

[66] Cornelius Baur & Dominik Wee. ManufacturingâĂŹs next act, 2015. http://www.mckinsey.com/business-functions/operations/our-insights/manufacturings-next-act.

[67] Bjorn Solvang & Gabor Sziebig & Peter Korondi. Multilevel control of flexible manufacturing systems. *Department of Automation and Applied Informatics, Budapest, Hungary*, May 2008.

[68] EFFRA. Factories of the future ppp fof 2020 roadmap, 2012. http://www.effra.eu/attachments/article/335/FoFRoadmap2020_ConsultationDocument_120706_1.pdf.

[69] Stephanie S. Shipp institute for Defense Analyses. Emerging global trends in advanced manufacturing, 2012. https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/ida-p-4603.ashx.

[70] J. Norberto Pires. New challenges for industrial robotic cell programming. *Mechanical engineering department, Faculty of sciences and Technology, University of Coimbra, portugal*, October 2010.

[71] C. Lindemann & U. Jahnke & M. Moi & R. Koch. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. *The University of Paderborn: Direct Manufacturing Research Center (DMRC) and Chair of Computer Application and integration in Design and Planning (C.I.K.)*, August 2012.

[72] A. Gebhart. Generative fertigungsverfaheren: Rapid prototyping - rapid tooling-rapid manufacturing. *Carl hanserVerlag*, December 2007.

[73] Specht G. & Beckmann C. & Amelingmeyer J. F&e-management kompetenziminnovationsmanagement. *Verslag Schaffer-Poeschel*, August 2002.

[74] Hopkinson N & Hague R. J. M. & Dickens p. M. *Rapid Manufacturing. An industrial revolution for the digital age.* john Wiley, 2006.

[75] Eleonora Atzeni & Alessandro Salmi. Economics of additive manufacturing for end-usable metal parts. *International Journal Advanced Manufacturing Technology 62*, February 2012.

[76] Douglas Thomas. Costs, benefits and adoption of additive manufacturing: a supply chain perspective. *International Journal of Advanced Manufacturing Technology*, November 2015.

[77] C. Lindemann & U. Jahnke & M. Moi & R. Koch. Impact and influence factors of additive manufacturing on product lifecycle costs. *The University of Paderborn: Direct Manufacturing Research Center (DMRC) and Chair of Computer Application and integration in Design and Planning (C.I.K.)*, August 2013.

[78] Robert G. Bierley & H.H. Siekmann. *Machining principles and cost control*. McGraw-Hill Book Company, 1964.

[79] Richard A Wysk & Ola L.A. Harrysson Guha Manogharan. Additive manufacturing integrated hybrid manufacturing and subtractive processes: economic model and analysis. *International Journal of Computer Integrated Manufacturing, 29:5, 473-488*, November 2015.

[80] Bill Koenig. 3d printing machine prices forecast to fall, 2016. http://www.sme.org/MEMagazine/Article.aspx?id=8589937976&taxid=1426.

[81] Yicha Zhang & RaviKumar Gupta &Alain Bernard. Two-dimensional placement optimization for multi-parts production in additive manufacturing. *Robotics and Computer-Integrated Manufacturing 38 (2016) 102-117*, April 2016.

[82] Renishaw plc. Renam 500m: Additive manufacturing for industrial applications, 2017. http://www.renishaw.com/en/renam-500m--30939.

[83] Post process. Benefits of postprocess hybrid solutions, 2016. http://postprocess.com/products-hybrid.php.

[84] Kalinina N. E. & Kavats O. A. & Kalinin V.T. Improving technological properties of casting aluminium alloys by modification with nano-dispersive particles. *Aviats.-Kosm. Tekh. Teknol. no 4. pp. 17-20*, September 2010.

[85] Peters M. & Leyens C. Aerospace and space materials. *Oxford: UNESCO*, September 2003.