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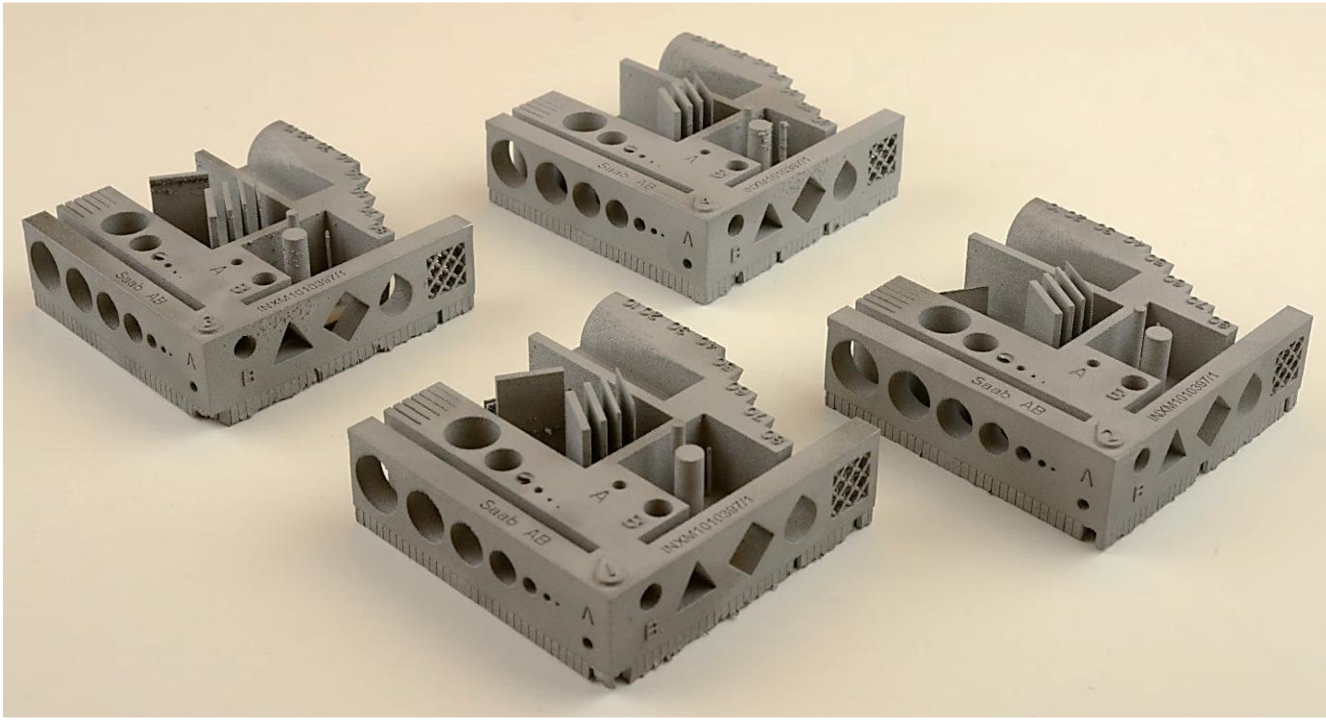

Industrialization of Additive Manufacturing

Development of an Additive Manufacturing Design Guide for Metal Laser Powder Bed Fusion

Master's thesis in Product Development

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Gothenburg, Sweden 2017

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A photo of four aluminum benchmark models can be seen on the front cover. These were manufactured in an EOS M290 machine using the standard machine parameters. More about the models can be read in Chapter 6 *Benchmark model*.

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ABSTRACT

Additive manufacturing (AM) is a relatively new manufacturing method that adds material instead of subtracting it as the traditional manufacturing methods do. The AM technology started with melting plastic and creating structures in three dimensions. However, this master's thesis focuses on the AM technology where metals can be used as material and more specifically the laser powder bed fusion process. More and more companies have found an interest in the possibilities AM provides but there are also limitations that are important to be aware of to fully utilize the potential of the technology.

The thesis was conducted with Saab AB Surveillance and the aim was to find and gather as much knowledge as possible regarding design rules for the laser powder bed AM method with a focus on aluminum. This was done through literature research and interviews that showed there are many general guidelines that apply to all metals. The result was collected in a document with the purpose for designers with limited or no previous knowledge about design for AM to read it and then be able to understand enough about the process to start designing self-supporting parts. To verify the design rules, a benchmark model was designed. The model was manufactured in an EOS M290 machine in aluminum and the result showed that more extreme features can be built than the theory indicated. Based on the results the model was redesigned and a new version was manufactured.

Keywords: Additive manufacturing, 3D-printing, design guidelines, Product Development, DfAM, design for additive manufacturing, powder bed fusion

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The last thanks goes out to everyone we interviewed for taking their time answering our questions and made this thesis possible.

Johan Sönegård
Maria Warholm

Gothenburg, June 2017

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If nothing else is stated the photo is taken by Hans Sjöberg, Research Engineer, Division Production Systems, Department of Product and Production Development, Chalmers University of Technology.

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LIST OF ABBREVIATIONS

AM – Additive Manufacturing

LS – Laser Sintering, sinters or melts the powder in PBF with one or more lasers. (ASTM International, 2013)

SLS – Selective Laser Sintering, using the LS technique but trademarked by 3D Systems Corporation. (ASTM International, 2013)

DMLS – Direct Metal Laser Sintering, a synonym is direct metal laser melting. Just like SLS it uses LS but it is trademarked by EOS GmbH (Electro Optical Systems). (ASTM International, 2013)

SLM – Selective Laser Melting, just like SLS and DMLS it uses LS but trademarked by SLM Solutions. (ASTM International, 2013)

EBM – Electron Beam Melting (an AM method using powder bed with an electron beam to melt the metal powder). Patent by ARCAM.

PBF – Powder Bed Fusion is "an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed." (ASTM International, 2013)

DED – Direct Energy Deposition is "an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited." (ASTM International, 2013)

DfAM – Design for Additive Manufacturing

AfAM – Adapt for Additive Manufacturing

ISO – International Organization for Standardization

ASTM – previously called "American Society for Testing and Materials"

CAD – Computer Aided Design

ETAM – Evaluation and Transformation for Additive Manufacturing

1 INTRODUCTION

It is getting common to use Additive Manufacturing (AM) for rapid prototyping because it is a relatively cheap and quick method to visual ideas through making a physical model. Most people know about the AM machines that use plastic but few know that there are also machines using metals.

AM is the common name for different manufacturing methods that all have one thing in common, namely that material is added rather than subtracted from a workpiece. In the media, it is common to call additive manufacturing for 3D printing. However, they are not synonyms to each other because 3D printing is “fabrication of objects through the deposition of a material using a print head nozzle, or another printer technology” (ISO/ASTM International, 2015). The focus in this project is on a technology called metal powder bed fusion which would not be included in the term 3D printing according to the ISO/ASTM standard. More about different methods can be found in Chapter 1.1.2 *Additive Manufacturing* and Chapter 3 *Frame of reference*. The project’s main focus is on PBF in aluminum but most of the guidelines presented throughout this report can be applied to other metals as well.

Today most designers use CAD-programs to realize their ideas and use as a foundation for the manufacturing documents. The problem is that CAD-programs often enable more design freedom than the manufacturing methods. Even though AM has restrictions it expands the possibilities that the traditional manufacturing methods give. Additive manufacturing is useful for the designers at Saab AB Surveillance when designing and manufacturing complex geometries for their products.

This master’s thesis focuses on what information Saab AB’s designers need when designing a new component that will be manufactured using AM. This information includes what the designer should keep in mind to avoid unnecessary iterations when designing a part for AM; including tolerances, preferred shapes, orientation and how to prepare the part for manufacturing. The result is presented as a handbook, see *Appendix M*. The aim of the handbook is to give designers a tool that will save the company time and money since the risk of having to redesign will be reduced and time-to-market could be shortened.

The people and companies that have been interviewed for this thesis have all been agreeing on that gathering design rules and giving designers the tools and information they need to make informed decisions is worth a lot for their company’s development. The challenge is that many companies have information they do not want to share. At the same time, most of them agree that sharing knowledge would be beneficial since “reinventing the wheel” can be avoided and instead one can continue the work where someone else left off. However, companies do not want to show their competitors what they are researching on. This seems to be a bigger deal in Sweden than abroad where the general view is that AM is just another manufacturing method. An important note is that designing for AM is much more than having guidelines, it takes practice and skill.

1.1 Background

Here more information can be found about the company, Saab AB Surveillance, including what this master's thesis can contribute with and how it is useful for the company. There is also a brief explanation of additive manufacturing and an insight into previous work regarding AM at Saab AB Surveillance. This is to give a background to the research question and the project.

1.1.1 Saab AB Surveillance

"Saab serves the global market with world-leading products, services and solutions from military defence to civil security. With operations on every continent, Saab continuously develops, adapts and improves new technology to meet customers' changing needs." (Saab AB). Saab AB currently has about 14 000 employees and annual sales on 27 billion SEK. Of this, 20 percent is invested in research and development, which includes a contribution to the department of mechanical systems. (Saab AB)

Saab AB Surveillance's department of mechanical systems is working with requirements, design, and verification of the mechanics that is included in the company's products. Their work includes requirement specifications and concept generation of future products to verification of end product. This was the department where the project was conducted.

Since AM is a relatively new manufacturing method there is a general lack of knowledge and know-how in the company. One issue today is that the designers are not aware of the restrictions and possibilities that the new technology brings. One part of this is the lack of knowledge about how AM works. Because of the lack of know-how, there has to be a close collaboration with the manufacturing company, who are the experts on their AM machines. In the future, this collaboration will still be necessary to ensure a good result. After reading this report, especially Appendix M *A Designer's Handbook for Metal Additive Manufacturing*, the designers can do more on their own before needing help from the manufacturer and also avoid designs that are difficult to manufacture. Furthermore, this will aid the person responsible to provide informed decisions early in the design process whether to use AM or one of the traditional manufacturing methods such as casting and milling.

1.1.2 Additive Manufacturing

AM is a manufacturing method that includes many different processes and here is a brief explanation of how some of them work and a more thorough explanation can be found in Chapter 3 *Frame of references*. The two main material categories used with this manufacturing method are polymers and metals. Since this master's thesis focuses on metal there will only be an explanation of the two technologies used for different metal alloys. The two main categories are Powder Bed Fusion (PBF) and Direct Energy Deposition (DED), where PBF is when the machine covers the whole building area with powder and a laser or electron beam melts the metal powder in specific places. The DED can use wire or powder and melts the material as it is deposited, which makes it more suitable for bigger objects or coating. In this master's thesis, the focus will be on PBF technique and laser in particular since it is the most common to use with aluminum powder. The EBM (Electron Beam Melting) technique will also be explained briefly in Chapter 3 *Frame of reference,* together with the main differences between using an electron beam and laser. Many terms emerge with new technologies and AM is not an exception. Several of the terms that are widely used describe the same kind of process because their names are trademarked, see *List of Abbreviations*.

1.1.3 Evaluation and Transformation for Additive Manufacturing (ETAM)

In 2015 Saab AB Surveillance had a master's thesis about developing a process for deciding when something can and should be made with AM and how the redesign process should work. This process is called "Evaluation and Transformation for Additive Manufacturing", ETAM in short, and was a move towards AM as a viable manufacturing process. This process contains two main parts: "Evaluation for AM" and "Transformation for AM". (Hedström Kuosmonen & Olsson, 2015) For a more in-depth explanation see Chapter 3.2 *ETAM*. The handbook in Appendix M can be used as a part of the ETAM process.

1.2 Purpose

The purpose of this master's thesis is to gather information and make a design method for designers and developers to use when developing something that will be manufactured with AM. The design method will contain information on "what to do" and also "what not to do" when developing something with AM in mind. The design method is included in a handbook together with basic information about different types of AM. Some general design guidelines exist but for a designer to fully take advantage of them it needs to be presented in a way that makes them accessible.

The design method will be used by Saab Surveillance hence it will be uploaded to their network for employees to use and should be revised when new discoveries are made.

1.3 Delimitations

The thesis is limited to additive manufacturing in metals, more specifically powder bed fusion AM with LS and EBM. The design method contains some very general guidelines and limitations but in most cases when numbers are involved it is specific for aluminum LS. A benchmark model is designed to find out how well the literature and theoretical values translates in reality. However, it is very specific because it only shows the result from those manufacturing conditions; the result can vary depending on many different parameters, which have not been investigated in detail. Titanium is a more commonly used material in AM because it is an expensive and hard material to process compared to aluminum, which is cheap and easy to process. This means that it is even more important that parts made in aluminum need to have a very advanced geometry and have no other way to be manufactured to be worth the high cost. The economic aspects have not been investigated any further than that.

The thesis is written by students from Mechanical Engineering and is aimed at people with similar educational background and others working with CAD-design with an interest in finding out more about additive manufacturing.

The thesis project resulted in a handbook and report where the handbook's purpose is to be the document that is used daily and the main focus is to fulfill the need for Saab AB

Surveillance. This means decisions are made to make it fulfill their need and may lead to a focus on a specific area in design they are interested in.

1.4 Problem analysis and research questions

Additive manufacturing has already changed how developers work when designing new products but, until recently, mostly in plastics. With the use of AM, manufacturers will be able to produce products with designs that were impossible to manufacture before, such as lattice structures. The use of topology design opens the door for new and lighter products that are as strong as or even stronger than their predecessors.

The research question is:

> *What does a designer need to know to design a part in a CAD-program and send it to the manufacturing company without them having to do any additional work on it?*

The deliverables for the project is a handbook that can be found in *Appendix M* and a benchmark model that is owned by Saab AB and its belonging pamphlet with all its features explained, which can be found in *Appendix N*.

1.5 Ethical, legislative and environmental aspects

To consider the ethical, legislative and environmental aspects of the master's thesis is important because having a thought about these aspects could be helpful when making decisions. By having considered ethical dilemmas it is easier to avoid them if necessary.

1.5.1 Ethical

Saab AB develops security equipment and military organizations are regular customers and could for some be a sensitive subject and an ethical dilemma. However, the world is a dangerous place and there is a need for these kinds of products. The part of Saab where this master's thesis has been conducted develops mechanical parts for radars. The radars developed are used to prevent hostile attacks and are therefore used to keep people safe.

Working at a company dealing with military equipment means that most information is classified on different levels. Some information is on a corporate level with the highest being national security, which means that the thesis will have to be carefully formulated to avoid any need for censorship.

Many interviews have been performed and to make sure that their integrity was kept, they were all asked if their names could be mentioned in the report or if they rather be anonymous. To reduce the risk of misunderstandings and relying on memory all interviewees were asked to approve that the interview was recorded.

1.5.2 Legislative

Additive manufacturing is a technology that is rapidly getting more accessible to the general public, which brings issues with legislation and ethics. Even though the AM machines that the common consumer has is of relatively poor quality and use polymers it is easy to use and can produce things without having to go through the controls set up today for manufacturing companies. As an example, anyone with a machine at home can download a design of a weapon that would only be sold and manufactured under strict control. The legislation has the challenge to keep up with the development to make sure to cover this type of manufacturing.

1.5.3 Environmental

From an environmental standpoint AM with aluminum will lead to less material waste in manufacturing and therefore a more sustainable manufacturing industry. Since it is a manufacturing process that is relatively quick, parts can be produced when they are needed without a long lead time. This is especially beneficial for spare parts because it enables the possibility to repair something that is broken instead of discarding it. This is usually the best option from an environmental perspective. However, a negative aspect of AM is the energy consumption for climate control, some machines need to be pre-heated and lasers require a lot of energy. (Muthu & Savalani, 2016)

2 METHOD

Qualitative research method was chosen for the project since the focus was to study how AM is used in companies and find the common problems they had during the design phase. For this problem, qualitative research methods were best suited, namely literature and interviews (Van Note Chism, Douglas, & Hilson, 2008).

The process followed during the project is shown in *Figure 1*. The problem was identified and a research question was formulated based on the identified problem. Through literature studies and interviews, the problem was further investigated. The solution was then based on the facts found during the investigation and resulted in a handbook, which can be found in Appendix M. The handbook was then sent for feedback and tested by making a so-called benchmark model. The benchmark model was made in aluminum in an EOS M290 with EOS' standard parameters for aluminum (Johansson, 2017).

Figure 1. The research process followed in this project.

2.1 Literature study

At the start of the thesis, everything about AM and 3D-printing was of interest in order to get a deeper understanding of the manufacturing method and its development. There is more information about using polymers as a material since it has been used in AM machines for longer than metal. Even though this thesis is focused on metal AM it is still relevant to learn about polymer AM in order to understand the basics. However, the main literature study was about using AM with metals since the focus is on the design rules for metal AM. The main material used at Saab AB Surveillance is aluminum and metal laser powder bed fusion is the AM process currently used for aluminum parts, which is why laser PBF is of more interest than others.

Metal AM is a relatively new manufacturing method with increasing popularity around the world (EPMA, 2015) but there are still many aspects that need to be studied and researched. The amount of articles and books newly released just before and during the course of the master's thesis show the increasing popularity among researchers and companies. The focus was on finding books and articles that were as up to date as possible to be sure that the thesis is based on currently used technology not outdated ones. Even though it is easy to find newly published literature the technology is developing at a pace that makes it difficult to be sure what the outdated facts are. To find design rules was a challenge since companies often view that sort of information as confidential and an industrial secret.

To find the literature databases were used, such as Chalmers Library's databases and Google Scholar. Some of the keywords used during the search were: Additive manufacturing, 3D-printing, design guidelines, powder bed fusion, joining methods for metals, AlSi10Mg.

2.2 Interviews

In many companies the main knowledge comes with the employees and documentation can be lacking in some areas, therefore interviews were chosen as a complement to literature. Interviewing designers and others working with AM gave an understanding to how they are working with AM today and how much they know about the manufacturing process. Through the interviews, an appreciation of what information is used, missing and misunderstood in development.

The method of interviewing was semi-structured (Van Note Chism, Douglas, & Hilson, 2008) where the main questions were prepared and used in all interviews, see Appendix A and B. However, two of the interviews were less structured when it became clear that either the questions prepared were unsuitable or the interviewee was best to let to talk freely about the topic. The reason to choose the interviews to be semi-structured was the freedom it would give since the interviewees came from a broad spectrum of different backgrounds and were working in different companies in different industries and therefore their knowledge would vary. To get the most out of the interviews it was decided that the best would be to leave room for further questions and to skip questions that were not suitable for that interviewee.

The questions prepared before the interviews were based on the information found during the literature study and what could be interesting to include in a handbook for designers. The handbook is made for people with previous experience regarding design and CAD-programs. Therefore the questions asked during the interviews were not about the fundamental process of CAD-design but directed in a way to find any advice regarding design specifically for additive manufacturing. The questions can be found in Appendix A and B. There are two sets of questions; one for designers and one for manufacturers and the latter one includes both manufacturers of AM machines and AM parts. The focus in the interviews was to find out how they work and how they would like to work, also if they had literature or information that could be used in the thesis.

For the research purpose, it was beneficial to have a diverse group of interviewees. When reaching out to companies there was just one criterion that framed the search: metal powder bed based AM. For a company to be interesting it was important that they worked with this to guarantee that there would be any useful knowledge at the company. A few of the interviewees were found through recommendations, so-called “Snowball sampling” (Van Note Chism, Douglas, & Hilson, 2008). Due to the limited amount of companies working with AM, every interview conducted was a step closer to understanding how companies work. Some of the people interviewed did not work with the laser powder bed fusion but had many years of experience from the AM process which made them good candidates for answering questions about AM and share their experiences.

During the interviews, all participants were informed of the purpose, asked if they agreed to have their names published in the report and if they agreed to have the conversation recorded. As a compliment, notes were taken during the interview as a backup if the voice recorder would stop working or the file would be corrupt. Having the recordings was good to ensure the risk of mishearing or misunderstanding is lowered. After the interviews, the recordings were listened to and more detailed notes were taken, see Appendix C to L, to later comparing the answers and be compiled in Chapter 4 *Interviews*. If possible, the interviews were conducted with two people present to reduce further risk of misunderstanding and also to keep asking questions while the other took notes. The aim was to have all the interviews through a meeting in person but since some of the participants were located outside of the Gothenburg area it was not feasible to have all interviews in person. Instead, they were held through phone on loud speaker or through email with only written replies.

2.3 Benchmark model

Dealing with a new technology that develops as rapidly as AM implies having to adapt to the new findings just as quickly. As mentioned in the Chapter 2.1 *Literature study* there are constantly new designs manufactured without a problem that previously was impossible. To test the findings from literature and interviews, a benchmark model was designed where all the features mentioned in the final handbook in Appendix M were tested. The first design was sent to the manufacturing company, Lasertech LSH AB, for feedback and from the input a second version was developed and manufactured in an EOS M290 machine in aluminum with its standard configuration. After seeing the result it was decided to make a third version where some features were changed and some added. For instance, a thread was added in one of the vertical holes after input from mechanical designers at Saab AB Surveillance and a support structure was changed to lattice structure.

Apart from being able to test the theoretical values, it is also valuable to be able to see the difference and how the surface and the shape gradually worsen the steeper the overhang or bigger the hole. The aim of this test is to show the features but also to show how it looks when it does not work. The purpose of the handbook is to reduce the number of iterations and the amount of feedback on basic features needed from manufacturers. Having the benchmark model as a test is therefore very valuable.

2.4 Feedback

Feedback has been an important part of the thesis, especially for the handbook. The feedback allows the intended users to give their opinion on whether it is understandable or not. Since Saab is a company dealing with highly confidential information they take great caution to what documents leave the building, both physically and electronically. The issue with confidentiality made the choice limited to whom the handbook could be sent. Hence the handbook had feedback from people associated with Saab, either mechanical designers working at the company or students doing their master's thesis there.

3 FRAME OF REFERENCES

To get a better understanding of the report, this chapter presents the theory behind some important aspects. First, the technology behind additive manufacturing is presented, then the result from the interviews with all the important information that was discovered from them. Lastly, there is an explanation of the ETAM (Hedström Kuosmonen & Olsson, 2015) process, which is a process for evaluation and transformation for AM.

3.1 Additive manufacturing

Additive manufacturing (AM) is a manufacturing process where parts are made by applying many layers of a material. Compared to other types of manufacturing processes where material often is removed, for example, milling. Unfortunately, parts produced with AM are more likely to contain some internal porosity but the mechanical properties can be better than casted even though they are not as good as wrought parts. As of today, there are many alloys available but in general, AM is limited to weldable metals. (EPMA, 2015)

In the industry, AM is most commonly used for prototypes and illustrating concepts. However, metal AM allows greater possibilities to produce complex parts with the material properties of a metal. This allows for a shift towards using AM in batch production in different types of metals. Additive Manufacturing is not suitable for simple geometries since there are cheaper ways to produce them; therefore AM is not the most optimal choice when mass producing such geometries (ISO/ASTM International, 2016). The technology is still quite new and developing continuously to make the process more efficient and cost effective. The potential of making metal structures with AM is becoming more and more interesting for companies where the traditional manufacturing processes prevent them from making complex, lighter and more efficient products. This means that the AM technology allows companies to design products for its function with the bare necessities, making them lightweight and go towards zero waste during manufacturing.

As AM is getting more and more efficient, cheaper and accurate, production increases. The global manufacturing was worth 10.5 trillion dollars in 2011 and estimated to rise to 15.9 trillion dollars in 2025, an increase of about 50%. Of that, the global manufacturing for AM was worth 1.7 billion dollars in 2011 and is estimated to be worth over 10 billion dollars in 2025, a rise of almost 600%. Even though these numbers are only predictions it can give an idea of the potential for the market. The companies that invest in the technology now will have great benefits over their competitors in the future. (Muthu & Savalani, 2016)

3.1.1 The general process

The general process that a part designed for AM goes through is the 8 steps according to Gibson, Rosen and Stucker (2015):

1. CAD
2. file format conversion
3. transfer file to AM-machine
4. machine setup
5. build
6. remove
7. post-process
8. application

In the first step the design is created in a CAD software and will then have to be converted to a file format that the AM machine can read, which often is STL but other formats are being developed such as AMF. Using the STL format can cause problems such as unit errors because the format is unit-less (ISO/ASTM International, 2016). Next step involves transferring to the machine's software and make sure the model is the correct size, orientation, and position. The fourth step is choosing the settings in the machine related to the build process such as layer thickness and energy source. Depending on the machine manufacturer, the machine can have all parameters open or they are fixed for every material. Once the building process starts there is rarely any need for supervision. The sixth step; the removal of the part from the machine can take time due to the removal of excess material, with potential health danger, and to cool down from the high temperatures that have been used. In the remove-step, all the support structure will be removed too. In the next step is where the post-processing is performed such as painting, milling, drilling, threading and heat treatment. The last step called "application" is where the authors mention the importance of making sure the properties of the final product meet the requirements. One thing to keep in mind is the mechanical properties that usually are anisotropic (differ depending on the direction). (Gibson, Rosen, & Stucker, 2015)

Additive Manufacturing includes many different technologies and in *Table 1* there is a list of some of them that use metal as a material. The general process described above will differ depending on the AM technology used. In *Figure 2* a schematic model of how different AM technologies relate to each other is shown.

Table 1. List of different AM technologies.

Word	Explanation
Binder jetting	Process where a liquid bonding agent is used to join the powder (ASTM International, 2013)
Material jetting	Process where the material is selectively dropped onto a surface to make a part (ASTM International, 2013)
Directed energy deposition (DED)	Process where material is heated and melted the same time it is applied onto a surface (ASTM International, 2013)
Material extrusion	Process where material is applied through a nozzle or orifice, traditional plastic 3D-printing (ASTM International, 2013)
Sheet lamination	A process where sheet metal is cut and fused in layers to form a structure. (ASTM International, 2013)
Powder bed fusion	A material is added in the form of a fine powder in layers and a laser or electron beam melts or heats up selective parts of it. (ASTM International, 2013)

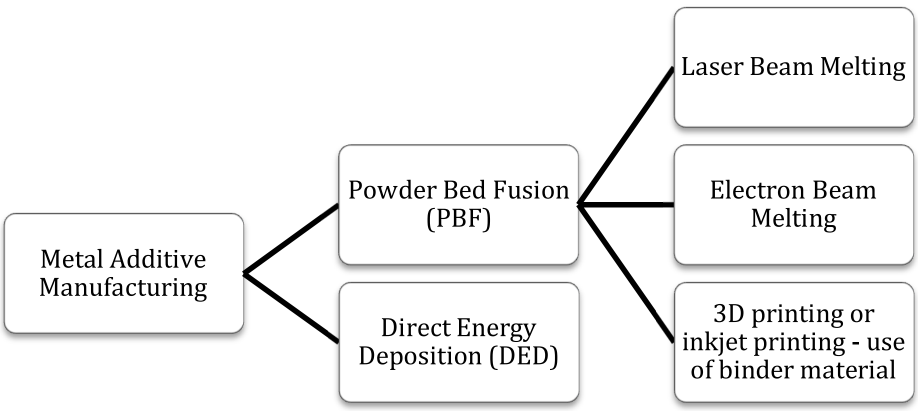

Figure 2. A schematic model of different AM technologies. (EPMA, 2015)

3.1.2 Metal powder bed fusion

Since this thesis focus is on the laser powder bed fusion process that will be further explained first. The laser beam melting process follow the general process described above. The machine has a build chamber that is closed during the whole building process because it contains a protective inert gas to avoid the powder from oxidizing. After the model has been transferred to the machine and the setup is done, a build platform is placed inside the chamber onto which the part or parts will be built. The machine only uses one material which means that any support structure will be made out of the same material as the part. Everything that is built will be attached to the build platform and therefore support structures are placed between the build platform and the bottom of the part, which also function as heat transfer.

First, the powder feeder adds a layer of powder, usually between 20 and 100 µm (EPMA, 2015), the recoater makes sure the layer is even and the laser beam melts selected parts that are needed to form the final shape. The platform is then lowered and a new layer of powder is added and the laser beam melts more powder. The final height of the part determines the number of layers and the higher it is the longer the whole process takes. All the parts used during the process can be seen in *Figure 3*.

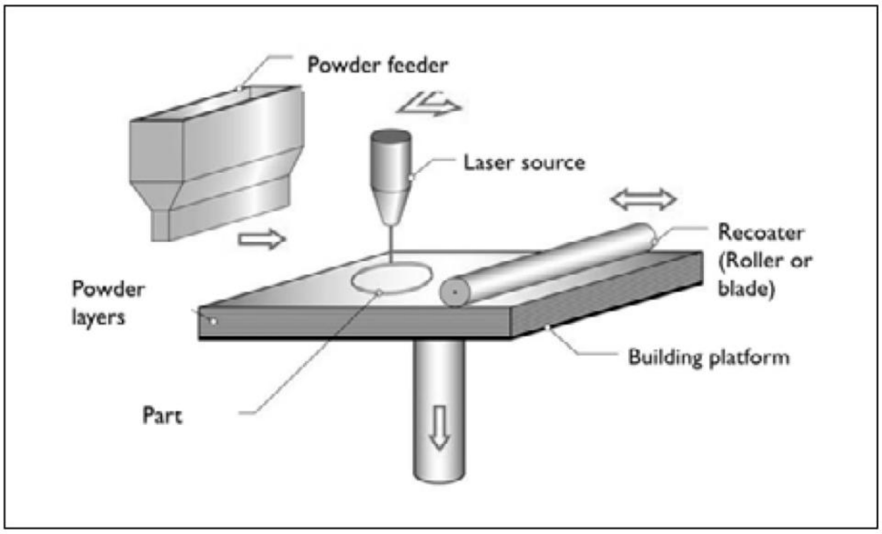

Figure 3. Showing how the LS AM technology works (Courtesy of EPMA).

Another way to melt the material is by using an electron beam instead of the laser. There are a few differences between the laser melting and electron melting technologies, which are listed in *Table 2*. Apart from the energy source, the atmosphere is a vacuum in the EBM machine and it is a warm process which means the powder is sintered before the electron beam melts the powder. The advantage with preheated powder is that the difference in temperature between where the electron beam hits and the surrounding powder is smaller and therefore the microstructure is more homogenous with less porosity. However, the disadvantage is that the heated powder is harder to remove.

Arcam is the company who currently owns the patent on the EBM technique and they have decided to focus on few materials, to begin with (Hakim, 2017). This was also a reason why the focus in this report is the laser technology. As mentioned before Saab AB Surveillance main interest is aluminum and it is not one of the materials that Arcam has chosen to focus on.

Table 2. Showing the difference in some aspects between EBM and LS. (Gibson, Rosen, & Stucker, 2015, p. 137)

Characteristic	Electron beam melting	Metal laser sintering
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder preheating	Use electron beam	Use infrared or resistive heaters
Scan speeds	Very fast, magnetically driven	Limited by galvanometer inertia
Energy cost	Moderate	High
Surface finish	Moderate or poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals, ceramics
Powder particle size	Medium	Fine

3.2 Evaluation and Transformation for Additive Manufacturing (ETAM)

ETAM is divided into three different blocks and is made to evaluate if a component should be manufactured with an AM method, see *Figure 4*. Block A contains aspects regarding if AM is the right focus for the organization and if it is the best strategy. Here the company needs to evaluate the benefits and the drawbacks of making something with AM. Block B focuses on what the company has to offer when it comes to structure, workforce, and experience, can they do it or is it necessary to hire others to do it for them.

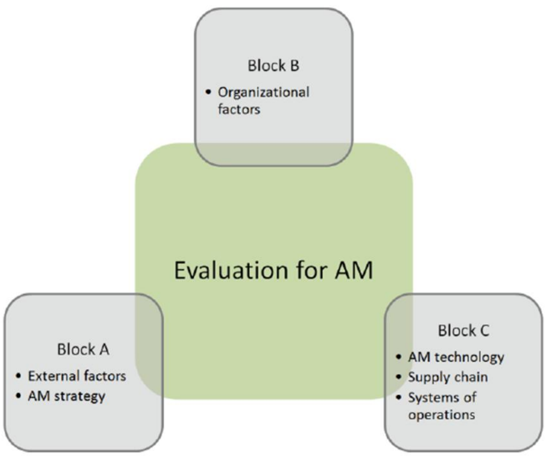

Figure 4. An overview of the ETAM process where the evaluation is the first step.

Block C "includes investigating the AM technology, AM supply chain, and systems of operations" (Hedström Kuosmonen & Olsson, 2015) and is also called "Transformation for AM". It is a step-by-step procedure for redesigning or designing something that will be produced for AM. The processes can be seen in *Figure 5*. It contains three different blocks with a specific focus in the development phase. The first block, C1, is divided in two: product and production analysis and is there to make sure that the list of requirements and production methods is checked before going into the design phase, C2.

C2 is the design phase where the new component is redesigned and tested/checked towards the requirements list. When the final design is set the next step, C3, is the “plan for manufacturing” and it is now the decision is made for how the component should be placed and produced in the AM machine. Material and type of AM are decided in the earlier part of development but here in a later stage, the preprocessing is finalized including placement, support structure and conversion to compatible file formats, such as STL or AMF.

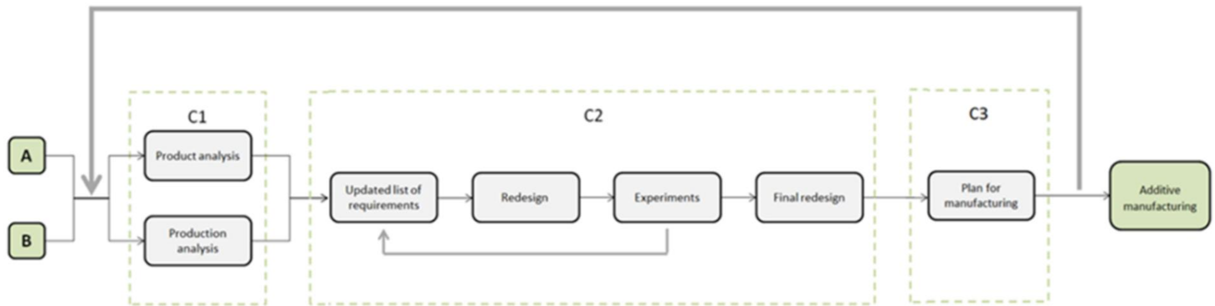

Figure 5. The process of block C.

4 INTERVIEWS

As the interviews were made in a semi-structured way some people talked more about one thing than others and new questions came up as the interview went on. This makes it somewhat hard to present the findings in its entirety in a comprehensive way. All the interviewees are listed in the appendix (see Appendix C through L) with their individual answer on every question and in this chapter, a summary will be presented. The questions with the most relevant answers to the handbook will be summarized here, regardless if they were answers from a single person or by several.

The list of interviewees is found below in alphabetical order by surname.

- Klas Boivie, a senior scientist within AM, working at Sintef AF in Norway. He is also working on developing standards for AM, in particular, terminology in the standard ISO/ASTM 52900.
- Olaf Diegel, Professor in product development at Lund University, has been working with AM for 10-15 years and is researching in AM but mainly with plastics but has produced components in metal.
- Anders Haevaker and Nicklas Johansson, working at Siemens as mechanical designers and have been working with AM for two to six years.
- Ali Hakim, as an application engineer at Arcam he is working with both the design of products and the technical parameters in the machine.
- Sebastian Hällgren, an industrial doctoral student at Örebro University with employment at Saab Dynamics. He is doing research on design for AM.
- Karolina Johansson, working at Lasertech LSH AB with two AM machines for metal powder and produce parts for customers.
- Torbjörn Larsson and Martin Ödlund, working with the strategy for AM at Volvo Cars.
- Dragan Matekalo, AM Technician at Siemens, responsible for the design being possible to manufacture, adding support structure and prepare the AM machine with the right parameters.
- Marc Saunders, director global solution centers at Renishaw. The centers' purpose is to help customers to develop an industrial process for AM and discover what the technology has to offer.
- Per Viklund, a mechanical designer at Sandvik who has been working with AM for 1.5 years.
- Fabian Wennergren, a mechanical designer working as a consultant at Saab AB Surveillance and has been working with AM for about two years.
- A person who wish to be anonymous with name, company and educational background.

4.1 Designers

This sub-chapter will go through the answers made by people working with the design of AM-parts, see Appendix C to I. Many interviewees did not only work with design, some worked with the setup of the support structure and orientation and some did both. This means that the people interviewed did not always work with the same things but what they all have in common is that they at some level made changes to a design before sending it to a manufacturer.

4.1.1 General

A majority of the interviewees have a background in mechanical engineering with different levels of expertise. The amount of time the interviewees have spent with AM is more varied; everything from 1 year to 15 years but the most common answer is around 2 years of experience.

4.1.2 The work today

As the thesis will result in a handbook or tool that will function as a support for designers and developers it was natural to begin an interview with asking about what kind of supports, if any, people use today. No person was the other one alike and everyone had their own combination of literature and processes. The majority of the interviewees mentioned how important it is with past experience from projects and that the only way to really become good at AM is to work with it.

As the interviews went on it became clear that everyone had different levels of knowledge about AM as a process and why some things are more crucial than others. The people with a good holistic understanding of how AM works seemed to be better at predicting problems in their design and why some things work and others do not. The reason for this can probably be linked to how well the communication work between designer and manufacturer. If there is a good collaboration the designer often gets feedback on the design. For those who only send parts for print and only see the result without knowing how it was oriented and how much supports were used it will be harder to learn how to improve for future parts.

Insufficient amount of courses and literature can be one reason why there is such a big difference in knowledge about AM and the surrounding processes. The knowledge a designer have seems to be connected to personal interests in learning about AM, how much internal courses and literature a company has. The same goes for design guidelines and documents they can use in their work as some interviewees had nothing, some had literature and the rest had company defined courses, literature and guidelines. Literature is not enough, experience and practice are needed too, and that is something almost everyone mentions during their interview. That experience matters can also be seen in their answers about rules of thumb they follow. Some rules are mentioned more than others, for example, the importance of radiuses, angles, and holes, but there is often one or two unique things they bring up. However, the answers ranged from placement on the build platform, shrinkage during print and post-processes. With other words: the advice received cover every stage of the printing process.

As stated earlier there are some areas in AM that lack data or are only explained briefly. A good example of this is how one should split parts that are too big for the build volume in the machine. The literature often only describes that it needs to be split but not really how. It was clear that the majority of all the people interviewed had never worked, nor had the need, to split something into smaller pieces. There were few who had but the most common answer was that if something is too big for the print it will be too expensive to print. However, one advice was to extract the functions that need to be printed and then manufacture one part with another method. The cost, time and work that need to be put into joining two pieces are usually not worth it (ISO/ASTM International, 2016).

Before sending a model to print the preprocessing with placement and support structures need to be done by someone at the company or manufacturer. A majority of interviewees describes how this is seldom done by the designer, instead, an AM-technician either in-house or at the manufacturer, is responsible for it. The reason for this differs but the general answers are often that companies want to keep designers doing what they do best. This works well most of the time as long as the communication between designers and AM-technicians is good and/or has a well-defined process on what needs to be defined and included with the model.

Working with the design and understanding the process is important but knowing what material is going to used is also important. There are not too many materials to choose from when using powder bed fusion as of yet but the decision will affect the print in more ways than load and fatigue. The most commonly used materials among the interviewees where Inconel and steel.

In general, the value is something that often comes up when talking about AM because the value in being able to manufacture advanced geometries needs to weigh up the higher cost. There is a reason why the two main industries that use AM today is aerospace and medical. AM is best suitable for small batches or for very small parts so a print can contain multiple parts. For more industries to start using AM the cost for each printed part needs to be lower or the knowledge about how to fully optimize the process needs to increase.

4.1.3 The work tomorrow

From the interviews, a lot of things came up on what they would like to have to ease their work. Firstly, raise the level of knowledge about the different processes in AM, not only for the people working with it but also people at the same company that in some ways come in contact with AM. The reason for including more people into how the process work is not only to spread the knowledge but also to keep the expectations of the process as realistic as possible. Due to lack of knowledge, many believe anything can be made with AM when the case is that there are a lot of limitations too. Secondly, designers mention design guidelines to have as a support when they come in contact with a new geometry they do not know how to handle.

Furthermore, regarding software, many talked about how the CAD programs used today are not optimized for AM and more advanced geometries and having better support included in the programs would be of great help. Lattice structures are a good example of a geometry that is commonly used in association with AM but not many CAD-programs have good tools for generating these types of structures. Software that is specifically made for preprocessing and generating support structure has these types of tools but this means that a big part of the construction is out of the designer’s hands. Better file-formats or conversions would also help when sending files between designer, AM-technician, and manufacturer. This is because of the loss of information when converting files from formats like STP or PRT to STL. The preferred solution is that the manufacturer generates the STL-file themselves to make sure that settings such as the resolution are good enough. However, a new file-format is wished for, one that works better than STL which is the standard today.

Two of the interview questions, “How do you think it will be?” and “How do you think it should be like?”, are similar because some people, when reflecting on how they think it will be, does not mean that they want it to be like that. They might see the industry going one way but want it to go in another.

The interviewees have a lot of different visions on how they think the future of AM will be. The general vision is that AM will be a part of more industries than aerospace and that more people will work with it. The reason why they think AM will become bigger in more industries is that better machines or even hybrid machines, that can print in more materials than one and automate some part of the post-process, will lower the cost for each part printed. Aside from having more people working with AM the tools and software will probably be better as well, specifically software that makes it easier to design for AM and can simulate the printing process.

When asking how the interviewees want the industry to look in the future is quite similar to how they think it is going to look. They want more industries to be able to use the technology, the cost of printing to go down and see more hybrid machines. Another thing is that people hope that the knowledge, work, and expertise will be kept and not outsourced to low-income countries.

4.1.4 The manufacturing company

As with any type of work that connects or affects more than one person, communication is vital for a successful result. Only about half of the interviewees said that they are working closely or have a good communication with the ones responsible for the manufacturing. The other half had little or close to no communication with the ones responsible for the AM machines and that this affects the quality and the knowledge of how to make the next product better. The range of what the manufacturers want from the designer is almost as varied as the companies. Some companies only want an STL-file, some have a long list of things they want to have attached to the model and others are somewhere in between.

4.2 The manufacturers

This chapter will go through the answers made by people working with the manufacturing of AM-parts, see Appendix J and K. Of the two people included in this category one works at a contract manufacturing company, producing parts with AM, and the other works at Arcam, a company making EBM-machines. However, he works closely with customers owning Arcam’s machines and has, therefore, an understanding of what they are looking for and how they work.

4.2.1 General

As of today, not one of the interviewees had any guidelines to give to designers to help them in their work but could give them tips on some things like support structure and radiuses. One also added that they often work closely with their customers and have continuous meetings during the design process. Both of the interviewees claimed that they have a good understanding of the strength of a printed part compared to a traditionally made part. The same thing goes for the machines which they have a good understanding of how they work and what they can do. When it comes to testing and quality assurance there are no standards to follow so it is up to the customers to make that decision.

One aspect that makes designers hesitant to use AM is the material properties have too many unknowns to consider it as safe as when using another process. Casting and machining have a big amount of data backing the processes and people have a good understanding of how a part will react to a specific load or stress. When talking to manufacturers they say that they trust the machines and that the parts will live up to the set properties set by the machines. Because of this faith, the manufacturers did not usually do any testing on the parts unless the customer specifically asked for it. This can be seen as both good and bad. It is good that manufacturers trust the process and that companies that are interested should do that too. On the other side having too much trust in something can lead to unforeseen problems because it should still be considered new and even if it is good there are still a lot of data and tests that need to be done to fully compare it to the other processes. It is good that manufacturers trust the process but a testing standard would be beneficial to make sure that the quality is kept and so that defective parts and machines are found and dealt with.

4.2.2 The process

Before a part can be printed a couple of things needs to be defined by the people who want to have the part made. These were categorized into two groups: “Before they have the CAD-file” and “After they have the CAD-file”. As only one of the companies (Lasertech) manufacture parts answers were received only from one of the interviewees. In the first category, questions were asked to find out what information they need from the customers to ensure they will deliver what the customer ordered. The answer was that apart from the CAD-model itself they need to know the material, important surfaces and other functions of the part so they can make a decision on how to position the part in the machine. Also to give feedback to the customer if there can be improvements or if there are features that will fail during the building process. The best result comes from when the designer and manufacturer work together on how the resulting part will be printed. If this is not possible the designer needs to tell the manufacturer if one orientation is preferred over another.

Secondly, questions were asked about how they work with the data and model they receive from their customer to successfully print it. Before printing they make simulations of the part in different programs to be able to detect what might go wrong during the building process. Most problems come from the fact that not many parts are designed nor optimized for AM, which results in more support structure. More support structure results in more post-processing, longer manufacturing time and higher cost.

5 A DESIGNER'S HANDBOOK FOR METAL ADDITIVE MANUFACTURING

The result of the project is a designer's handbook that can be found in Appendix M and in this chapter, an explanation can be found of why the different parts are in it. The structure of the chapter follows the same as the structure of the handbook. It starts with an introduction where the background, function, and content of the document are presented.

The thesis project started with the research question:

> *What does a designer need to know to design a part in a CAD-program and send it to the manufacturing company without them having to do any additional work on it?*

At the start of every new product, there need to be people who know how the manufacturing processes work and their strengths and weaknesses. This is to ensure that the right type of manufacturing method is used for the type of product that is being developed. The choice of manufacturing method impacts the product more than just in speed and cost for each part produced, it also affects the design.

When a designer sits down and starts designing a part in any type of CAD-program he or she needs to know how that specific part is going to be made. There are big differences in how different parts need to be designed depending on the chosen manufacturing process. This transpires through the entire design process because there need to be different types of pre- and post-processes for every part. If the designer does not understand the limitations of a manufacturing process, problems might occur during production. The earlier a problem is discovered the easier and cheaper it is to fix. Not understanding the manufacturing process can also slow down the development of a product because it means more iteration before the design is producible.

By studying how AM works with all its strengths, weaknesses, limitations and opportunities some guidelines can be created, summarized and made into a handbook for designers and developers to use in their work. By making this handbook people can get a quick understanding of the possibilities. Most rules have its exceptions, which mean each type of AM needs to be studied individually and with each different type of materials. The handbook needs to be made in a way to allow people to keep adding to it continuously when more information is gained.

A base for the handbook has been made where general rules are collected and presented in a way for people to easily understand how to think when working with AM. Overall, the rules and guidelines are general but in some cases, specifics are presented. However, as previously mentioned this should be a document that more companies than Saab AB Surveillance can use, which is also a reason to leave room for adding information.

5.1 What is additive manufacturing

The first chapter contains four parts; *terminology*, *how it works*, *software* and *strengths and weaknesses*. The purpose of this part of the handbook is to give an understanding of what AM is and how to work with it. By reading the first chapter it should be clear that there is a difference between AM with metals and plastics, which is the first type of AM most people encounter.

The terminology is explained early in the document for two reasons. The first is to more easily understand the content and the second is that a majority of the interviewees commented on how many people they meet say one thing when they mean another. The chapter contains a list of terminology used in the document and the most misused and misunderstood terms used when people talk about AM.

Next is the description of the printing process which here is described in general terms with two functions. The first is for people to understand how the printing process works and the second one is so they can create and imagine it while reading the rest of the handbook.

The third part is called *software* and is there for people to better understand what types of processes and programs a model goes through before it is printed. This part is especially important for people who only work with design and outsource the support structure generation and placement. Examples of different types of programs are also good so people and companies have some things to compare with. The reason to put this after *how it works* is to give the reader a chance to understand the necessity of having a CAD-part going through all the steps in the pre-print process.

Lastly, *strengths and weaknesses* are explored because one of the main reasons to read the handbook is to find out whether AM is suitable for their product. If any of the weaknesses are a problem for the part that is going to be designed this manufacturing method will have to be excluded (Bandyopadhyay, Gualtieri, & Bose, 2016).

5.2 What to know before designing

This chapter is largely a collection of questions that needs to be asked and hopefully answered before starting to work with a new component that will be printed. The questions are a result from the literature study (Muthu & Savalani, 2016) and the interviews and the reason for why both designers and manufacturers were interviewed. The answers from these questions will in some way alter how the component will be made and can be used as a base for when the product specification is to be set. Like every type of process alterations on the component should be done as early as possible otherwise a lot of work might have to be redone.

The questions are divided into three different areas: design for function, design for manufacturing and design for post-processing. “Design for function” contains questions a project leader, company or customer is best suited to answer or to consider. “Design for manufacturing and post-processing” is more aimed towards manufacturers, which sometimes can be an external part of the company in charge of design.

The questions listed in this chapter have many different functions and are meant to be asked to different people, which will have to be judged from case to case. Some questions are there for the designer to understand the limitations in things like volume, material, tolerances or what kind of freedom they have with the design. Some questions are there to make people rethink some aspects one more time, such as features and material choices that might have been made based on another manufacturing method.

Every question has a reason for being there and this is stated next to the question. There are many reasons for why this is good: the person asking the question can more easily understand why some things need to be clear from the beginning. For a first time user, it is difficult to come up with many of the questions and even for someone who has worked with AM before it takes time and experience to keep track of all aspects. If someone would decline to answer the questions the reason why it is there can be a help to argue for its importance. In addition to this many reasons have “notes” and/or chapters attached which contains examples, exceptions to the statement or links to other chapters in the document.

5.3 Design rules and guidelines

It is possible to break down what to aim for when designing but because it is guidelines and not rules there will be many cases where “it depends” on different factors. The existing guidelines are often focusing on one specific material which makes it easier to specify what works and what does not. To give people a good base for future knowledge to be built upon, rules that are valid in most situations are presented together with a better understanding of the process. This document should help people avoiding corruptions in their print and to focus on design for function.

Most rules consist of a presentation of a problem and then describing how to avoid it or to design around it. The order in how the different rules are presented in the document is based on a combination of importance, understanding and follow up. The most important parts are presented early in each chapter and then go into details later. This is not always the case because sometimes things are connected to each other and if separated, the flow of information would start to feel inconsistent.

The order of the chapters is based on what designers need to base a design on and later what they hopefully can avoid through smart design. The chapters about orientation, layers and splitting parts are things one need to base the design on. This means that as the model takes shape some things can more easily be changed than others. For example changing the orientation will probably result in a large amount of work because all the angles and shapes need to be revised. “Support structures” could also be included here but “placement and orientation” touch upon this a bit and it would be confusing to have the last phase of the process (adding support structure) earlier in the design rules and guidelines’ chapter.

The resulting chapter contains recommendations regarding features that designers hopefully can design around or more easily change without having to put too much extra work.

5.3.1 Placement and orientation

The orientation of the part is repeatedly one of the most crucial parts when optimizing for AM and also the first thing to make a decision about, why it is natural that it comes first. The orientation of the design will affect everything from mechanical properties to cost and if not fully analyzed before printing many things regarding the design might need to be changed.

Deciding upon how the print should be executed at an early stage can be difficult, especially when designing something completely new. Therefore, orientation must always be kept in mind when making changes.

5.3.2 Layers

In the chapter about layers, it is mentioned that the layer thickness should be chosen after considering cost, time and quality. Thicker layers mean faster and cheaper product but the surface quality and the tolerances are worse. The reasoning behind this chapter is that if there is a choice between different thicknesses one should carefully consider all aspects around it and what it may affect. Even if it may sound like the layer thicknesses are small (often between 30 and 100 µm) the effects can be crucial for the tolerances. However, the experience with the benchmark model, see Chapter 6, shows that it is not always possible to change the parameters on the machine.

5.3.3 Split parts

Today many of the parts produced with AM are relatively small, mainly because of the cost aspect and that they are easier to mass-produce with the limited size of the AM-machines. Typically a build platform in an AM machine is about 250 mm squared. When it comes to making bigger parts that need to use AM for its capability of making complex geometries not much has been done to clarify how one should do it with the best outcome. Splitting parts is more common with polymers, compared to metals, and it is problematic but can often be fixed with designing some kind of connection to align the parts and then use glue to keep them in place (Diegel, 2017). Plastic components are rarely made to withstand large amounts of stress and fatigue compared to metals but instead used for prototypes. Metallic components often come with high requirements on strength and fatigue but the fundamental idea with connections is the same as for plastic.

However, if a part with a more advanced interior geometry needs to be split welding is usually the better option compared to using rivets or screw joints. If the interior geometry has a specific function like keeping air or fluids separated it is especially important with a tight seal, see *Figure 6*.

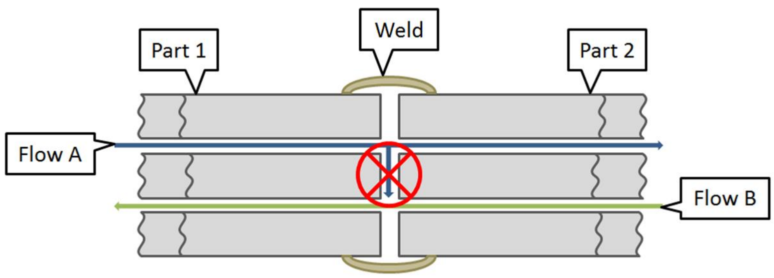

Figure 6. Illustration of why advanced geometries can be hard to join. Flow A and B should not mix but if not joined correctly they might leak into each other.

Another problem with joining two parts produced with AM is that the surface of the parts is so uneven that if not considered when starting the joining process problems may occur. In the ISO/ASTM standard 52910.2 in Chapter 5.3.7, there is a note about how splitting parts "may not be technically or economically feasible" (ISO/ASTM International, 2016).

5.3.4 Volume

AM is very much like casting when it comes to stress buildup so many of the rules when designing for casting can be used here. Aside from trying to avoid thick sections in geometry, AM gives designers the ability to make hollow constructions to keep weight at a minimum and if strength is an important aspect, lattice structures can make parts both lightweight and strong. These aspects are one of the reasons why companies are interested in this technology. In *Figure 7* an example of a lattice structure is shown. The manufacturer did not want to print the square hole without support structure and then it was decided that a lattice structure would be the best option.

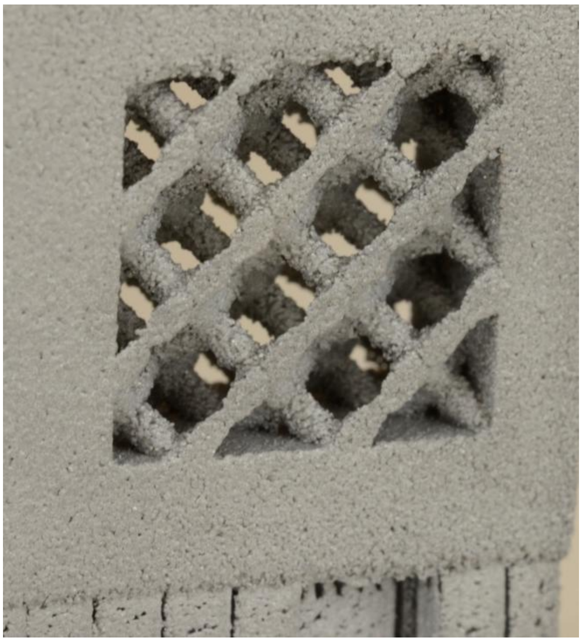

Figure 7. An example of a lattice support structure.

5.3.5 Powder removal

When a model has been printed the first thing to do is to remove all the excess powder that has not been melted or sintered. This is usually done with brushes, abrasive blasting, and tools that use compressed air. The powder is kept in a sealed container to protect the operator. The powder is very fine and is unhealthy to inhale.

Because of how the printing process works with the combined fact that designers can make hollow structures, the powder can be trapped within a model if no gaps or holes are present. When designers make cavities or hollow structures it is important to make sure some holes are implemented in the design or drilled in post-process but it is then an added cost (Hedström Kuosmonen & Olsson, 2015). The powder can in some cases be left inside the model but this adds unnecessary weight to it.

From an environmental point of view, this excess powder can be reused and is the reason why AM, if used correctly, can be considered as a zero waste manufacturing process.

5.3.6 Corners

One problem with additive manufacturing is that the way the technology works it creates stress in the component during the manufacturing process. Especially all right angles have a high risk of cracking and one way to prevent this is to round off the inner corners (Johansson, 2017). It is important to keep in mind that the AM machine will mimic the CAD part exactly which means that all small details are important.

5.3.7 Walls

This chapter in the handbook is very short but with the potential of being expanded. Here a lot of data can be added as the person/company use the guidelines and learn more about machines, materials, and geometries. The main issue with walls and the dimensions is that it all depends on many factors such as recoater direction, surrounding geometry and the height to width ratio. This chapter is important because many guidelines and literature only mention that wall thickness should not fall below 1 [mm] (Crucible Design, 2015) but that it highly depends on height, material, machine, and geometry. It is important to be aware of the different problems so they can be avoided if possible, see more in Chapter 6.3.1 *Results from first print* where this issue is addressed briefly.

5.3.8 Horizontal segments

The chapter *Horizontal segments* also have a big potential for added data as people and companies learn more about the AM process. Not only can data from surface roughness and angles be added, it can also contain data from what machines that have been used and parameters used during earlier prints. This might not be crucial information for other designers in their work when designing but it can be used when talking to different manufacturers and negotiating prices. As more knowledge about AM is gained, customers to other manufacturers can push for higher standards and know what they can expect in terms of quality. This chapter is the first one to suggest self-supporting structures and will continue in *Holes*.

5.3.9 Holes

This chapter has, like the two previous, potential to be filled with data about possible hole sizes to make without a support structure. Also, the height of a hole in Z-direction before sag starts to appear, because when it does support structure is needed or a redesign (Crucible Design, 2015). The maximum size before corruption for a bore in stainless steel is only 9 mm in diameter (Adam & Zimmer, 2015) which is proven to be smaller than that of aluminum, see Chapter 6.3.1.

5.3.10 Support structures

As stated earlier, the support structure is the last thing added to a design before it goes into the printer so it is natural that it is the last thing in guidelines. Many aspects of why support structure is needed and how to be avoided are brought up in other chapters. The reason to have a separate chapter as well is to find the facts more easily in case people are only interested in that section. Some parts such as the thermal aspects of supports have not been addressed before and the fact that it is often generated automatically in a separate software, for instance, Materialise Magics (Reischle, 2016).

Designed support structures are only touched upon briefly in the document and one could argue that more can be said about it. The reason for only mentioning it briefly is because the document is a made for people who have not worked with AM before. If a designer is skilled enough to start to design their own supports this document might be too general.

5.4 Pre- and post-processing

The preprocessing is what needs to be done with the file after the design is finalized but before the machine starts. What the designer needs to prepare is up to the manufacturer to decide but from the interviews, it was found that it is best to receive the CAD-file in a raw format, not STL. It is also important to include all the specifications such as tolerances, material and important features (Matekalo, 2017). If any support structures are added in the preprocessing it might need to be removed later in the post-process.

The post-process is necessary to remove excess powder and support structure and different methods will affect the surface more than others. Removing excess material can in some cases give the part a better surface finish if the right process is used. However, in general, the surface finish is rougher on a part that is produced with AM than a part made with a subtractive manufacturing method. Depending on what post-processes the part will go though there might need to be preparations made, such as adding fixtures (Wennerberg, 2017).

5.5 Examples

The reasoning behind this chapter is to encourage people to add to the document when they have examples to show. Since there are many good ones already made, the decision was made that it could be useful to have a chapter dedicated to examples.

5.6 Future work and notes

As with everything in life you will not become and expert only from reading literature about something. This is a very important thing that needs to be part of the document. There are a lot of things that either was too specific for a new to fully understand and other things have not been tested and need more data. This data needs to be added to the document as it is discovered, both from work and from literature people come in contact with, to keep it relevant. AM is a relatively new manufacturing method so if the people using these documents do not update them on a regular basis the same problems will keep occurring.

5.7 Recommended reading

The document is made to be a start for people who want to work with AM so most things have either been simplified or shortened. If not, the document would be a lot longer and fewer people would read it in its entirety. As it is a new manufacturing method many things will probably change with time, for example, the list of materials, processes, and programs.

6 BENCHMARK MODEL

The second part of the thesis was to make a part, in this thesis called benchmark model, to test how well the rules and guides mentioned in the handbook are.

This kind of part can also be called benchmark or test artifact; there are many names but also different purposes. NIST (Moylan, Slotwinski, Cooke, Jurrens, & Donmez, 2017) mentions a few different reasons to make and use a test object: compare processes for decision making, evaluating an individual process, metal-based processes and other uses. Main purposes in the "other uses" are research of different features.

If one, for example, would like to test every hole size, angle and height the benchmark will quickly become quite big and costly. This is mostly done to fully understand how well a specific machine works with a specific set of parameters. To save money and time one can choose the functions that are most interesting and then put as many of them as possible on a piece and print it. The cheaper it is the chance of people using it and testing machines with it becomes more likely.

As stated earlier the benchmark will only contain features that are mentioned in the guidelines to test how well the literature and theory work in practice. The features chosen, are the ones considered most interesting or unclear.

6.1 Features

Before starting with the benchmark design, the features that would have to be included onto the part needed to be sorted. Ideally, every rule and recommendation should be included but some were more interesting than others and some are hard to test. After some deliberations, split parts, volume and powder removal was excluded all because they are very hard to test in a benchmark. Testing splitting parts would mean to make a design that is hard to split and then test different ways of connecting it. Just the different ways of joining two parts would mean a lot of post-processing with welding alone so this was discarded. Volume could be included but would mean that a large area of the part is left untouched and it was decided that this could be used for other things. Powder removal could more easily be included but because the print would take place off-site and the powder is removed before leaving the facilities this was in the end discarded.

The features chosen to be included on the final version was angles, radiuses, aspect ratios, gaps, walls, holes, shapes, threads, channels, lattice structure and supports. All features were grouped together as well as possible to make comparing features easier.

6.2 The process

Before creating the benchmark, some research was needed to see how other benchmarks looks, how big they are and just general inspiration. The benchmarks found where at first mostly made to test one specific feature and not for multiple ones. The search for benchmarks shifted from powder fusion laser melting with metals to plastics. Plastic benchmarks do not have the same tolerances and features but they could be good for inspiration.

3D-printing with plastics is a more widely used technology and have more users so the chance of finding different types are greater. The two main sites used during this research was “Thingiverse.com” and “Grabcad.com” where the search terms used was “Tolerance” and “Benchmark”. With this and a model given during a visit to the “Advance engineering fair” (Gothenburg, 8th of March, 2017) with a size of 80x80x27 [mm] was decided upon as base.

After some work, the first part was made and sent to Lasertech LSH AB for feedback, see *Figure 8*. It was then recommended to move the different shapes to another side having one side with circular holes and another with bigger shaped holes. The part was then remade with the recommended changes and some extra alterations as well. The new model, see *Figure 9*, had an extra wall added, bigger holes on the side, changed how the walls look, letters/numbers added to make some features more easily understood and two channels added. The features that have the greatest chance of falling apart during print have been moved to the corners, like with the 10 degree angle, so that if they fail it will not affect any other part of the benchmark.

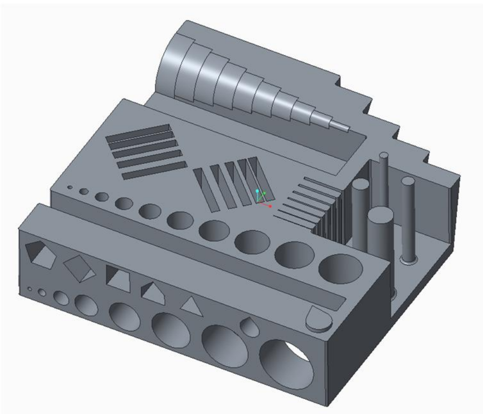

Figure 8. Benchmark version 1 visualized in Creo 3.0

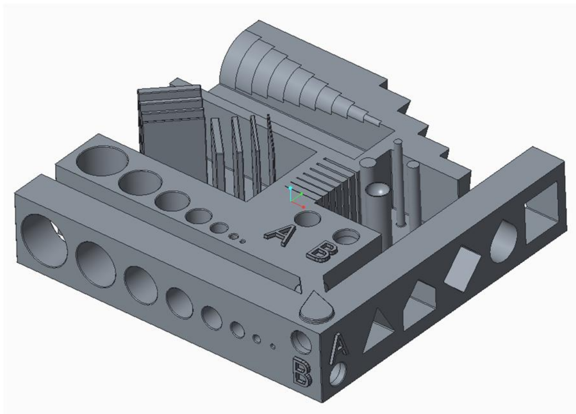

Figure 9. Benchmark version 2 visualized in Creo 3.0

6.3 First print

Before the part could be printed, placement and amount of parts needed to be communicated with Lasertech LSH AB. As the interviewees mentioned the quality of the print might get worse the closer parts are to the build platform edge (Diegel, 2017). It was decided to print two parts where one is placed closer to the center and the other closer to the edge, see *Figure 10*.

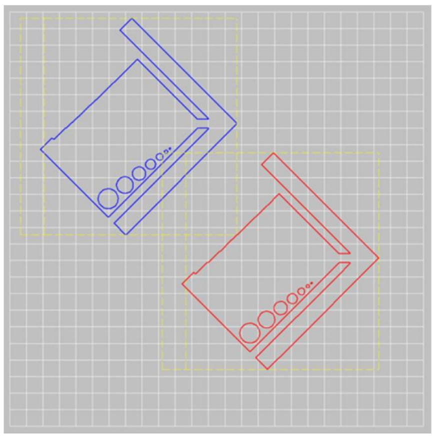

Figure 10. Placement of parts on the build platform

The machine used was an EOS M290 with a max print volume of 250x250x325 [mm] and the material used was aluminum. This material was chosen because of the limited amount of data accessible in the literature compared to other materials like Titanium and Inconel. The machine parameters used were EOS's standard parameters; layer thickness 30 μm, the scanner direction turns 67 degrees every layer and the build platform heats up to 35 degrees Celsius (Karolina Johansson, personal communication 2017-05-10)

Just before starting the print the manufacturers made a decision to add support material inside the square-shaped hole. The reason for this was because the risk of machine failure would be too high. The hole would no longer test the potential for square holes but could instead show how hard it is to remove auto-generated supports which are not offset from the part.

6.3.1 Results from first print

When looking at the print, when it still was in the machine and the excess powder not removed it is clear that the corrupted walls have affected the powder surrounding it and the features after, see *Figure 11*. After removing a majority of powder from the build platform, *Figure 12*, it became clear that the four walls angled zero degrees towards the recoater had either broken off or was crooked and are surely the reason behind the uneven powder bed.

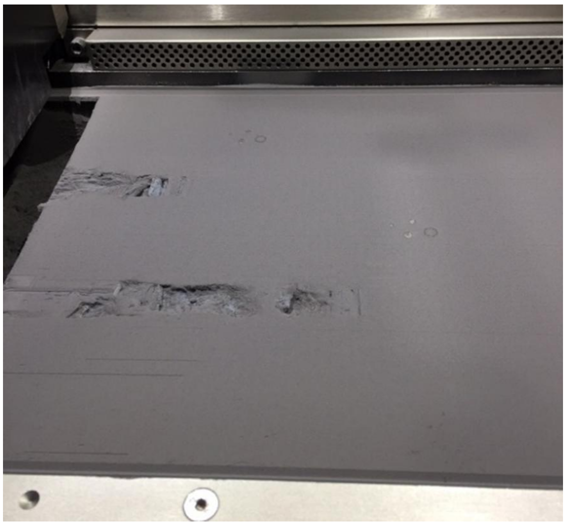

Figure 11. Benchmarks version 2 embedded in excess powder (Courtesy of Lasertech)

Figure 12. Benchmarks version 2 still on the build platform with a majority of excess powder removed (Courtesy of Lasertech)

The benchmark was designed to have over-dimensioned features, under-dimensioned features and things in the middle so that manufacturers and designers can see what works and what do not. The over- and under-dimensioned features was based on the literature and interviews used to make the design method. The material used when printing was aluminum which is softer compared to other metals used for printing and has, compared to for example titanium, worse self-supporting capabilities and might more easily collapse during print. when the benchmark came delivered from the manufacturers there was a lot of small surprises.

The first thing was how well the print had built the more extreme angles without the use of support structure, the 10 – 30 degrees. These were expected to look bad and in a worst case scenario collapse the entire corner. Instead the angles had a bad start but in the end, all three angles looked almost the same, see *Figure 13*.

Figure 13. The angles on benchmark version 2

The second was the two largest holes on the side, 12 – 14 [mm/ø], where they were expected to be less circular than the others and that the largest one might creep through the roof making a small hole like how the smaller angles crept upwards, see *Figure 14*. Instead of collapsing, both circles only had some irregularities and was clearly not as circular as the smaller ones ranging from 1 – 10 [mm/ø].

Figure 14. Holes printed on the side of benchmark version 2. The two holes on the left are 14 and 12 mm in diameter

The third thing was the aspect ratios, specifically the fact that the smallest pin with a ratio of 12:1 was uncorrupted with no sign of collapse, see *Figure 15*. This was unexpected because the literature recommends a ratio of 8:1 and anything greater than that has a risk of collapsing.

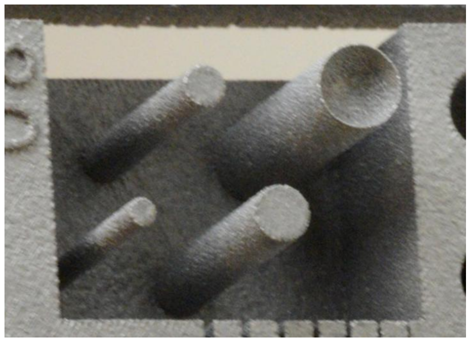

Figure 15. Aspect ratios on benchmark version 2, from right to left the aspect ratio goes from 12:1 to 4:1

The fourth and most interesting one was how the walls ended up. It was expected that the thinnest walls, 0.5 [mm], would collapse or at least be a bit corrupted in both angles towards the recoater. This was in the end not the case. All the walls positioned at a zero degree angle, the thinnest side towards the recoater, ended up uncorrupted. Instead, all the walls positioned at a 0 degree angle towards the recoater had either collapsed in the first print or was corrupted in the second. In *Figure 16* benchmark version 2 part 1 has only a small part of the thinnest wall left standing and in *Figure 17* benchmark version 2 part 2 has some walls left standing but all very corrupted.

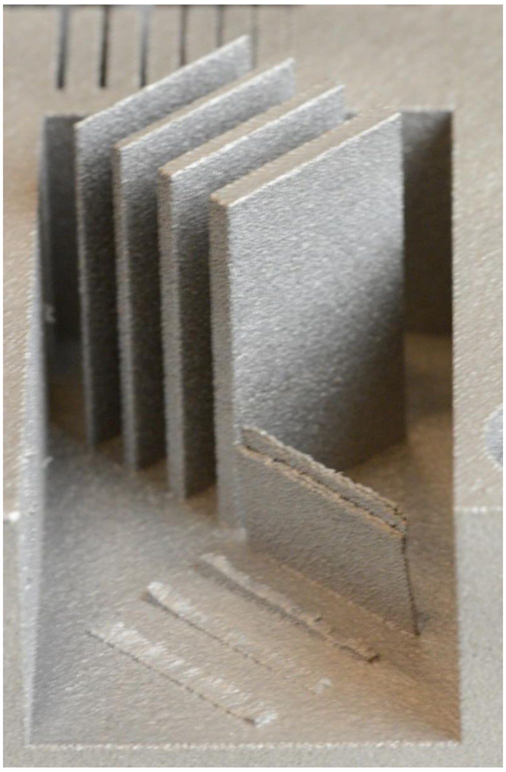

Figure 16. Failed walls on benchmark version 2 part 1

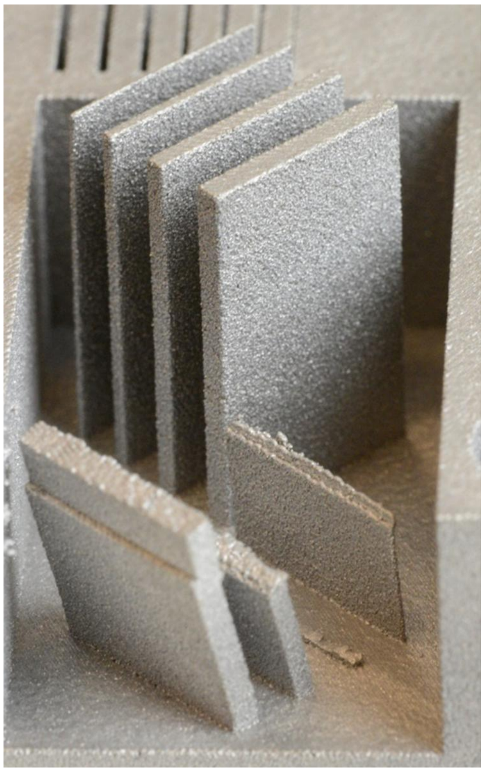

Figure 17. Failed walls on benchmark version 2 part 2

6.3.2 Tests

After closer inspection, the gaps in the benchmark did not have the size that they had specified. With the help of feeler gauge, the gaps were measured and they were about 0.1 mm smaller than the specified size in the CAD-file, see *Table 3*. The smallest one which was 0.1 mm was smaller than the smallest available gauge which was 0.05 mm. The measurements were made on both benchmarks but the result was the same. The gaps can be seen in *Figure 18*.

Table 3. The result from measuring the gaps where the measurement in the CAD-file is in the left column and the measured with feeler gauge is in the right column. Both of the manufactured models had the same result.

In CAD-file	Measured
0.1	Less than 0.05
0.2	0.1 but can feel the rough surface
0.3	0.2
0.4	0.3
0.5	0.4
0.6	0.5
0.7	0.6

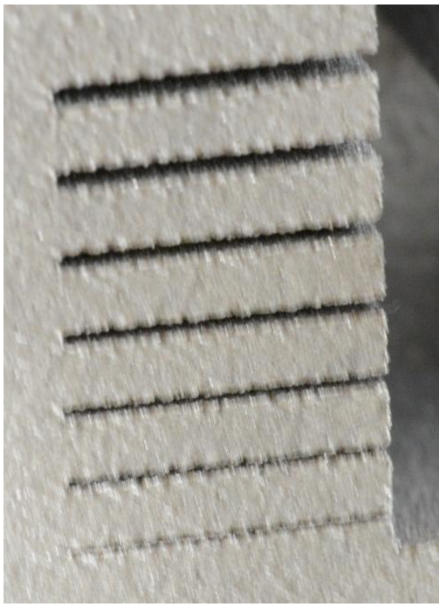

Figure 18. The gaps on benchmark version 2

Some additional tests were made to check if the tolerances stated on the EOS are correct, how accurate the print was compared to the CAD-model and if there is any difference between part one and two. The tools used for this was a ROMER Absolute Arm equipped with an HP-L-8.9 lasers scanner and a software called PC-DMIS, all from the company Hexagon Manufacturing Intelligence.

After scanning the first part and generated a 3D-model in the software the STEP-file used for printing was put as a reference, the result can be seen in *Figure 19*. The pictures show the scanned model on top of the STEP-file so green areas mean that the two models are identical and the chart shows how much the two differs from each other. As the chart shows the largest difference between scan and STEP-file is around -0.15 and 0.05 [mm]. As the EOS-machine has a tolerance on 0.1 [mm] this seems reasonable. One thing to note is that the chart has more difference in blue than red which can be explained by looking at what the blue represents.

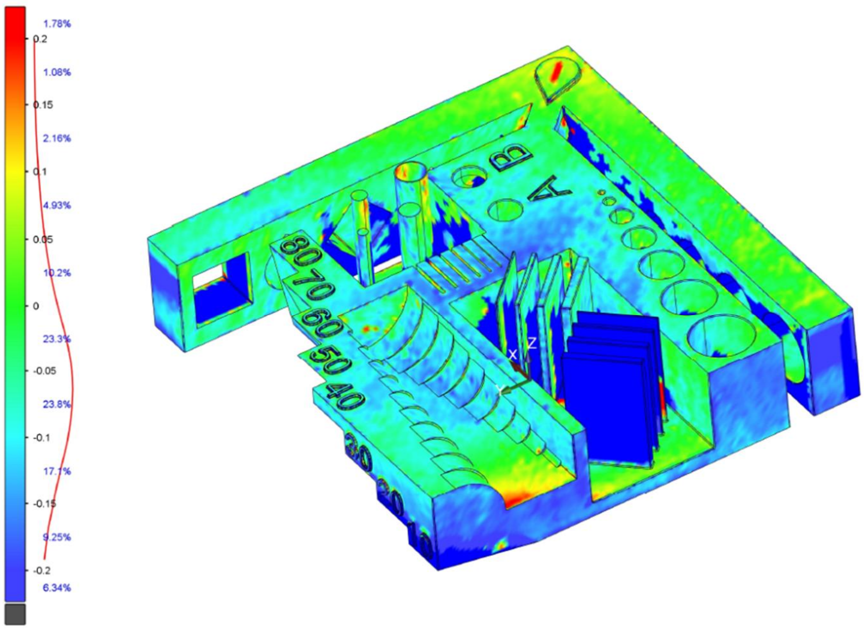

Figure 19. Result from comparing a scanned model to an STEP-file of the same model. The chart to the left shows how much the two models differ from each other.

Some areas like the walls in the middle and bottom corner with 10 – 30 degree angles are blue as the printed model do not have these features as they are corrupted. All areas that are deep blue but are not corrupted or missing are areas that the laser could not reach the squared hole in the left corner which is filled with support structure making it impossible to reach. This means that the things missing weight the chart in one direction.

6.4 Final version

As some of the features showed unexpected results and because the benchmark is made to test the build quality and what the machine is able to do/not do some changes is needed. A majority of the features did show what they were supposed to and even if some results were unexpected they still filled the function. The alternative changes needed on the benchmark are to add another aspect ratio with higher value, make changes to the walls and to make the part smaller. Some features could be changed or moved to make this possible. Some examples of this would be to swap one of the channels making it smaller/bigger, making the square-shaped hole smaller so the manufacturers would be up for printing it without supports, to implement some kind of lattice structure and making the benchmark smaller. After some feedback from Saab AB, they also would like to add threads to one of the holes printed in Z-direction to test if it is possible. The literature states (Crucible Design, 2015) that threaded holes are possible, but only in Z-direction, but some interviewees said it is not which made it an interesting feature to test. The text spelling “Saab AB” and “INXM1010397/1”, which is the benchmarks number in their PLM system, was added on the top of the benchmark and “Johan Sonegard & Maria Warholm, 2017” was added to the bottom, which will not be visible after print, as a reminder of the parts origin.

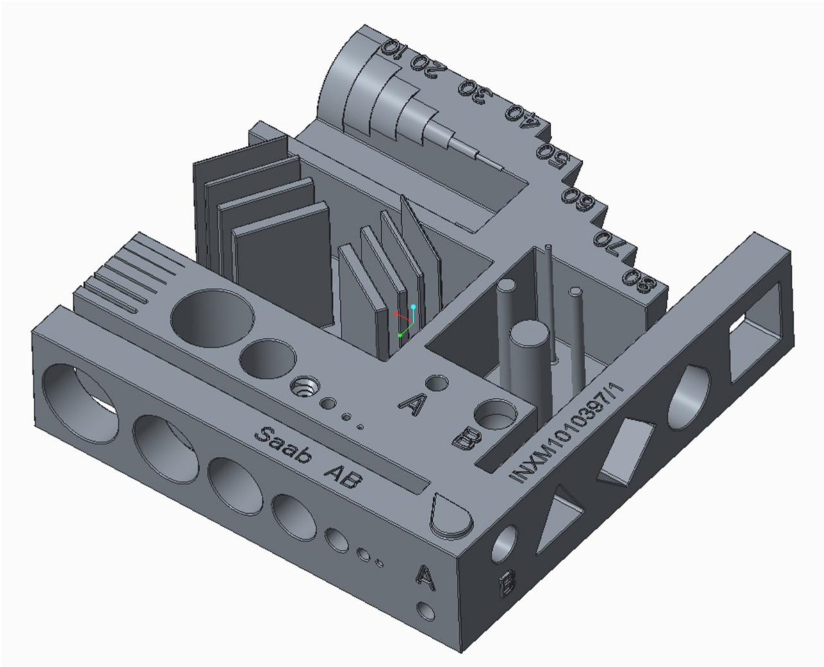

Figure 20. Benchmark version 3

The final version of the benchmark was constructed to fix the problems the first version did not show, see *Figure 20*. As stated earlier some features was kept, some changed and some added like different sized channels and a hinged hole.

6.5 Second print

During the second print, four benchmark models were printed compared to the first print where only two were printed. The positioning of the four parts was made with the knowledge of potential powder corruption and particle movement. As there were no real difference between parts printed in the center and in the corner this print would more clearly indicate if there is a difference in positioning, see *Figure 21*.

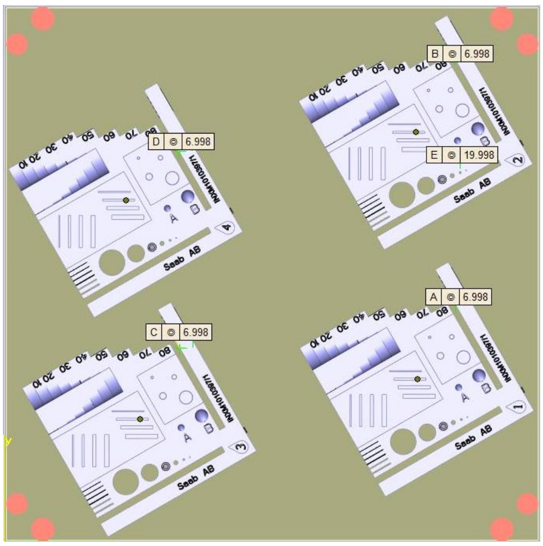

Figure 21. Positioning of Benchmark version 3 on the build platform, the recoater will come in from the right

When looking at the first print, see *Figure 11*, it clearly shows how corrupted features affected the powder surrounding it but as there were no other parts to affect so no real assumptions could be made. But as seen in *Figure 22* particles can break loose from one feature and travel with the recoater to another part of the build platform, see red arrows, affecting the powder or corrupting the part in other ways. In *Figure 23* more and bigger particles have broken off from the parts on the right and affected the parts on the left. The green lines show the outlines of two benchmarks making it easier to compare the two figures.

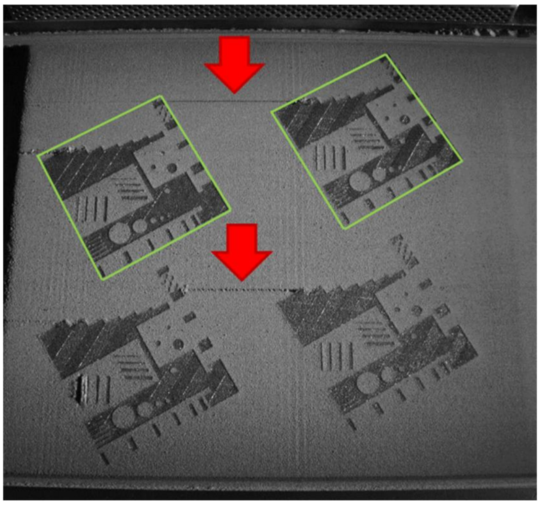

Figure 22. Powder bed layer 510 after laser exposure showing how particles from corrupted features starts to affect other parts of the build platform (Recoater going from right to left)

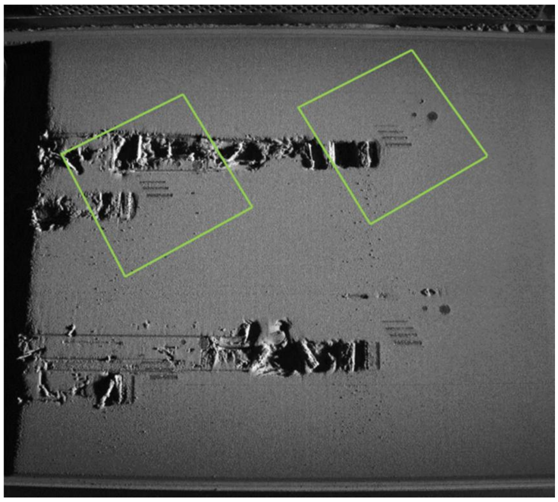

Figure 23. Powder bed layer 1100 before laser exposure clearly showing how powder and particles affects other parts on the build platform (Recoater going from right to left)

6.5.1 Result from second print

As stated in the earlier chapter, the particles from two parts affect the other two on the same build platform. After removing them from the build platform and the excess powder brushed off the result shows that the damage is not as big as one might think visually. The two parts, on the left side of *Figure 22*, that have been affected by the other twos, the right side of *Figure 22*, particles only have small lumps on some places but it does not seem like it has affected the features in any major way, see *Figure 24*. An example of this is the aspect ratios on part number 4, see *Figure 25*, which actually is the only part still having the 12:1 rod still standing, more on that later. Aside from that, they all seem to be visually the same. Positioning on the build platform seems to have some significance as the two bottom parts still have a thick wall standing but the two on top do not. The key word here is “visually” because the material properties and general material quality of the print need to be tested before determining how the particles affected the parts. When comparing the rest of the features to the first print they all seem to have kept the same quality. Every feature is described and analyzed in a pamphlet meant to be used with the benchmarks and can be found in Appendix N.

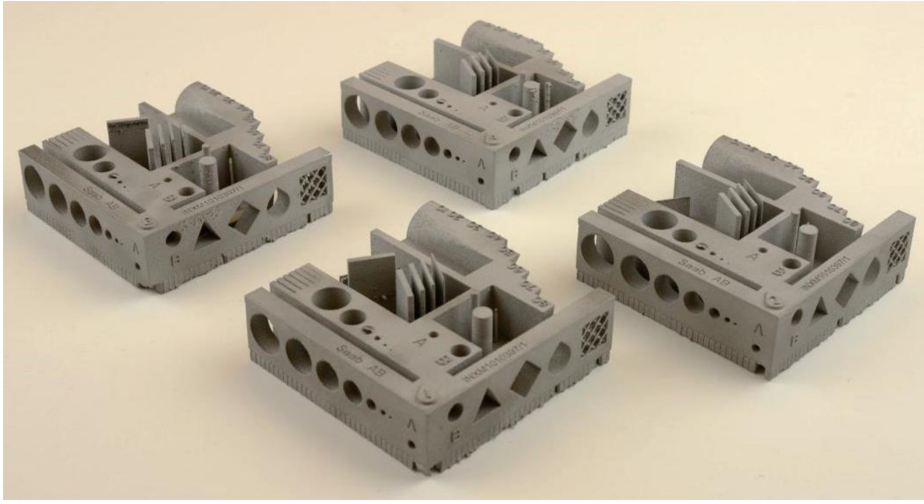

Figure 24. The four printed benchmarks

When looking at the features changed from the first print the first thing to look at is the aspect ratios, see *Figure 25*. As stated earlier only one part still had the aspect ratio of 12:1 still standing but with a clear corruption and not at full height. Why this differs from the first print to the second is unknown and can be anything from luck, circumstance, defects, particles, bad handling from manufacturers or damage caused by the company in charge of delivery.

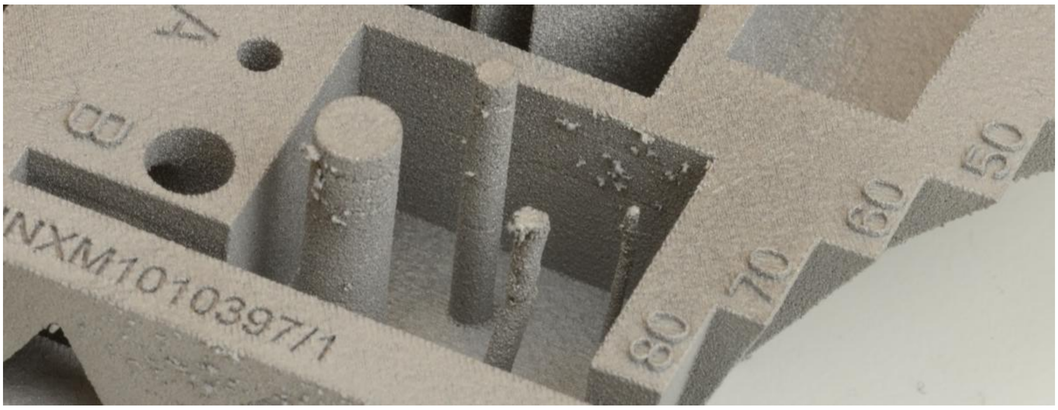

Figure 25. The feature "aspect ratios" on benchmark numbered 4

The other changes were the walls positioned at a 0 degree angle towards the recoater where the thickest wall is hit first instead of the thinnest, see *Figure 26*, and a smaller channel added instead of two with the same dimensions, see *Figure 27*. As theorized the thicker walls worked but only on two of the four parts where one is bent and the other affected by particles. The smaller channel works, a test by blowing into it show that it is hollow, but other tests can be made to make sure that all the powder has been removed.

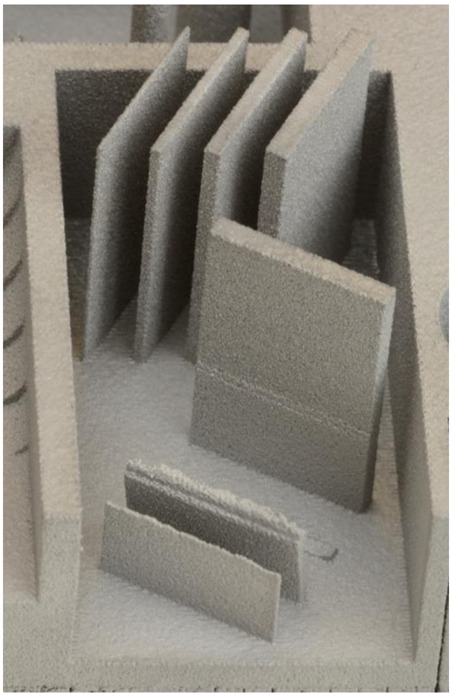

Figure 26. The walls on benchmark numbered 1

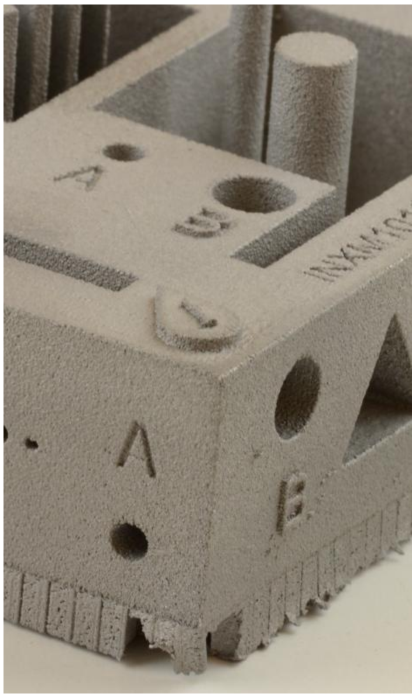

Figure 27. The channels A and B

The first new feature added to the benchmark was the lattice structure inside the squared hole which looks stable and uncorrupted on all the parts, see *Figure 28*. The second new feature was the threaded M4 hole which looks good, but unfortunately, a miss calculation during design, using diameter instead of radius, made tests with an M4 screw impossible, see *Figure 29*.

Figure 28. Lattice structure on the benchmark

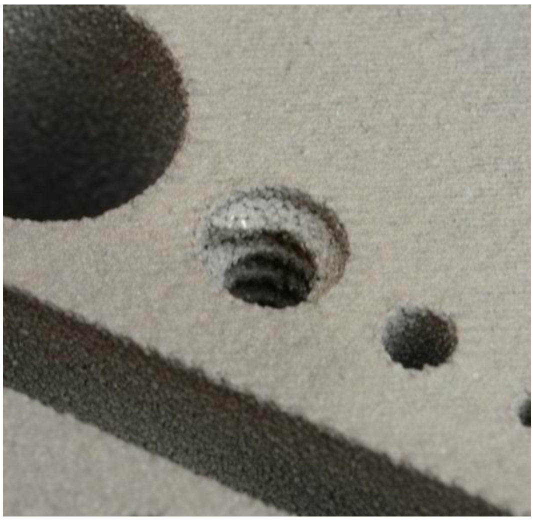

Figure 29. The threaded hole on the benchmark

7 DISCUSSION

As data is collected and tests conducted some discussions about credibility and assumptions is needed. This chapter will contain results and analysis from how the work was conducted and why certain decisions were made.

7.1 Literature

When searching for relevant literature and research articles it soon became clear that a lot of people are working with AM. After a couple of weeks, it was decided that everything older than 5 years will be considered too old and not used unless it is unique data, recommended from people with good insight into the technology or not mentioned anywhere else. This was decided because the machines used in powder bed fusion seem to be a lot better today than what they were 10 years ago. Data and research done on old machines will probably not correctly reflect how well the machines work today. Another reason for this is also that during the literature study a lot of articles and books were released during the study and in 2016. Neglecting old data and literature by focusing on new data would most likely make the handbook and report as up to date as possible.

7.2 Interviews

When starting this thesis work it was understood that some companies would not want to give out certain information because it will, at some point, be published. However, it was not realized how secretive many of the companies would be. In hindsight, it is somewhat understandable that they would want to keep much of their information a secret. AM is a new technology where small advantages can make a big difference. It was harder to get people to share information than expected and the more talkative people were often very busy with other things. This was even if they started by showing interest in helping and supporting the project.

In a couple of years when AM hopefully is more commonly used in production the information that was tried to get a hold of is not as hard to find or companies have their own way of doing things. As Sweden is considered to be behind when it comes to using AM in industries (Boivie, 2017) helping each other and working together might help to catch up with the rest of Europe, America, and Asia.

7.2.1 The designers

As the designers had a different amount of experience and responsibilities when it comes to design they all came with good advice and insight on how it is when working with AM. Even though most of the answers and advice were similar, it differed in a few aspects, for example, whether you had to compensate for shrinkage or not. Two people said that this is something you have to do before sending a model to print but another said that this process is automated. These people work at the same company, which makes it even more confusing. If they would have worked at different companies it would be assumed that they have different software, machines or processes that take care of shrinkage. When working with shrinkage people will have to check with the manufacturer first to make sure that the problem is dealt with before print.

As with the uncertainties around shrinkage new processes need to be developed to work with AM but not only regarding who will do what but also on how the organization deals with printed components. As AM needs specific tests and has its own standards, companies need to develop an AM-specific work-process which will differ from the others. A good example of this is that as AM do not really need any type of special tools to manufacture, only a CAD-file of the part and a machine that can print it with the set material, tolerances and parameters. The concept and development phase will be longer than for other processes, like casting. The companies also need to educate everyone who might be part of a project including AM so that everyone understands why and why not something should be printed. Before AM can be used to its fullest it would be recommended that companies learn the strengths and weaknesses of AM and then recommend components they have that will gain something from the process. By doing this the people will learn how to better work with the process and gain experience for when something new comes that needs AM to live up to its full potential.

As for the people worried that AM will be outsourced to low-income countries this does not seem likely. As AM needs at least as much expertise as when designing something for machining or casting and that expertise is still valued in the west it does not seem likely that AM will be any different.

7.2.2 The manufacturers

On the manufacturing side of the interviews, there were only two participants, which is not bad, but it is very low when comparing to the designers. When more people are interviewed more data can be gained, strengthened or debunked. This does not mean that the data and answers from the manufacturers are bad but it is harder to base a method on something that needs a little more data to be considered true. As designers and manufacturers often work close to each other the designers’ experience can somewhat strengthen the manufacturers’ answers. However, the handbook is designed for designer and therefore the focus was to interview designers.

From what the designers and manufacturers are saying it is not yet set on how the workload should be divided when it comes to generating support structure and preparing models for print. It seems that companies prefer to have these workloads separate, letting designers focus on what they are best at and hiring AM-technicians who only works with preparing models for print. This is not bad as it makes people experts on one specific thing but it can be argued that the knowledge on how support structure is generated and implemented is crucial to be able to fully optimize models for AM. Orientation is a good example of work that many designers do not work with today but it is still a vital part of the process and must, therefore, be set as early as possible. As the handbook moves this responsibility from AM-technicians to designers it can be argued why not letting the designers do the support structures as well. It will be up to companies to decide on how they want to divide the workload. As long as there is good communication between designers and AM-technicians this separation will probably not be a problem.

7.3 Implementing the new guidelines

Implementation of new guidelines at a company can be hard as it, at its core, will change how some people work and many people do not want to change. As the handbook is made to be a base for new designers and developers who want to use AM in their work they might read it through from start to finish the first time. After that, they can use the document as support when making decisions and this will hopefully make people more likely to use the document. As this thesis only focuses on making the handbook and making recommendations on how it should be used, how well it is implemented and if the recommendations are followed can only be hoped for. If the document is not updated as new information and data are gained the document will soon lose its relevance. To keep this from happening it needs to be available for everyone to update continuously.

As Saab AB Surveillance is interested in this manufacturing process, the handbook will most likely be used in some way but updating the document might be harder. As the handbook is meant to be used with their current processes some studies were made into how people work with projects. After some meetings and discussions on the processes people need to follow when working on new designs, there is no obvious conflict with implementing the handbook into the process as it is today.

When it comes to updating the handbook there seem to be some problems. At the end of each project, people will need to fill in a document called “Lessons learned”. This is a common thing to do after any type of project but the fact that this document is a static document will be a problem. The fact that it is static and not linked to any type of summary or the text accessible outside of the document means that it is up to each person to use what they have learned in the next project. To make sure that the handbook is continuously updated there should be an entry in the process telling people to make changes and updates parallel to “Lessons learned”.

7.4 Benchmark model

The handbook is based on literature and interviews so to test these guidelines and rules out in some kind of practical example felt like a good idea. After some discussion and deliberation it seemed to be three ways to go:

1. Design a part by ourselves based on traditional manufacturing processes and optimizing it for AM
2. Saab provides a component used in their current products and optimizing it.
3. Design or redesign a component used for testing machine and material limitations.

The first option was the best one but also the one taking the most time and work. It was decided to not go that route because it would take too much time away from the handbook. The second option would have been good because then it would be a real life example and having all the data necessary to make it. To find a part suitable for AM is a process by itself and it also needed to be general enough for Saab to be willing to release it for publication. In the end, the third option was the best when comparing the workloads and the purpose of the model was to test if the rules of thumb work in practice and to check some features on which no data was found.

When making the model it was interesting to see if the recommended way of developing a model for AM worked in practice. Another interesting part was to discuss with the manufacturers what they thought about the model and hear their feedback. After only one consulting session the benchmark was sent to print and the result surprised everyone. Some features worked better than expected and some did not work at all. After some more discussions, an updated benchmark was made and sent to the manufacturers for print.

The second time printing, this time benchmark version 3, the features on the parts did not really change in any way from the first print. To see how particles from corrupted features on one part affect other parts on the build platform was very interesting. As stated earlier in Chapter 6.5.1 *Result from second print*, the particles from one part to another looked like it would have a big effect but in the end, the visual quality was noticeable but still very small. Tests need to be done on material properties to make sure that the particles only affected the parts visually and not altered things like strength or fatigue. Of course, the best solution would be to make sure no features get corrupted during the build.

The fact that some features had different success rates depending on where they were positioned was interesting. The expected result would be that features closer to the center of the build platform would be better than the near the sides and corners. Instead one corner, bottom right, was the best one in general and the other corners all had something the others did not. The top right was not corrupted by any particles from other parts, down left had a thick wall still standing and top left was the only part with a 12:1 aspect ratio still standing. The manufacturing company should know if there is a preferred part of the build platform. If not the end result can be considered as random.

The conclusions made from the benchmark will not affect the layout of the handbook or alter any guidelines in any major ways. This is grounded in the notion that just because something works on one machine with one material does not mean that it will work for all other machines and materials. The benchmark can be seen as a way to check how well the knowledge and work ethic works in practice and to make changes if something is far off from the guidelines. The handbook is meant to be seen as general guidelines and more tests and data need to be collected before changing something stated in the literature. When studying the results nothing differs from the rules in any major way.

To be clear this was not a part used in an existing product but the process of making this benchmark model shows how fast and flexible AM can be. Within three weeks a model was printed, delivered, altered, printed and delivered which is more than impressive.

8 CONCLUSION

This chapter will present what conclusions that have been made from the thesis and recommendations on what areas to keep working on in the future.

8.1 Design method

Additive manufacturing with powder bed fusion using lasers has a lot of potentials and can with its unique capabilities manufacture products previously impossible. To use this technology correctly and making it cost effective is not easy. The aim of the projects was to give people working with AM a common ground to stand on and this was achieved by making a document containing some basic information on how the technology works, terminology, rules of thumb, and recommendations. As stated in the handbook: "learning by doing" is still the best way to become good at designing and working with AM. Rules of thumb and recommendations are always good to have but experience and knowledge are often more important.

Everything in the handbook is either based on literature or interviews made with people working with AM on a daily basis or having knowledge in the field. As the handbook contains recommendations and guidelines from secondary sources there is no guarantee that using this document will make people work better or more efficiently with AM as it has not been "field tested" apart from making a benchmark, see Chapter 8.2 *Benchmark model*. On the other hand, it has been sent out to people working with AM and people with little to no knowledge about the process for feedback. These feedback sessions resulted in some small changes but only on making the handbook more understandable to read and follow. This increases its credibility somewhat but as the technology, processes, and machines are in a constant cycle of improvements the document must be updated on a regular basis as people use it.

Standards are being developed as of writing this but it will take some time before they are finished and the absence of standards should not hinder companies from using this technology. Documents, such as the handbook in Appendix M, are always useful to have in a company as it keeps people on the same level of knowledge and helps new people to faster learn what it means to work with AM.

8.2 Benchmark model

As the handbook mainly contains recommendations and rules from secondary sources a benchmark model was made to test features with insufficient data or credibility. After three iterations of the model and two version manufactured, the handbook with its guidelines shows promises on making a designer's work more efficient and new knowledge was gained from the model. The most vital piece of information made from the benchmark was that the angle of the recoater is even more important than expected and that vibrations can result in big problems and result in a domino-effect.

Except for the vibrations, the features tested on the benchmark did in some situations differ from the guidelines but not so much that the rules needed to be rewritten. As the rules are made to be general guidelines more tests need to be done with different materials and in different machines.

8.3 General

Aside from the handbook and benchmark, some future work needs to be considered on an organizational level. The method will only work if people at the company have access to it, are introduced to it and have the ability to update it. AM is a technology that has changed a lot the last 10 years and the forecasts say that it has not found its peak yet. This makes it even more important for people and companies to make sure to be up to date on standards, machines, design guidelines, parameters, and processes.

On an organizational level AM differs from other manufacturing processes as it has no need for anything else but a CAD-file, machine and powder. The step from 3D-model to finished part is shorter than for most other manufacturing methods but what process the part needs to go through is vastly different depending on the chosen manufacturing method. Companies will have to look into making new processes for how to work with AM in a project just as with any other type of manufacturing process that is new to the company.

As AM is a manufacturing process best suited for small batches of highly complex components, companies need to look at it from more angles than just cost of a part. In some cases, an expensive part produced with AM can be cheaper than a, for example, casted part in a lifetime perspective. AM does not need any casting forms, can make more advanced geometries, shorten lead times from model to finished part and it is moving towards a zero waste production.

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APPENDIX A Questions to designers

Here are all the questions listed that were asked the designers that were interviewed but since the interviews were semi-structured, there were some spontaneous follow-up questions and some that were answered before they were asked.

General:

- Is it ok that we record this conversation?
- Can we use your name or do you rather be anonymous?
- Occupational title?
- Company?
- Education?
- What software(s) do you use?

The work today:

- How long have you been working with 3D-printing?
- What kind of support do you use today? Any method or process or have you made your own?
- Any "rules of thumb" you working with? Design guidelines?
- What do you think is missing in terms of knowledge at the moment? (Educational material, courses, literature, knowledge within the company, at the manufacturing site etc.?)
- How much freedom do you normal have for problem-solving or is the part already "done"? (Who is normally making the design decisions?)
- Are there particular geometries that often need to be redone?
- Who's doing the preprocessing before printing? Do you have specialists or are all designers also adding support structures/orientation etc.? (You, someone else at the company or the manufacturing company?)
- What 3D-printer do you use for manufacturing?
- What materials do you normally print in?
- How much knowledge do you have about the printer?

The work tomorrow:

- What would you like to have to make your work easier? (Available courses and course material?) What is missing to make AM bigger and even more popular and usable?
- How do you think it will be?
- How do you think it should be like?

The manufacturing company:

- How much contact do you have with the manufacturing company?
- What do they need to approve your parts? (What are they asking from you?)

Splitting components:

- How do you reason when you are splitting bigger components to smaller?
- What's the biggest problem according to you?
- How much can you change the design to solve the problem?
- Any "rules of thumb" you work with?
- How do you plan the joining? (Can you choose between many welding methods or are you limited?)

APPENDIX B Questions to manufacturers

The questions for the manufacturers were even more customized for the interviewee than the questions for designers. This was because some companies only manufacture the AM machine and some companies manufacture parts using the AM technology hence the irrelevant questions for that particular interviewee were left out.

General:
- Is it ok that we record this conversation?
- Can we use your name or do you rather be anonymous?
- Occupational title?
- Company?
- Education?

The work today:
- What software(s) do you use?
- What AM-machines do you have?
- How much of your own manufacturing do you have? Or are you only selling the machines?
- Do you have any design guidelines in the company? (Any advice you share with your customers?)
- Do you have any particular processes you use when working?
- Any course and/or literature you use (within the company and outside)?
- How much do you learn about the material properties, like yield strength etc.? What's the difference between a printed part compared to a molded part for instance?
- Do you have any documents with useful information that you give your customers? (List with tolerances, limitations etc.)
- How do you find new knowledge? Do you read science reports or do you have your own methods or a mix?
- What do they need to approve parts that will be printed? (What are they asking from you?)

Before you get the CAD file:
- What information do you need to manufacture a part?
- What information is often missing in the order?
- How do you calculate the cost of a part?

When you have the CAD file:
- How do you control the component before manufacturing?
- What shapes are usually a problem on parts you are asked to manufacture?
- What is the most common reason for having to redesign a part before manufacturing?
- Who is usually doing the preparatory work of the CAD file? (Converting it to STL file format)
- Who is adding the support structure and decides where it should be and what it should look like?

The machines:
- How much do the people standing by the machines (operators) know? (Education, understanding of the preparations etc.)

- How limited are the machines? Is it easy to change the parameters, how much information about tolerances etc. do you give the customers? (Minimum wall thickness etc.)
- What do you consider when placing the parts in the machine? (Cost, quality or time?)
- How do you check the quality of the printed parts? (Tests that are done on the machine, material, printed parts, especially after material has been changed in the machine)

APPENDIX C Questions and answers Fabian

Education: Bachelor’s degree in Mechanical Engineering

Software: Creo

Arbetet idag:

- Hur länge har du arbetat med 3D-printing?
    - 2 år men har erfarenhet från lite prototypbygganden sen tidigare

- Vad använder du för stöd idag?
    - Det mesta baseras på erfarenhet eftersom de flesta problemen är väldigt produktspecifika och därav svåra att använda metoder på det man gör.

- Några tumregler du jobbar efter?
    - Man måste tänka på att saker ofta kommer efter bearbetas på något sätt efter tillverkning och att man jobbar med två olika modeller, ämnesmodell och bearbetningsmodell.

- Vad tycker du fattas kunskapsmässigt just nu?
    - Att kommunicera med folk om vart hål och fixturer skall sitta. Att om något skall bearbetas så skall man lämna den delen solid om möjligt eftersom det underlättar. Materialmässigt fattas mycket med hållfasthet och utmattning eftersom man jobbar med pulver men man liknar arbetet vid gjutning med tanke på ämnesmodeller. Begränsningar hos maskinerna vet inte mycket om heller eftersom tillverkarna pressar dem på sitt sätt.

- Får du mycket frihet när du löser problem eller finns delarna redan "klara"?
    - Olika, om den interna geometrin eller interfacen är satt, vilket görs väldigt tidigt, kan jag inte göra något men annars så är det väldigt fritt så länge den behåller hållfastheten. Små ändringar brukar heller inte vara något problem.

- Några former/saker som du ofta får göra om?
    - Oftast vinklar som inte får finnas eller bara önskemål på saker som kan göras om.

- Vem gör förarbetet inför tillverkning?
    - Lasertech håller i det till 100% men meddelar vad de skall göra så jag har en chans att göra ändringar i underlaget. Man vill se till att stora ändringar kommer med i modellen. Har ingen koll på hur de ställer upp modellen i maskinen. Om man vet processen innan kan man simulera i huvudet hur den skall tillverkas vilket skulle underlätta och blir då mindre frågor till Lasertech.

- Vilken AM-printer används vid tillverkning?
    - En EOS, kan ta reda på mer men är inte så viktigt att veta för en konstruktör.

- Hur mycket vet du om maskinen som skall printa ut delen?
    - Att det är pulver och att det är en kall process till skillnad från Arcam. Toleranser och storlek får man alltid reda på i början.

Arbetet imorgon:

- Vad skulle du vilja ha för att underlätta ditt arbete?
  - Ingen litteratur eftersom man löser problemen mellan alla påverkade parterna. Skulle dock vara väldigt bra att ha kunskapen om hur alla bearbetningsprocesser fungerar så man tidigt kan optimera för dessa. Detta kan fungera genom att först vända sig till Lasertech och sen till bearbetningsfirman. Just nu kommer bearbetningsfirman med förslag om hur vi skall göra om modellen så man måste skicka den till båda för att få feedback. Nya produkter innebär nya optimeringar. Jag vet mycket om hur man jobbar men vet inte hur man skall föra ner det på papper som byggritning, fixturer och grejer.

- Hur tror du det kommer se ut?
  - Just nu är det ganska lång bit mellan koncept till färdig produkt vilket i framtiden nog kommer att vara kortare.

- Hur tycker du det borde se ut?
  - Att kompetensen ökar hos alla företag och att underleverantörer börjar känna igen saker. Ökad kompetens gör att allt går fortare.

Tillverkande företaget:

- Hur mycket kontakt har du med tillverkningsföretaget?
  - Tät kontakt och blir mycket bollande fram och tillbaka.

- Vad behöver de för att godkänna dina delar?
  - På Saab så kräver de bara att de klarar de fysiska testerna, vibrationer och simuleringar. Sen skall det ju fungera med toleranser och likanande också.

Övrigt:

- Toleranserna Lasertech går efter är 0.2 men inte mindre
- Man vet inte hur tunna väggar man kan göra och hur höga de sen får vara
- Nu lägger jag till 1 mm på alla ytor som skall bearbetas
- Man måste tänka på att om utsidan är ganska symetrisk men inte insidan så behövs något typ av referenssystem så den mänskliga faktorn tas ner
- Svårt att modelera för 3D-printing från början eftersom man först behöver komma fram till hur den skall se ut och sedan kolla på hur vi skall fixa det i maskinen med bearbetning och annat
- I nuläget löser man sammanfogning med dopplödning med en hylla

APPENDIX D Questions and answers Per

Education: M.Sc. in Mechanical Engineering

Software: NX, Magics and Ansys

Arbetet idag:

- Hur länge har du arbetat med 3D-printing?
  - 1,5 år

- Vad använder du för stöd idag?
  - Det beror på eftersom vi jobbar både med interna och externa kunder men har ingen direkt process att följa eftersom alla är på olika stadier i sina projekt så handlar mest om att hjälpa dem kunskapsmässigt.

- Några tumregler du jobbar efter?
  - Vi har metoder att jobba efter men mest hjälper man kontakten för de har dålig koll på AM, toleranser, ytjämnhet, support strukturer och minskning av material. Allt som spara tid i byggprocessen. Har sätt att uppskatta kostnad men vill inte dela med sig av detta.

- Vad tycker du fattas kunskapsmässigt just nu?
  - Får hjälpa andra att komma igång eftersom folk ligger kunskapsmässigt på olika nivåer och förväntar sig att man kan göra allt vilket inte är sant samt vad som är realistisk med toleranser och ytor. Mycket kunskap saknas CAD-mässigt när det kommer till avancerade former och borttagning av material vilket sätter högre krav hos konstruktören. Vid jobb med topologi så behövs ett bättre format än STL för avancerade strukturer och mjukvaror i allmänhet behöver bli bättre, topologi, beräkning, simulering etc.. Konvertering fram och tillbaka i STL är inte bra så att få det som en CAD-fil är bättre. Nya format är säkert på väg men detta ligger mycket hos de som gör programmen.

- Får du mycket frihet när du löser problem eller finns delarna redan "klara"?
  - Väldigt olika, fritt då man är med från scratch eller låst om befintligt del ska in i befintlig produkt eller en ritning med krav.

- Några former/saker som du ofta får göra om?
  - Oftast är det överhäng som behöver göras om eftersom folk inte tänker på supportstrukturer.

- Vem gör förarbetet inför tillverkning?
  - Vissa jobbar mer än andra men just nu delar vi upp arbetet mellan varandra

- Får du många korrupta filer (trianglar som behöver fixas)?
  - Föredrar att få allt i CAD-format eftersom det kan bli problem att jobba med STL-filer som inte har toleranser eller jobbiga att föra ihop med andra filer. Konverterar helst själv till STL i slutet.

- Hur mycket kontakt har du med den som designar?
  - Olika men bra nog att man kan kommunicera om vad som måste göras.

- Vilken AM-printer används vid tillverkning?
    - Två Concept laser (M2) som är pulver baserade lasermaskiner, en Arcam och en X1 som är för binder jetting. Fler pulver maskiner på väg med laser eftersom det är den mest mogna tekniken just nu.

- Hur mycket vet du om maskinen som skall printa ut delen?
    - Har bra kommunikation om vilken maskin som skall användas.

- Vilket material använder ni?
    - Vi jobbar med verktygsstål, inconel och plast fast det är inte något som vi levererar.

Arbetet imorgon:

- Vad skulle du vilja ha för att underlätta ditt arbete?
    - Fortsatt utveckling av mjukvara specifikt för AM och topologi samt så måste STL-formatet måste bytas ut mot något bättre. I stort så är det industrialiseringen och processen med AM som behöver bli bättre för att västvärlden skall kunna behålla tillverkningen. Just nu är det väldigt mycket labbmässig hantering men vi måste gå mer mot massproducering för att få ner priserna vilket även tillverkarna av maskinerna gör.

- Hur tror du det kommer se ut?
    - Kommer vara en mer industrialiserad process, kostnad per komponent kommer att gå ner och maskinerna kommer att vara mer optimerade. Konstruktörer kommer nog också sitta med i produktionsflödet och att AM kommer in på andra marknader än flygindustrin.

- Hur tycker du det borde se ut?
    - Tycker att det borde gå åt det hållet och hoppas att det hålls i västvärlden. Som sagt så måste vi automatisera och industrialisera mer för att detta skall fungera. Tror också att det kommer att vara en vanlig del av tillverkningen med mer komplicerad och komplexa former.

- Hur lång tid tror du att det kommer att ta?
    - Är nästan där i att många satsar på det idag som Siemens och Sandvik. Det kommer dock snart att explodera inom kort i antalet maskiner och företag som ger sig in.

- Behövs det inte nya maskiner?
    - Maskinerna räcker men man behöver följa upp med bättre teknik och processer. Det måste gå ner i pris och den som designar måste tänka om vid tillverkning av en produkt. Idag gör man lite tvärt om i att man bara vill göra om en komponent i 3D-printing utan man bör ha AM i åtanken från första början. Sätter som sagt stort krav på konstruktören.

- Bör nyexaminerade ha bra koll på tekniken?
    - Ja de bör ha lika bra koll på det som allt annat. Man måste dock få in mer arbete med optimeringsprogram och liknande som topologi i utbildningarna.

Tillverkande företaget:

- Hur mycket kontakt har du med tillverkningsföretaget?
  - Har en god kontakt med tillverkarna men påverkar inte direkt vad de gör.

- Vad behöver de för att godkänna dina delar?
  - Vi skickar våra delar till tillverkarna som lägger på support och gör analys över hur de skall tillverka den.

Vid delning av komponenter:

- Hur jobbar du när du skall dela upp stora delar i mindre delar?
  - För oss så är saker som är för stora oftast för dyra att tillverka men om vi skall dela upp en del så bygger vi oftast på ett ämne. Vi bygger helt enkelt en simpel del på traditionellt sätt och sedan printar den avancerade delen. Eftersom AM är likt svets så är det inga problem att svetsa på delar.

- Vad är det största problemet enligt dig?
  - Att de är för stora och för dyra men om du kan argumentera och motivera varför något så stort skulle printas så är det möjligt.

- Hur mycket kan du ändra designmässigt för att lösa problemet?
  - Beror på vad det är för komponent eftersom om den är låst kan jag inget göra men om man är med i idé-stadiet så går det bra.

- Hur planeras sammanfogning?
  - Bygger oftast vidare på en komponent eftersom det inte finns någon anledning att göra mer än man behöver.

Övrigt:

- Material och maskinspecifika saker är ofta saker som skiljer mellan varandra när man skall göra något för AM, helt andra krav på en Arcam-maskin och en EOS
- Andra krav på laser och EBM
- Porösitet är också viktigt och utmattning
- Toleranser och ytfinhet är väldigt beroende på material, pulverstorlek och annat

APPENDIX E Questions and answers Nicklas and Anders

Education: Nicklas – Technical college graduate, Anders – M.Sc. in Mechanical Engineering

Software: NX

Arbetet idag:

- Hur länge har ni arbetat med 3D-printing?
    - Nicklas: Mindre omfattning sedan 2011 (ca 6 år)
    - Anders: Mer regelbundet sedan 2015 (ca 2 år)

- Vad använder ni för stöd idag?
    - Använder sig av designregler som är framtagna inom Siemens.

- Några tumregler ni jobbar efter?
    - Ja, printriktning, ytors vinklar (minst 45 mot horisontalplan), kompensation för krympning, utformning av hål (blir inte runda om de byggs tvärs byggriktningen). "Taket" sjunker ofta in vilket man måste kompensera för eller göra hålen droppformade. Printar först en modell som vi sedan skannar och gör korregeringar om det behövs.

- Hur kompenserar ni för krympning?
    - Krympning beror ofta på tjocklek eller mängd material i ett snitt. Ofta så 3D-skannar vi efteråt för att hitta avvikelser vilket ofta ligger på ställen man har mest material eller annat som vi kan kompensera för.

- Hur mycket experimenterar ni med parametrarna i printern?
    - Ofta är det låst men man kan ändra scanningsmönstret. Ett stort problem ligger i att tunna strukturer kan få in för mycket värme men det tittar teknikerna på hur man kompenserar för. Om komponenter blir för varma kan de svälla och slå i recoatern som fördelar nytt pulver. De lägger även till fler saker på plattan för att ta ner kostnaden per print.

- Vad tycker ni fattas kunskapsmässigt just nu?
    - Tunt med kunskap om materialegenskaper, nu tas nödvändig materialdata fram i samband med utvecklingsprojekt.

- Får ni mycket frihet när ni löser problem eller finns delarna redan "klara"?
    - Vissa ramar gällande funktionen (areor och ytor) som vi måste förhålla oss till. Även interface mot kringliggande delar styr. Annars stor frihet.

- Några former/saker som ni ofta får göra om?
    - Horisontella ytor utan stödjande struktur, "tak". Hål, kompensera areor för krympning och formändring.

- Vem gör förarbetet inför tillverkning?
    - AM-tekniker

- Vilken AM-printer används vid tillverkning?

    - Vi har en EOS M270, tre M290, en M400 och en M280 som vi använder för reparation av bränslespridare.

- Har ni märkt nån skillnad på printrarna?
    - Hos de tre M290 maskinerna har vi inte märkt någon skillnad i att vi inte kan se vilken maskin det kommer från. Repeterbarheten är väldigt bra. Dock så har den större maskinen M400 fyra st. lasrar och placering är mer viktigt i den eftersom det kan bli vissa avvikelser. Det är också viktigt att inte ställa komponenter för nära varandra då uppvärmning kan påverka.

- Kan en produkt använda alla lasrar eller är det en produkt med en laser?
    - Tror man bygger en produkt per laser men det skall också gå att använda alla fyra. Dock är det oklart hur det blir med materialegenskaperna. EOS jobbar på det men inte något vi gör. Finns heller inte mycket materialdata så det får vi ta fram själva vilket gör att vi är hårt styrda av våra parametrar. Om vi ändrar något så kommer det innebära många nya tester även om vi vet att det kommer lösa problem. Kostar helt enkelt för mycket.

- Hur mycket vet ni om maskinen som skall printa ut delen?
    - Vi har koll på printvolymen (höjd och bredd) samt toleransen på repeterbarheten mellan printjobbet. Väggtjocklekar är beroende av höjd kontra tjocklek.

- Vilket material använder ni?
    - Största volymen printas i nickelbas sen är det rostfritt och lite incornel. Tittar just nu på andra material också.

Arbetet imorgon:

- Vad skulle ni vilja ha för att underlätta ditt arbete?
    - AM stöd i CAD-verktyget. (överhängande ytor, radier)

- Hur tycker du det borde se ut?
    - Återföring direkt i CAD-modell för att se sannolikhet för byggbarhet.

Tillverkande företaget:

- Hur mycket kontakt har du med tillverkningsföretaget?
    - Tät kontakt med AM-tekniker och programmerare. De bedömer byggbarhet och tar fram tid och kostnad för tillverkningen.

- Vad behöver de för att godkänna dina delar?
    - 3D-modell, materialkrav, ytfinhetskrav, renhetskrav, byggriktning, bygglagertjocklek, geometriska toleranser, krav på provningsomfattning.

- Vilka prover gör ni, vilka standards?
    - Beror på vad som skall printas och vad den skall användas till, finns ofta en teknisk specifikation. Med det vanligaste som görs är dragprov, slagprov, kornstorlek och porositet. Vid en serie skickas oftast 1/60 till röntgen eller förstörande provning. Alt. så printar vi en/flera provstavar i olika riktningar med komponenterna till olika prover.

- Har ni det per default i alla körningar?
    - Nej det anger vi. Exempel på en batch på 30 där man printar två åt gången gör man kanske en provstav var 6:e eller 10:e körning på olika maskiner för att studera förändringar. Oftast gör teserna vid nya pulverbatcher för att kontrolera kvalitén.

- Provning var 6e körning, vad baseras siffran på?
    - På vilken instruktion som sats, men kommer nog från erfarenhet av jobb med gjutning där man testar var 20-30:e komponent. Tester görs nog mest för att kolla hur regelbunden maskinen är dock är jag inte säker.

- Efterbearbetar ni alla saker som printas?
    - Nej men det första som görs är att rengöra printen när den är på byggplattan i ett slutet utrymme så inte pulver sprids, sedan sågas komponenten av. Bearbetning görs för att få rätt ytfinhet och ev putsas, printen ger ganska grova ytor. Hål bearbetas inte. Egentligen bara för ytfinish eller när vi ska ansluta den till nåt annat.

- Få ni ofta feedback från AM-teknikerna?
    - Ja, vi börjar lära oss vad som går och inte men nu så jobbar vi med att vi skickar modellen till AM-teknikerna som sedan kollar hur väl de kan printa den. Sen stämmer vi av med dom hur det ser ut, hur printen kommer gå till och hur modellen kommer att se ut efteråt med ytor och annat. Vi brukar använda oss av en romersk båge eller gotisk båge för att undvika ostödda ytor. Sen görs en provprint. Stoppas processen så har det ofta att göra med svällningar i materialet eller annat men hör vi inget så går allt som det ska. Fram till dess så är det tät kontakt.

- Jobbar ni något i Magics?
    - Nej men det gör AM-teknikerna. Oklart om de använder Magics eller Netfabb.

- Har dom lärt er nåt om hur magics funkar? Har ni nån tanke om hur placeringen ska va redan när ni konstruerar?
    - Ingen alls, vi gör bara modellerna och hur de skall se ut. Positionering och orientering sköter AM-teknikerna. Brukar få bilder på vart stödstrukturen kommer sitta och så överväger vi om vi skall göra en omdesign eller efterbearbeta de ställena ifall stödstrukturen inte går att efterbearbeta eller om man skall låta den vara kvar. Stödstruktur kostar ju att bygga och ta bort. I början gjordes mycket stödstruktur men vi har lärt oss mer nu.

- Ni har lärt er allt eftersom, ni har inte gått nån kurs?
    - Ja det är mycket erfarenhet och om konstruktören är ny så talar AM-teknikerna om vad som funkar och inte. I värsta fall har ingen tid men då får man fortsätta jobba och hoppas att det inte blir för många ändringar senare.

- Hur många AM-tekniker har ni?
    - Tror det är ungefär 5 AM-tekniker på 35-40 konstruktörer, dock jobbar inte alla mot AM. AM-teknikerna jobbar mot alla, även England, USA och Kanada.

- Hanterar AM-teknikerna produktionen också?

    - Nej de har hand om förarbetet och sedan står det operatörer vid maskinerna som tar hand om komponenterna, bearbetning, rengöring och liknande.

- Så det finns tre grupper; konstruktör, AM-tekniker, operatör?
    - Ja

- Hur mycket kan operatörerna?
    - De går en tvåveckorskurs hos maskinleverantören i Tyskland vilket även AM-teknikerna gör.

- Är det något ni tycker fattas i era guidelines som vi borde ha med i vår handbok?
    - Designreglerna är extremt beroende av den typ av AM-teknik som används med deras egna plus och minus. Även om samma maskin används så har byggbarheten med vilken typ av material man använder, så om de funkar i rostfritt kanske det inte funkar i AsteroX. Men det är bra att ha en mall för vilken information som behövs. Man har börjat med designregler med byggbara vinklar och tjocklekar men svårt att hålla det levande.

- Har ni nån process där ni aktivt uppdaterar dokumentet?
    - Man gör ryck lite då och då. Man kollar då bara om det något nytt man lärt sig sen senast men har inte varit något stort fokus på det. Lite ändringar kommer att läggas in om hur konstruktörer skal jobba mot AM. Tanken är att skapa en AM-grupp som i sin tur har koll på de designreglerna. Just nu fyller folk i det allt eftersom folk kommer i kontakt med det. Vilket är lite tråkigt eftersom vi ibland uppfinner hjulet omigen, tyvärr.

- Ja, det är väl ganska vanligt i stora företag att det blir så?
    - Ja, kommunikation är svårt. Även om vi sitter på samma våning så är vi olika avdelningar. Det är flera personer som börjar med AM, det kommer in nya hela tiden

- Med AM kan man ju göra en mer riktad funktion.
    - Ja, vi är på olika fas inom företaget men på vår sida var vi ganska tidiga. Produkten är ganska tacksam eftersom den inte roterar och drar nytta av interna kanaler. Vi har stor nytta av att utforma kylmönster på ett bra sätt. Nu börjar även personer som inte är konstruktörer att förstå fördelarna med AM, till exempel CFD-beräknare och de som tittar på kylning eftersom vi inte längre är begränsade av raka borrade hål. Vilket ställer högre krav på konstruktören gällande CAD-kunskap och komplexitet nu när man kan göra det. Problem kan dock uppstå när folk tror att vi inte har några begränsningar längre, vilket vi har. Vi har gått igenom vågen om att vi kan göra nya grejer och kan nu fokusera på vad vi verkligen kan göra.

- Gör ni någon topologi optimering?
    - Nej inte direkt. Delarna måste passa i maskinerna vilket begränsar lite. Men nu när vi kan utnyttja materialegenskaperna bättre och styra kylningen som vi vill blir idéerna allt vildare.

Vid delning av komponenter:

- Hur jobbar du när du skall dela upp stora delar i mindre delar?

    - Vi har inte hanterat komponenter med större storlek än tillgänglig printvolym.

- Vad är det största problemet enligt dig?
    - Stora komponenter blir dyra att printa. Bättre då att göra de större delarna ”konventionellt” och svetsa eller löda in mindre printade delar.

- Hur mycket kan du ändra designmässigt för att lösa problemet?
    - Funktion och interface är styrande.

- Hur planeras sammanfogning?
    - Beror på materialkombination. Lödning, svetsning eller skruvförband är de vi använder.

Övrigt:
- Printupplösningen påverkar ofta en hel del

APPENDIX F Questions and answers Dragan

Education: Bachelor's degree in Mechanical Engineering and Product Development

Software: NX and Magics

Arbetet idag:

- Hur länge har du arbetat med 3D-printing?
  - Jobbat på Siemens med AM i drygt 1 år.

- Vad använder du för stöd idag?
  - Har Siemens standardprocesser som vi följer.

- Använder du någon mjukvara för att simulera tillverkningsprocessen?
  - Har ingen simulering för spänningar men kan göra bedömningar i magics programmet, annars är det övning och erfarenhet.

- Några tumregler du jobbar efter?
  - Man kan inte printa överhängande ytor utan stödstruktur, placering på platta så recoatern inte slår i och att fördelningen av pulver blir bra och vilken vinkel man kan printa i. Hur många modeller vill man printa, om man har för många modeller kan det bli spänningar tillexempel.

- Hur kompenserar ni för krympning?
  - Vet att man tar hänsyn till krympning genom att kalibrera maskinen men vet inte hur mycket man gör det. Vet att det finns men inte hur det går till. Kalibreringen gör EOS.

- Hur mycket experimenterar ni med parametrarna i printern?
  - Generellt så har man en standard uppsättning. Det är labbet som experimenterar med parametrarna. Laserstyrkan, laserhastighet men funkar ofta med sunt förnuft, blir det smält eller bränt. Inte för mycket energi på ett för tunt lagret, som svets ungefär. Använder ofta EOS parametrar som de testat under en längre tid. Inget vi brukar experimenterar med, kan inte garantera hållf egenskaper om vi ändrar parametrar. Spårbarheten blir svår annars, kan då hänvisa till standardparametrar.

- Vad tycker du fattas kunskapsmässigt just nu?
  - Litteratur kommer mer och mer. Säger man 3D-printning tror folk det är som att printa ett papper. Det är inte att klicka på en knapp så funkar allt utan det är svårare än man tror. Det fattas kunskap om hur lätt och svårt det är. Måste gå igenom det grundläggande för kunden, regler och vad som måste göras. Omdesign, stödstruktur måste man ofta nämna för de har inte koll på det. Hade varit bra med en snabbkurs eller litteratur för kunden.

- Får du mycket frihet när du löser problem eller finns delarna redan "klara"?
  - Svårt att svara på, har frihet i hur detaljen skall printas. Om jag tror 45 grader är bäst för denna modellen och vilken yta som skall stödjas upp, hur ska jag placera och lagertjocklek. Får bestämma en hel del men måste göra det

tillsammans med konstruktören efter det är det dem som gör om designen, det kan inte jag göra. Får sällan en modell som kan printas utan omkonstruktion.

- Några former/saker som du ofta får göra om?
    - Hål horisontellt måste ofta ändra taket så det inte kollapsar in i sig själv. Standard men kan bli trixigt. Radier, faser som är för skarpa, former som kan skada recoatern. Hål måste nästan alltid göras om.

- Får ni den i STL format eller CAD-fil i tex STEP?
    - Om kunden inte har NX så är parasolid att föredra så gör vi själva om filen till STL. Då kan jag själv bestämma upplösningen. Får man den i STL så får man dra i handbromsen och kolla kvalitén.

- Andra format i framtiden?
    - För mig så fungerar STL bra men skulle varit bra med ett finare format. Att man slipper jobba i flera olika verktyg. I framtiden kommer vi nog kunna lägga till stödstruktur och liknande direkt i NX. Och att det finns fler AM funktioner i NX.

- Vem gör förarbetet inför tillverkning?
    - AM-teknikerna

- Hur kontrollerar ni komponenter innan print?
    - Kontrollerar CAD-modellens kvalité. Tar och för in den i Magics så jag kan se hur den blir med trianglar och annat, vilken kvalité den har. Kan se "pixlarna" i Magics. Det gäller att upplösningen på STL-filen stämmer överens med upplösningen på printern för att det ska bli bra resultat.

- Vad är det första du tittar efter när du får en modell?
    - Tittar på överhäng och geometrin. Hur komplex är den i printningsperspektiv. Ju enklare desto bättre. Är det möjligt eller inte och behöver jag ändra något? Ändra så den blir mer printvänlig.

- Går du tillbaka till konstruktören och säger att den kan gjutas eller svarvas etc?
    - Ja det är vanligt. Det vanligaste är att få in modeller som är optimerade för en annan process som gjutning eller CNC. Kan du ändra denna ytan eller denna radien. Detaljen skall helst vara självbärande. Det är väldigt vanligt att man går tillbaka och bollar med konstruktören.

- Vilken AM-printer används vid tillverkning?
    - Samma som Niklas/Anders

- Hur mycket vet du om maskinen som skall printa ut delen?
    - Som AM-tekniker kan det grundläggande i maskinen, kan inte plocka ner den men kan den grundläggande. Kan hur den fungerar.

Arbetet imorgon:

- Vad skulle du vilja ha för att underlätta ditt arbete?
    - Många saker men flyter på ganska bra. Maskinerna i sig kan jag inte klaga på men ett mer effektivare sätt att printa. Att maskinen själv kan välja laserns

effekt och liknande, fixar saker själv. Att maskinerna blir smartare, vrida plattan under processens gång. Mjukvaror som är mer integrerade. Ett system istället för flera. Lättare kunna kommunicera med konstruktören. Visa dem vad som behöver göras. Istället för att peka på saker. Ett bra verktyg.

- Hur tror du det kommer se ut?
    - Det kommer bli en mer vanlig tillverkningsmetod. Att fler privatpersoner kan starta egna företag. Att det blir mer spritt.

- Hur tycker du det borde se ut?
    - Hoppas att människan inte tas bort ur processen. Att vi fortfarande är en faktor i det hela. Att SLM skapar fler jobb än att den tar bort.

- När det kommer till stödstrukturer, vill du att det skall automatiseras eller att man skall göra det för hand?
    - Idag är det ett ont måste men kommer nog inte finnas i framtiden.

Tillverkande företaget:

- Vad behöver de för att godkänna dina delar?
    - Att vi kommer överens om det vi sagt tidigare, jag behöver detta för att kunna printa den och vill då att vi gör ett testförsök. Finns allt som vi pratat om och gjort de ändringar som behövs. Måste kunna kommunicera och mötas halvvägs. Självklart så behöver vi ritningar och kravspecifikationer på den slutgiltiga konstruktionen. Utöver ritning och fil så behöver jag material och legering, vart skall den sitta och användas till? Designen är perfekt men vilket material behövs.

- Vilken information saknas ofta vid beställning?
    - Inget som de vet vanligvis så kommer fram väldigt fort vad som fattas. Kunden får sen ofta en spec över vad vi kan och så får de kolla upp det. Material saknas ofta på externa kunder. Samt vilken maskin de vill printa i. Att detaljen kan vara större än byggplattan.

- Hur uppskattar ni kostnaden för en 3D-printad del
    - Avdelningen är ganska ny. I början var det svårt men idag så har vi beredning. Om vi får något så kommer vi överens med kunden vad som behövs och gör sedan ett test. När vi sedan kan uppskatta hur lång tid det kommer att ta så kan vi uppskatta kostnad per timme. Börjar med printtid och sedan tar det mot en beredare som uppskattar efterprocessen med stödstruktur och tester.

- Hur går det med kvalitetssäkring? Bestämmer du eller andra?
    - Efter att allt är klart så gör andra personer tester. Kunden ber om olika typer av tester och ber om bilder på materialstruktur och hållfasthet. Men det är inget jag gör, jag ansvarar bara för själva printningen.

Vid delning av komponenter:

- Hur jobbar du när du skall dela upp stora delar i mindre delar?

Inte något jag gjort ännu, frågan är nu om det är värt det. Man har funderat på det men är det kanske för dyrt. Delar men upp i flera olika så kan det bli för mycket efterbearbetning när man måste sätta ihop det igen. Har stött på en detalj som hade en diameter som var lite för stor för plattan, den stack ut lite, då kunde jag bara hänvisa till en större maskin som dock var dyrare. Detaljen bör passa innanför de parametrar som finns.

APPENDIX G Questions and answers Anonymous

Education: N/A

Software: N/A

Arbetet idag:

- Vad använder du för stöd idag?
    - Jag jobbar just nu med hur vi ska bevara kunskap från våra projekt och dokumentation om hur processen påverkar utskriften, men även med hur vi ska nå ut med kunskapen till personer på företaget - i detta så skapar man ju stöd för konstruktörer och beslutsfattare om när man bör använda tekniken, i nuläget så är "stödet" att vi håller presentationer och möten men i framtiden så kanske vi har ett datorprogram som underlättar. Vi använder redan idag stöd för automatisk generering av stödstruktur men kanske även simulering av byggprocessen i framtiden.

- Några tumregler du jobbar efter?
    - Att skapa vridstyva konstruktioner och kolla på termodynamiken i modellen, alltså göra radier och tjocklekar som lätt leder bort värmen till byggplattan. Kan använda mycket kunskap från andra tillverkningsmetoder om man tänker till lite. Design av stödmaterial är också viktigt att tänka på för att minimera byggtid och tid för efterbearbetning men även kvalitet på utskrift. Undvik att placera stödmaterial där produkten kommer att utsättas för drag vid belastning, kan ju bli defekter i och med borttagningen av stödmaterial.

- Vad tycker du fattas kunskapsmässigt just nu?
    - Designregler och terminologi är väldigt krångligt mellan olika företag, de säger en sak men kanske menar en annan eller använder gamla benämningar. Processflöden är också ganska bristfälliga i hur man hämtar och bevarar kunskap. Verktyg som underlättar tidigare val av tillverkningsmetod vore önskvärt och även simuleringsverktyg som kan upptäcka dåliga konstruktioner av detalj och stödmaterial, så vi slipper ha kunskapen i PDF-form och kan gå mer mot plug-and-play och därmed minimera ledtid, kostnad och miljöpåverkan. Det vore önskvärt till exempel att samtidigt optimera topologi och stödmaterial så att man får minimerar ledtid och kostnad.

- Får du mycket frihet när du löser problem eller finns delarna redan "klara"?
    - Jag jobbar mest med prototyper och där har jag inte så stor frihet i designförändringar, men ofta kan andra tillverkningsmetoder vara bättre lämpade. Det gäller att stå på sig och säga ifrån om något inte kommer att gå och att de slösar pengar på en "dyr julgran". Demonstratorer är bra för att ge exempel på varför vissa saker går och andra inte. Därför utvecklar vi också demonstratorer, när jag har ett sådant projekt så är det huvudsakligen jag som bestämmer över designen.

- Några former/saker som du ofta får göra om?
    - I och med att jag jobbar mest med prototyper så får jag oftast inte göra några förändringar med geometrin.

- Vem gör förarbetet inför tillverkning?
    - Varierar, personen som gör stödstrukturen bör även göra STL-filen annars kan det bli problem med upplösning och annat. Eftersom tekniken är dyr så blir kommunikation extra viktigt så utskriften helst blir rätt andra gången, men det kan ju krävas många fler utskrifter även med god kommunikation.

- Vilken AM-printer används vid tillverkning?
    - Eftersom vi tittar holistiskt på additiv tillverkning gällande material och teknologier så är varierar det mycket.

- Hur mycket vet du om maskinen som skall printa ut delen?
    - Eftersom vi oftast beställer så vet jag om vilken typ som används. Ofta ger leverantörer tre olika alternativ: As-built, lite optimerad build eller fullt optimerad build. Oftast så får man inte till sig nyttig kunskap när man beställer utskrifter från leverantörer eftersom de vill bevara viss typ av kunskap inom företaget. Det har börjat dyka upp kunskapsbanker som man kan vända sig till på olika ställen, forskningsinstitut eller företag som delar på en "maskinpool".

Arbetet imorgon:

- Vad skulle du vilja ha för att underlätta ditt arbete?
    - Att fler personer inom gruppen kan mer om konstruktion för AM så de själva kan se om något är fel eller inte går. Många vill snabbt få till sig kunskapen med designregler och potentialer med additiv tillverkning men det finns inga bra genvägar just nu. Det är viktigt att ha dedikerad personal med god kunskap centralt i organisationen och utbildning av ambassadörer som man kan ta hjälp av.

- Hur tror du det kommer se ut?
    - Ju nu är det mesta bara "smäck" och tjänar inte något till men efter hypen lagt sig så kanske folk kan koncentrera sig mer på möjligheterna AM ger för produkten och miljöaspekter. Att alla har tillgång till någon typ av stöd vid inriktningsbeslut och konstruktion för att minimera ledtid, minska frustration, möjliggöra designmöjligheter, bara använda additiv tillverkning där det är befogat, mm. Jag tycker inte att hjälpmedel som underlättar detta bara bör finnas hos "experter" inom additiv tillverkning, då kommer det gå för långsamt.

Tillverkande företaget:

- Hur mycket kontakt har du med tillverkningsföretaget?
    - Inte så mycket, det är andra som har den kontakten. Jag får mest reda på om det funkar eller inte.

- Vad behöver de för att godkänna dina delar?
    - Räcker oftast med STL-fil, de klarar oftast resten utan problem. Jag brukar alltid skicka med förslag om orientering med förhoppningen att de ska kommentera om det är bra val eller inte, ibland hålls en diskussion om detta.

Övrigt:

- Har du märkt en stor skillnad mellan maskiner? (Mellan samma modeller)

    - Ganska fina skillnader som i toleranser men mycket i hur väl man själv har optimerat STL-filen. Blir alltid vissa skillnader men kanske mer är beroende på valet av maskinparametrar.

- Har det mycket med hur CAD-modellen ser ut eller är det parametrarna på maskinen? Vad skall man tweaka?
    - Beror ju på problemet. Design av stödmaterial är också viktigt för att resultatet ska bli bra, design av CAD-modell kan behöva ändras för att det ska bli bra. Väldigt svårt att välja orientering om ingen hänsyn till orientering har tagits vid konstruktionen. Jag har bara begränsad erfarenhet av att tweaka maskinparametrar så kan inte riktigt svara på vad man skall ändra på vid olika situationer och hur mycket tid som går åt till detta, men antar att tidsåtgången minskar med erfarenhet.

- Hur tänker du när du väljer orientering?
    - Det beror på, hål blir ju bättre utskrivna horisontellt och sen tänka på om det finns en anisotropi i materialet som kan ge brister i ytan. Stödmaterial är också viktigt att tänka på så att det är möjligt att ta bort och om det är en komponent som ska klara laster så undvik att placera stödmaterial där det förekommer stora dragkrafter. Stödmaterial måste man ju alltid ha så man kommer ju inte riktigt undan det men man kan nog komma undan lite grann.

- Delning?
    - Inte gjort det men vet andra som gör, bäst att slippa om möjligt, Magics gör det automatiskt, som jag har fattat det så görs delningen bara rakt igenom, maskinoperatören kan ofta fixa de problemen, behöver ha tillräcklig tjocklek, i plast så limmar man ofta bara ihop dem, jag har ingen riktig erfarenhet inom området just nu, ändrar hellre designen om det är en end-product som ska skrivas ut kanske att dela upp den i flera komponenter och bara printa de delar där det är befogat.

APPENDIX H Questions and answers Olaf

Education: Professor in Product Development

Software: Solidworks, Creo, Inspire and Magics

Arbetet idag:

- Hur länge har du arbetat med 3D-printing?
  - Officiellt i 10-15 år men startade med prototyper i början av 90:talet

- Vad använder du för stöd idag?
  - Man måste vara bra och snabb på att konstant lära sig nya program.

- Använder du någon mjukvara för att simulera tillverkningsprocessen?
  - Nej, tyvärr så är dessa program bara i utvecklingsfasen. Att simulera lager funkar men länken mellan lagren är väldigt svårt. Om något år så kommer de säkert ha löst det dock.

- Några tumregler du jobbar efter?
  - Många som tjocklek och storlek på väggar. Att minimum storlek på hål växer med tjockleken. Annars så bygger vi på en databas med överhäng och liknande hela tiden.

- Vad tycker du fattas kunskapsmässigt just nu?
  - Att ingenjörsutbildningar börjar inkludera AM-konstruktion med alla andra tillverkningsmetoder. Inte bara i masters utan också i grundutbildningarna. Metall är mycket svårare än plast.

- Finns det någon typ av litteratur som du saknar?
  - Problemet ligger mer i att de som lär ut AM lär ut sin egen grej, det finns ingen kontinuitet i lärandet. Det fattas även databaser med guidelines och allmän data, tråkigt nog finns detta men företag håller det för sig själva. Alla måste då göra sina egna tester, de måste uppfinna hjulet igen.

- Finns det ett behov av standardisering?
  - Ja, de tittar på det men det finns ingen på hur man utbildar folk.

- Får du mycket frihet när du löser problem eller finns delarna redan "klara"?
  - Det varierar mycket på projektet. Just nu är ca 90% av delarna inte designade för AM utan för andra tillverkningsmetoder.

- När du hjälper företag med AM förstår de fördelarna med att designa för AM?
  - Flyg och medicin förstår vikten i att göra saker så lättviktigt som möjligt men mer konsument inriktade företag som Bil-tillverkare och liknande är det fortfarande för dyrt. Är produkten inte högprestanda så är det svårt att argumentera för det. Handlar fortfarande om pengar men ändras nog inom de kommande 2-5 åren.

- Några former/saker som du ofta får göra om?

    - Inte riktigt. Säger ofta till dem att vi kan printa det men det kommer inte vara värt det om den inte är komplex nog. Sen är problemet att få bort supportmaterialet.

- Gör personer ofta för stora hål eller har de svårt att förstå relationen mellan stora hål och ojämna hål?
    - Ja och vi kommer då tillbaka till printorientering och hastighet. Exempel med min guitar där de en gång lade på stöd där det inte behövdes och jag fick sitta länge med att ta bort jobbiga support. Jag skulle inte gjort det men de använde "default settings".

- När det kommer till fil-format vet du några fler som skulle vara bättre än STL?
    - Ja, STL är ett antikt fomat som inte bör användas, AMF och 3MF är mycket bättre. Men varför inte printa direkt från CAD? Vi förlorar information varje gång vi konverterar till STL. Man jobbar på det men är inte där än.

- Vem gör förarbetet inför tillverkning?
    - De med printern. Det vore bra om designers som skall jobba med AM får arbeta med en maskin så de lär sig processen. När jag skickar en beställning så får jag den redan efterbehandlad så ber dem nu skicka obearbetad så jag kan lära mig hur jag kan göra den bättre.

- Så företagen berättar inte för dig om det har varit problem?
    - Nej eftersom de inte vill berätta för dig om den är svårt att göra eller inte, denna information vill de behålla för sig själva. Att förstå fördelarna med att designa något för efterbearbetning är väldigt viktigt eftersom största tiden, och ibland pengarna, läggs nu på att ta bort stödmaterial för hand. Maskiner som tar bort stödmaterial automatisk är nästa steg.

- Vilken AM-printer används vid tillverkning?
    - Har egna LS-maskiner men enbart i plast och nylon, skall dock köpa in en metall-skrivare i år. När jag gör något i metall så är det mestadels SLM. Det är bättre för ingenjörer och EBM är bättre i medicinskt syfte. Finns ingen direkt skillnad mellan de olika märkena när det kommer till SLM, dock har vissa öppna parametrar och andra inte.

- Hur mycket vet du om maskinen som skall printa ut delen?
    - Vid metall så behöver man mycket mer kunskap än för plast eftersom allt är mycket mer kritiskt och behöver då förstå processen bättre. Man kan likna det med "barely controlled chaos" så beroende på hur bra du kontrollerar det får du bättre kvalité.

- Vilket material använder ni?
    - Mestadels stål för vetygtillverkning vilket företagen vi har kontakt med är intresserade av.

Arbetet imorgon:

- Vad skulle du vilja ha för att underlätta ditt arbete?
    - Designutbildning måste ändras och införa hybrid maskiner som kan göra delen och efterbearbeta den efteråt automatiskt.

- Hur tror du det kommer se ut?
    - Om 3-5 år så kommer vi se hybridmaskiner, maskiner som kan använda flera material samtidigt och att integrera fackverk i CAD-programmen så vi slipper använda 3-5 olika typer av mjukvaror.

Tillverkande företaget:

- Hur mycket kontakt har du med tillverkningsföretaget?
    - Inte riktigt, om något riktigt dåligt så får jag reda på det annars så hör jag inte så mycket eftersom det mesta går att printa men kanske inte optimalt. Om det inte går bra första gången måste vi betala för samma modell igen.

- Vad behöver de för att godkänna dina delar?
    - Eftersom det mesta går så måste man oftast skicka med en förklaring om hur man vill positionera den för att minska stödstrukturer och vilka hål som är kritiska och vilka som inte är det. Nästa problem är att få saker certifierade då man måste använda samma orientering och position i maskinen annars kan kvalitén skilja sig. Eftersom det inte finns någon standard. Gör man det i hörnet måste man alltid göra det i hörnet.

- Är de ten stor skillnad mellan maskinerna?
    - Det har blivit bättre, nu har man till och med flera lasrar i en maskin för. Dock är de ännu inte så bra att de lasrarna kan samarbeta. Styrkan och hållfastheten kan skilja sig där de överlappar. Man har börjat införa kameror som studerar processen likt Arcam.

Vid delning av komponenter:

- Hur jobbar du när du skall dela upp stora delar i mindre delar?
    - Inte jobbat med metall ännu men brukar dela komponenter symetriskt och lägger till hjälpmedel för att ställa upp dem korrekt. Likt hål och pins eller hanar och honor av olika slag.

- Hur mycket kan du ändra designmässigt för att lösa problemet?
    - Ofta kan man införa en "cosmetic line" för att gömma delningslinjen.

APPENDIX I Questions and answers Marc

Education: Masters of Engineering in Economics and Management

Software: NX, Magics, Renishaw QuantAM and whatever the customers use

The work today:

- How long have you been working with 3D-printing?
  - 2-3 years at Renishaw

- What kind of support do you use today? Any method or process or have you made your own?
  - There are different ones to follow, don't really know, spend a lot of time in the concept stage and think of how to position it and design it,

- Do you use any software for simulating the printing process?
  - We do, we work with a lot of different providers in that area, we don't develop ourselves but work with companies with good software, eg 3Dexperience suite (Dassault Systems), Semifacts, 3Dsim (US) there are quite a lot of companies developing these types of programs, we're helping with practical experiments to see how well the simulation predict the build. None make an optimal prediction and there is a lot of things that needs to be tested in concept now but it is on the way, it's quite a complicated process with a lot of parameters.

- Any "rules of thumb" you working with? Design guidelines?
  - Sure, there are basics on what works better than others, and guidelines about what support to use and where. rules are quite general and established, now it is more on how to design without the use of supports, you really need to spend time in CAD to really optimize for AM, how to position it in the machine and how to make it more optimal for AM, basically you deconstructing into its basic features and include the interfaces to other components around and the metal connecting it all is up for grabs, how do I connect all the parts in the best way possible.

- What do you think is missing in terms of knowledge at the moment? (Educational material, courses, literature, knowledge within the company, at the manufacturing site etc.?)
  - They do not have any experience and do not understand how to make things more buildable, want to make customers optimize designs for AM, now they might start with a design that is better than the one before and the next time they want to cram more functions in the parts, you go through stages for each iteration, building knowledge and gaining confidence in what can be done. We are making our own education material, we are making courses that describe why some things work and some don't, but the critical thing is when applying these general theories to a practical case. We have theoretical training courses to make people think and then go into a practical problem, we need schools to start with this as well, the tools are not yet mature but it is on the way, as more people goes through the learning experience there will be more.

- How much freedom do you normal have for problem-solving or is the part already "done"? (Who is normally making the design decisions?)
  - It depends on the customer, in aerospace they will be reluctant to change the design and material, there is a lot of testing that needs to be done, consumer products where the development cycles are shorter they are more willing to change the design, also a lot about the company culture.

- Are companies afraid?
  - Not really, they are limited in skill and resources. it is a shortage of experienced engineers, so it is hard to take on big engineering challenges. It's about how strategic they are, the ones who are investing in AM realize it can make them competitive on the market both cheaper and better products. now the engineers needs to persuade the tops to put money into AM,

- Are there particular geometries that often need to be redone?
  - No particular geometries, the problems is that they are designed with another manufacturing method in mind, they are bulky - slow to build and have awkward overhangs, need to talk to customers to understand that they need to think about the next product not the one from three generations ago, lattice structures are hard to make in CAD but good in AM

- Are there some misunderstandings/misconceptions?
  - Some people think that they can do anything in AM, comes from plastic, most people pick that up quickly and understands that even this manufacturing method has rules and limitations,

- Will it be closer to plastics in terms of design freedom?
  - Fundamental physics cause limits with SLM but technology will expand the range of geometries and materials, there is a trade-off between productivity and complexity. There are other types of AM metal technology that are emerging that are quite interesting like binder jetting and sintering type technology.

- Who's doing the preprocessing before printing? Do you have specialists or are all designers also adding support structures/orientation etc.? (You, someone else at the company or the manufacturing company?)
  - Both designers and experts, we are usually working with designers who aren't interested in how they're made but how they perform. But also people like material scientists whose concern is how to make things and what it cost. We also interact with supply chain people because companies design but don't manufacture and they want to know how they can get them built in for instance Asia.

- What 3D-printer do you use for manufacturing?
  - We sell two different models, both are similar physical size. one is more multi-material, you can change between materials fairly quickly, it's more of an R&D platform and one that is more automated, industrial manufacturing platform. They are about 250*250*300, this midrange size is the most sold one

- What materials do you normally print in?

  - A wide range, titanium, Inconel, nickel alloys, steels, aluminum, cobalt chrome, tungsten, copper, innovation in materials will be as important as geometries, new materials mean potentially new product performance, that’s why we have an open model so customers can modify the parameters if they want to use their own material and process parameters so any material can be used in our machines.

- Is it important to think about the material when designing for AM
  - Yes, it is, it's a huge part of how the product will perform. An important part is that you really have to understand what you want your component to do and choose material accordingly. I think we'll see new alloys that won't be machineable.

- Is there a difference in thickness and things like that?
  - Yes, you use different processing parameters for the machine. The different material absorbs energies in a different way which means that the features you can make will differ. So you have to design with that in mind, the material, process, and design all interact. We still have to experiment to learn more about that.

- How much knowledge do you have about the printer?
  - Often not very much, one of the key challenges to making them understand what they can and can’t do. there are some range depending on the history of the company and how much time they've invested

The work tomorrow:

- What would you like to have to make your work easier? (Available courses and course material?) What is missing to make AM bigger and even more popular and usable?
  - Over time the customers will be more familiar with the benefits and limitations with additive technology, have more realistic expectations, it's a very exciting time right now because we're all learning a lot. The more we work the more everyone is gaining. It's rich in learning opportunities in the next 10 years we will see a huge amount of progress and change.

- How do you think it will be?
  - AM will become a mainstream manufacturing process for the products that can benefit from its capability; the complexity, customization, lightweight and efficiency. As technology gets more cost effective and widespread the range of opportunities will grow. People will understand how to use it more, it is scaling quite well right now, AM will regularly be used in factories but won’t be making simple things, instead it will be used for more complex things.

- How do you think it should be like?
  - I think it should be as I think it will be. It will be a compliment for the other types of manufacturing. It won't mean an end to machining, casting and forging but it will have an increasingly important role to play.

APPENDIX J Questions and answers Karolina

Education: N/A

Software: Solidworks, Magics, EOSprint and PSW

Allmänt:

- Vilka programvaror använder ni?
    - Solidworks lite grann, Magics, simuleringar i EOS program EOSprint och PSW.

- Har ni några design guidelines på företaget? (Tips och trix som ni delar med er till kunder)
    - Vi brukar tipsa om de enklaste att tänka på, att göra radier istället för skarpa hörn. Att tänka på att det inte går att börja bygga i löst pulver utan att det då behövs stödmaterial.

- Har ni några speciella processer som ni jobbar efter?
    - Nej.

- Hur ser ert arbete ut mellan företagen med diskussioner om delar och hur de skall tillverkas?
    - Det är mycket olika. Med en del har vi många möten, både på telefon, skype och IRL (In Real Life) för att diskutera. En del skickar bara en fil och vill ha den som den är, då finns det inte så mycket att diskutera om.

- Några kurser eller litteratur som ni använder?
    - Vi fick en väldigt kort introduktion av maskintillverkarna när vi skaffade maskinerna. Sen har det varit ”learning by doing” som gäller. En del mjukvara får vi lite utbildning på när det är uppdateringar.

- Hur bra koll har ni på hållfasthet och liknande? Vad skiljer en 3D-printad komponent från en solid del?
    - Enligt tester som vi gjort skiljer det i princip inget i hållf på en printad och konventionellt tillverkad detalj. I vissa fall har den printade visat bättre egenskaper än smidda detaljer. Vi har materialspecar från maskintillverkarna på deras material som stämmer mycket bra.

- Har ni ett färdigt underlag med information som ni ger kunder? (Lista med toleranser, begränsningar etc.)
    - Nej.

- Hur hämtar ni den kunskapen? Läser ni forskningsresultat eller är det "trial/error" som ni främst lär er på?
    - Vi deltar i en del forskningsprojekt som ger oss värdefulla kunskaper. Men mycket lär vi oss genom att bygga och bygga och bygga…

Maskiner:

- Hur bra koll har de som står vid maskinerna? (Utbildning, förståelse för arbetet innan etc.)

    - Mycket bra koll. Vi som jobbar här med printningen är med hela kedjan, från diskussion med kund och beredning till preparering av maskinen.

- Hur begränsade är maskinerna, följer ni vad som står på dem eller har ni egna toleranser? (Minsta tjockleken på väggar till exempel)
    - I regel så stämmer maskintillverkarnas data om vad som är möjlig att bygga. Men det är klart att vi provar att tänja på de gränserna, med blandade resultat.

- När det kommer till placering och uppställning vad tänker ni på? (Kostnad, kvalite eller tid?)
    - Kvalitet/Kostnad. Alla vill ju ha så billiga detaljer så möjligt, men de måste ju samtidigt vara bra. Kan vara svårt för en del att förstå.

- Hur kontrollerar ni kvalitén vid alla printar? (Tester som görs på maskinerna/materialet/färdiga komponenter)
    - Vid behov utför vi mätningar med mätmaskin, röntgen, penetrantprovning, dragprov mm.

Innan ni fått CAD-filer:

- Vad för information behöver ni för att kunna skriva ut en del?
    - Material, viktiga ytor och andra funktioner.

- Vilken information saknas ofta vid beställning?
    - Viktiga ytor och funktioner.

- Hur uppskattar ni kostnaden för en 3D-printad del?
    - Vi simulerar ett bygge i mjukvaran och får fram ett exakt pris, det är det enda sättet. Att gissa innan vi fått fil blir oftast väldigt fel.

När ni fått CAD-filer:

- Hur kontrollerar ni komponenter innan print?
    - Vi synar detaljen i olika mjukvaror. Oftast upptäcker vi konstigheter snabbt.

- Vilka former brukar ofta vara ett problem?
    - Det största problemet är att vi får filer på detaljer som ifrån början ej är tänkta att 3D-printas. Många har inte kunskapen för att kunna optimera konstruktioner för 3D-printing. Kan inte säga en specifik form som är extra svår. Skulle vara detta med radier då, gör alltid radier istället för skarpa hörn!

- Vad är den vanligaste anledningen till att ni måste be företag att göra om komponenter?
    - Att vi märker att det blir väldigt mycket stödmaterial som blir svårt att ta bort.

- Vem tar hand om förarbetet av CAD-filer? (Göra om till .STL eller .AMF)
    - Torbjörn (Karolinas kollega) eller jag, mest jag

- Vem tar hand om stödstrukturer?
    - Torbjörn eller jag, mest Torbjörn.

APPENDIX K Questions and answers Ali

Education: Technical Physicist

Software: Magics, Build processor and EBM control

Allmänt:

- Vilka programvaror använder ni?
  - Mycket från Materialise som Magics och Build processor, EBM control för att styra strålen.

- Hur mycket egen tillverkning har ni? Eller är det bara försäljning av maskinerna?
  - Inga delar, har ett dotterbolag som är krontrakt tillverkare, i Sverige har man bara maskintillverkning, Disanto heter dotterbolaget som är i USA

- Har ni några design guidelines på företaget? (Tips och trix som ni delar med er till kunder)
  - Har guidelines för Magics men inte något för konstruktörer. Många experimenterar mycket själva med designen och skapar erfarenhet men vi kan hjälpa dem beroende på hur långt de kommit i designen.

- Har ni några speciella processer som ni jobbar efter?
  - Nej

- Några kurser eller litteratur som ni använder?
  - Vi har två kurser som vi lär ut, lvl 1 och lvl 2. Lvl 1 är en e-learning för hur man hanterar maskinen och underhåller den, magics, material och annat. Lvl 2 kommer senare och handlar om hur hela processen fungerar, man sen ändra parametrar och annat.

- Så du säger att design o förberedelse av design och struktur är mer viktigt?
  - En bra design är ett stort steg i rätt riktning. Att allt är genomtänkt spelar stor roll och parametrarna är redan ganska optimala.

- Hur bra koll har ni på hållfasthet och liknande? Vad skiljer en 3D-printad komponent från en solid del?
  - Vi har väldigt bra koll på det och det liknar gjutning väldigt mycket så funkar det i gjutning så funkar det i AM.

- Hur skiljer de sig från laser?
  - Nästan samma mellan EBM och laser men de visar ofta siffror från efterbehandling vilket de inte alltid säger. Om man jämför EBM och laser direkt efter maskinen så finns det nog stora skillnader.

- Vilka material fungerar i EBM
  - Allt som är ledande fungerar med EBM men lämpar sig olika mycket. Vi fokuserar på att det skall fungera bra så har bara 4 material just nu, fler är på väg. Har lagt fokus på vissa industrier.

- Har ni ett färdigt underlag med information som ni ger kunder? (Lista med toleranser, begränsningar etc.)
    - Finns specat i maskinerna.

- Hur hämtar ni den kunskapen? Läser ni forskningsresultat eller är det "trial/error" som ni främst lär er på?
    - Till viss del forsning men mycket är hör ifrån.

Maskiner:

- Hur bra koll har de som står vid maskinerna? (Utbildning, förståelse för arbetet innan etc.)
    - Operatörerna har bra koll på hur de sätter upp maskinerna hårdvarumässigt men mycket mer.

- Hur begränsade är maskinerna, följer ni vad som står på dem eller har ni egna toleranser? (Minsta tjockleken på väggar till exempel)
    - De är inställda för att ge bästa toleranserna från början och dess specifikationer finns kommer med alla maskiner.

- När det kommer till placering och uppställning vad tänker ni på? (Kostnad, kvalite eller tid?)
    - Har guidelines men kan tyvärr inte dela med oss av dessa.

- Hur kontrollerar ni kvalitén vid alla printar? (Tester som görs på maskinerna/materialet/färdiga komponenter)
    - Olika mellan brancher och kunder. Det kommer en byggrapport med varje print med hur maskinen arbetat under printen så man kan se ifall något sticker ut samt att det tas bilder på varje lager för att kolla porösitet. Händer inte ofta utan problem uppstår oftast när man inte håller maskinerna rena, i bra skick och upprepar samma sak mellan varje laddning. Vanligen gör man testbitar för att kolla allt innan man kör.

- Ofta skillnad från körningar?
    - Inte mycket, oftast blir det skillnad om man använder gammalt pulver som tagit upp för mycket syre.

Övrigt:

- Vad tycker du fattas kunskapsmässigt inom AM just nu? (Material, kurser, litteratur, kunskap hos företaget, hos tillverkarna etc.?)
    - Stor brist på kvalitetskontroll och validering så man kan lite på produktionen. Kommer ske en stor ändring de kommande 5 åren eftersom det finns en stor efterfrågan. Vet man inte vad som kommer ut så kan man inte argumentera för det så behövs mer försäkringar och validering.

- Är det kunskap eller standards som fattas?
    - Kunskap om vilka parametrar man skall hålla koll på för att säkerställa kvalité. Finns mycket att kolla på nu men man vet inte vad som är viktigt och inte. Fattas kunskap om AM just nu och kraven ökar hela tiden, 3 av 4 räcker inte utan varje gång måste man få samma resultat.

- Så mer forskning behövs i detta?
  - Ja, forskning och standarder.

- Några former/saker som du ofta får göra om? (något du märkt som funkar bättre/sämre, något som folk ofta gör fel på?)
  - Väldigt små hål så är det svårt med EBM, pga upplösning, svårt att få ut pulver ur håligeter eftersom blästring inte fungerar så bra i detta läget, storleksbegränsningar, väggtjocklek kan man gå ner till 0.6 till 0.7 mm, du kan designa under detta men det som kommer ut kommer ha denna storleken.

- Finns det max diameter på hål innan det säckar ihop?
  - Ställer man den upp så kommer man få en ihopsäckning hur man än gör, kan vara bättre att borra hål och annat efteråt, om hålet har höga krav, annars kan man bygga den vertikalt, detta är ett bra exempel på där erfarenhet och liknande kommer in hos konstruktörer, om toleranser är viktiga på hålen så designa inte in dem utan borra in dem efteråt.

- Hur tror du det kommer se ut? (vem gör förprocessen o liknande)
  - Vet inte hur det kommer se ut, de som CADar kanske ger sig in lite på AM delen men kommer nog fokusera på CAD som de gör bäst, mindre företag så blir de lite både och men i större företag blir det säkert olika personer som gör saker, blir lite för stort annars, om man jämför med dagsläget så kan man kolla på konstruktörer som gör saker för gjutning, de vet hur de fungerar men står inte o sätter upp saker o ting.

- Är det en stor tröskel för att lära sig Magics och AM?
  - Inte jättehög tröskel men behöver erfarenhet i området.

- Har ni jobbat något med delning?
  - Håller inte på med det, har en kund som delar och svetsar ihop sedan, inte många delar just nu upp i två.

APPENDIX L Interview with Sebastian

Sebastian är industridoktorand som jobbar på Saab Dynamics, den delen av företaget som gör vapen etc vilket kan vara förklaring till att AM bäst lämpar sig för prototyper för dem och att han är kritisk till att värdet på en AM produkt kan betala för en så pass dyr tillverkningsmetod.

Hans uppfattning efter 2 års studier kring DFAM är att det inte är så svårt att följa designreglerna (eller att hitta dem). Han anser att det ofta är bättre att prata med tillverkarna direkt eftersom dem ofta har mer kunskap kring hur maskinen fungerar och ofta testat den och vet vad som funkar designmässigt. Enligt honom är det mer intressant att undersöka värdet på produkter i första hand. Hans erfarenhet säger att konstruktörer använder enkla former som går snabbt och lätt att göra i CAD program som löser problemet dvs uppfyller kraven. Först därefter anpassas det till tillverkningsmetoden. Han anser att det idag inte är många konstruktörer som är duktiga på designregler kring tillverkningsmetoder vilket innebär att det alltid blir ett tätt samarbete med tillverkare, oavsett metod.

Han pratade mycket om hur man kan rättfärdiga att använda AM eftersom det är så dyrt. Ofta är argumentet att det inte går att tillverkar på annat sätt men då är ju följdfrågan huruvida man kan ändra produkten på något sätt för att kunna tillverka på annat sätt och därmed få ner priset. Ett sätt att se DFAM är topologi optimering vilket ofta leder till komplexa geometrier men om dessa är värda att printa är en annan fråga. Hur mycket är det värt att få ner vikten? Betalar det för den extra tillverkningskostnaden?

De två huvudspåren han hade var att man antingen har avancerade former eller material som då endast lämpar sig för AM. Men dessa måste vara värda den extra kostnaden.

Ett annat problem är att få bra kvalité och ha jämn kvalité vilket Siemens har löst, enligt honom, genom att ha sin egen produktion vilket gör det enklare att utveckla kunskap in-house och ha bättre kvalitetskontroller och styra över produktionen.

Sammanfattningsvis så var han väldigt fokuserad på värdet och rättfärdigandet av AM snarare än DFAM då han ansåg att det fanns mycket kunskap kring detta redan men samtidigt trodde han inte att det användes i industrin. Han trodde att de snarare testade sig fram på sina maskiner än satt och läste avhandlingar.

A Designer's Handbook for Metal Additive Manufacturing

Part of the Master's thesis Industrialization of Additive Manufacturing

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A handbook for designers curious about metal additive manufacturing (AM). This handbook provides some general knowledge about the technology, specifically metal powder bed fusion AM, and some general design rules and guidelines.

1 INTRODUCTION

This document is aimed for people who want to know more about powder bed laser additive manufacturing (hereafter shortened AM) and are interested in the technology and the design restrictions and possibilities it presents. Since it is a relatively new technology the general knowledge is low and therefore the decision was taken to be thorough in the explanations and not assuming that the reader has any previous knowledge. Electron beam melting (EBM) is a similar process to laser sintering (LS) but it is not the same so before applying this document on EBM ask the manufacturer for differences in everything from parameters, build quality and post-processing.

It is important to remember: the more communication between designers, manufacturers and post processors the better because it is beneficial for everyone. Like with every other type of manufacturing process parts need to be optimized for that type of method. It is not always easy to know what process is the best one. Because AM is new and relatively expensive it might be hard to convince the company that AM is the right choice and some assurance is always needed before investing in something. One way of assurance could be using a process like DfAM or ETAM, see 2.1 *Terminology* and 8.3 *Articles/thesis*.

The first chapter is this introduction chapter and the second one describes how AM works, the tools needed to create a product for AM and presents the process of designing for AM. The third chapter gives useful questions to consider as early as possible in the design process, ideally before starting with the design. The forth chapter, there are rules and guidelines presented and illustrated with some more general advice and some numbers. Pre- and post-processing is an important part of the method and this is presented in chapter five. Chapter six is intended for adding illustrations with examples of DfAM (Design for Additive Manufacturing) and finding inspiration. In the seventh chapter advice for future work is given together with general comments, for instance, it is important to continue to update this document. Lastly, in chapter eight a list of recommended reading can be found. This is a good idea to have a look at if there are questions about the sources or if a deeper investigation is of interest.

2 WHAT IS ADDITIVE MANUFACTURING

Additive manufacturing (AM) is the common name for different manufacturing methods that all have one thing in common, namely that material is added rather than subtracted from a workpiece. The process focused on in this document is powder bed fusion because it is the most commonly used AM process in industries today. This means that models are built layer by layer in a machine, more on that in Chapter 2.2 *How it works*.

One common misunderstanding is that anything can be made using AM but the reality is that there are limitations, just like traditional manufacturing methods. Another common belief is that AM will replace all other manufacturing methods but this is unlikely, it will rather complement traditional processes instead of replacing them. AM is a relatively slow manufacturing process so it is often used in smaller production batches.

2.1 Terminology

The difficulty with AM is all the terminology that easily can be used in the wrong way if not being careful. Many terms that are used are trademarked and therefore one has to be aware of what they mean. The terminology is being standardized as of writing this method and the list is constantly growing. In *Table 1* some of the most commonly used and misunderstood terms when it comes to AM are shown. For instance "3D printing" is commonly used in the media for all AM technologies, which is not what it actually means, as seen in *Table 1*.

Table 1. Terms commonly used in AM context and their description. Some of the terms are commonly used in the wrong context but here are the right descriptions.

Terminology	Correct description
3D-printing	"The fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology"[1,2]
Additive manufacturing	Making objects by joining material, usually, layer by layer[1,2]
Subtractive manufacturing	"Making objects by removing of material (for example, milling, drilling, grinding, carving etc.)"[1]
Powder bed fusion (PBF)	AM process where some sort of heat source, usually laser, "selectively fuses regions of a powder bed"[1,2]
Rapid prototyping	AM is used to quickly build and test design or function, usually associated with plastics rather than metals because of the cost[2]
Laser Sintering (LS)	Sinters or melts the powder in PBF with one or more lasers.[1,2]
Selective Laser Sintering (SLS)	Using the LS technique but trademarked by 3D Systems Corporation.[1]
Direct Metal Laser Sintering (DMLS)	A synonym is direct metal laser melting. Just like SLS, it uses LS but it is trademarked by EOS GmbH (Electro Optical Systems).[1]
Selective Laser Melting (SLM)	Just like SLS and DMLS it uses LS but trademarked by SLM Solutions.[1]
Electron beam melting (EBM)	Powder bed fusion process where an electron beam is used in a vacuum to fuse powder. Patented by Arcam AB.[3]
Design for Additive Manufacturing (DfAM)	The process of breaking down a part or product to its functions and optimizing it for AM[4]
Adapt for Additive Manufacturing (AfAM)	The process of taking an existing part or product and making it better suitable for AM[4]
ETAM	It stands for *evaluation and transformation for additive manufacturing* and it is a method to evaluate if AM is the right choice.

Terminology is one of the first standards that were made for AM and it is still an ongoing project. When it comes to more complicated issues such as quality insurance, often the

[1] ASTM F2792 – 12a
[2] ISO/ASTM 52900:2015 (en)
[3] Arcam AB, http://www.arcam.com/technology/electron-beam-melting/
[4] Marc Saunders, Kevin Brigden. 2016. https://www.linkedin.com/pulse/adaptation-clean-sheet-design-am-dfam-strategies-marc-saunders

standards for casting is used since the material properties in some ways are similar to casting. See Chapter 8 *Recommended reading* to find standards containing more terminologies.

Design for Additive Manufacturing (DfAM) can be used to break down a product and to make sure that AM is used to its fullest. Many times this process is used as Adaptation for Additive Manufacturing (AfAM), which means that the full potential of AM has not been used. Instead of breaking down the functions and requirements of a product to make something new with AM it is used to redesign an existing product to use fewer parts or add features that are otherwise impossible to do. New processes are being developed all the time so be sure to check for one that works for your company.

2.2 How it works

Powder bed laser additive manufacturing works in short by first choosing what type of machine is going to be used which will determine things like material, maximum dimensions, and tolerances. A 3D-model is then uploaded into the machine in the file formats STL, AMF or 3MF with data containing information like layer thickness, laser speed, and intensity.

The building process is illustrated in *Figure 1*. A build platform is inserted into the machine, Arcam recommends their customers to use it only once but to save money it can be used again. If used multiple times it needs to be processed in some way and when it gets thinner the thermal properties changes. Often the top 1 [mm] is machined to make sure that the recoater will not hit anything that might be left on the build platform. Now the machine is ready to start.

The machine uses a powder feeder and recoater, see *Figure 1*, to add a thin layer of powder onto the build platform with a thickness ranging from 20 to 100 [µm] and then a laser is used to melt the powder in specific areas of that layer. When this is done the powder feeder adds another layer of powder on top of the other, the recoater make sure it is even, parts of the powder is melted and then repeats the process over and over until the part is done.

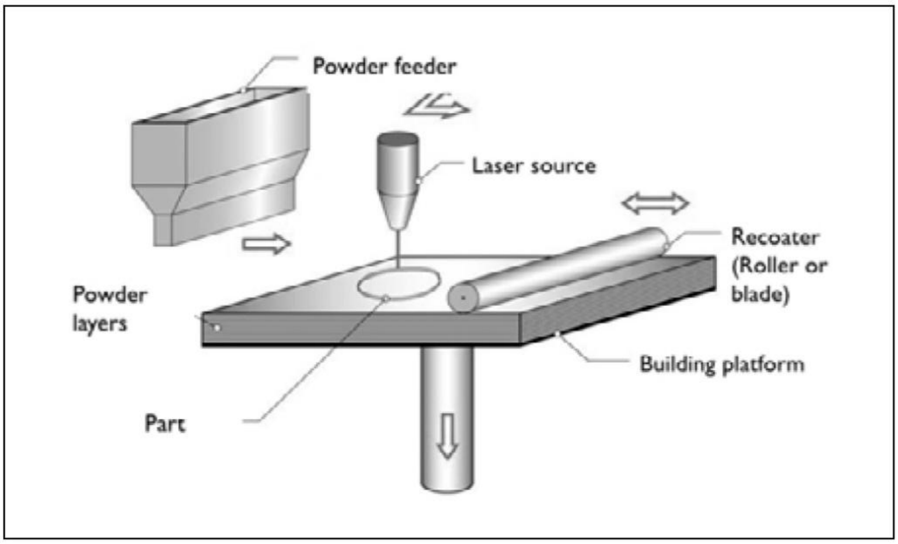


Figure 1. Illustration showing how powder bed fusion works (Courtesy of EPMA)

Excess powder is brushed off and the build platform is removed from the machine and the machine is emptied from excess powder, which is sieved and reused. In some cases, companies might only use fresh powder, no reused parts, for their products, like in medical applications. The part is then cut from the build platform and goes into post-processing. The first part of post-processing is to remove the support structures and to empty all cavities of powder previously inaccessible. The part will then go through more processes but more on this in Chapter 5 *Pre- and post-processing*.

2.3 Software

As of today, there is a lack of software integration on the market and at least three different software have to be used throughout the design process, see *Figure 2*. First, a CAD program is used for the initial design (e.g. NX, CATIA or PTC CREO) and then a program is needed to prepare the design for the manufacturing, which means orientation in the machine and support structures (e.g. Magics or Netfabb). Finally, the AM machine will have a software for slicing and setting the parameters for the building process. It is in the last step the layer thickness of every coat of powder is decided; how thick slices to make the computer model. Thicker layer means faster building process but rougher surface. Also, the machine parameters, such as laser effect, laser speed, and laser pattern can be changed, which will also affect the result and the material properties and therefore often standard parameters are used to ensure repeatability.

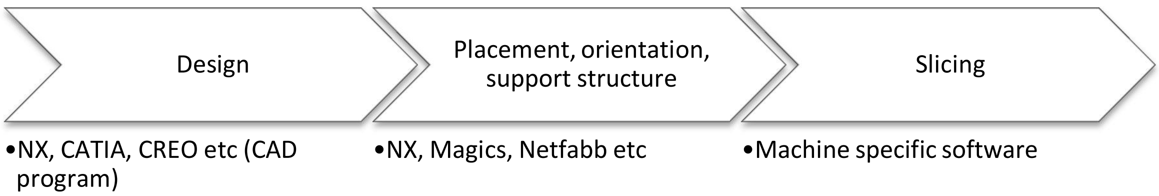


Figure 2. The different kinds of software that the design has to go through for AM

AM makes impossible designs possible but this also means that designers will have to work with more advanced geometries. CAD-programs are often made for making parts that will be machined or casted but not 3D-printed so it is often time-consuming making these advanced geometries. Lattice structures, see *Figure 3*, and topology optimization are often used in AM designs but very hard to make with the traditional CAD tools. Software is being developed to automate this type of work, this will save time and money. As AM becomes more used it might be a good thing to invest in a software that can more easily make more complex shapes like curved surfaces and lattice structure.

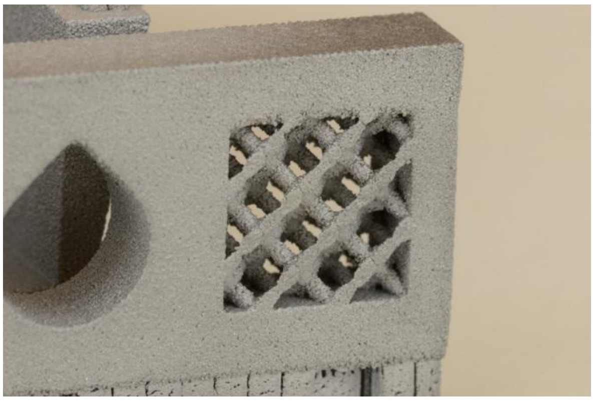


Figure 3. A part containing lattice structure, it is not solid and not hollow but similar to a truss structure or a net.

2.3.1 Creo Parametric

As an example of the development of CAD software; in Creo 3.0 PTC has added a feature called 3D print, which can be useful for analyzing parts. It is possible to set the machine's print volume and by moving the part around this will be helpful to decide on the orientation and placement of the part and if it is possible to fit with more than one at a time. The potential need for support structure can be checked with the "Support Material" function by setting the maximum angle for overhang. The "printability validation" function is useful for analyzing walls and gaps since there is a limit to how thin walls and narrow gaps that can be manufactured. "Clipping" is used for analyzing the interior of the part and could be useful for visual confirmation of the buildability. However, even though all of these features are good to use for analyzing the part it is still quite primitive compared to other software such as Magics by Materialise for adding support structures, choosing orientation and so on.

In Creo 4.0 the adaptation for AM is even greater where auto generated lattice structures can be added and a function called tray assembly which allows the designer to prepare for the manufacturing including information such as the parts, orientation, colors, and materials.

2.4 Strengths and weaknesses

The main weaknesses with AM are that it is a relatively slow manufacturing method and can be very expensive, depending on how it is used. There are advantages with using AM and if used well, a part or product can in some cases be made cheaper with AM than other manufacturing methods and if not cheaper it can shorten lead times and save costs in other areas. An example of this is that if it is possible to merge many parts into one with AM it can lead to shortened lead times, no need for expensive tools like in casting and by using AM; industries can start to move towards "zero waste" production.

AM also gives possibilities for manufacturing geometries that are unique for this type of manufacturing process. With powder bed fusion internal geometries are now possible which means new ways of making things. Two common uses for this are to make more effective cooling channels that are integrated into the design and to make use of lattice structures. Topology optimization is also something that can be used to its fullest, which in short is a process where a software generates a model with material optimized for the given conditions.

3 WHAT TO KNOW BEFORE DESIGNING

There are some crucial questions that you should find the answers to since they can vary depending on the machine used and might be deciding whether to use AM at all. These questions are focusing on the three different stages that will affect the design: design for function, design for manufacturing and design for post-processing.

If no one can answer a question and no information can be found in the machine- or material specifications you might have to make your own tests or ask people with knowledge in similar manufacturing processes that might be able to help you.

For example, Powder Bed AM is often compared to casting in many aspects like shrinkage and stress buildup in thick areas so if no standards can be found or questions arise check with people with knowledge in casting.

3.1 Design for function

In *Table 2* is questions collected that are useful to find answers to before designing and they all have to do with the function of the part.

Table 2. Questions to ask and find answers to regarding the function of the design.

Question	Reason
What dimensions are we working with? (HxLxW)	Find out what design space there is to work with. There is a risk that the part needs to be split in some way. See guidelines on "Split parts". Note: You have to weigh the costs of using a bigger machine and costs of joining smaller parts.
What tolerances are we working with?	Check what tolerances and what surface finishes the part requires. When using AM the tolerance and surface finish depends on many factors; see 4 *Design rules and guidelines*. Note: You might have to consider another manufacturing method or the cost for post-processing (money and added material/changed design).
Any crucial design features that are fixed?	Depending on the available design space and the features that are already set, it might be difficult to optimize for AM. This will also affect the print orientation and where to put supports. Note: It is particularly important to question the design decisions when redesigning an old product for AM. Old specifications and demands might be unnecessary when shifting to AM.
What materials are available?	Check material specific design parameters and that the manufacturer has the material or choose material depending on availability. Note: By keeping the material specifications open you can optimize the part for its function. An "expensive" material, like titanium, can make the part lighter, which leads to less material and ultimately to a cheaper part. Other material properties such as heat conductivity should also be considered.
What are the part applications?	The design will change depending on demands, function, and environment. Also finding what it should be optimized for is important.

3.2 Design for manufacturing

There are some important aspects to consider regarding the manufacturing, which is presented in

Table 3. If the company does not have in-house manufacturing these questions will typically be asked a subcontractor.

Table 3. Questions to ask regarding the manufacturing.

Question	Reason
What is the build volume? (HxLxW)	To make sure that the AM-machine can make the part. If not the part has to be split and rejoin. See guidelines on "Split parts".
What tolerances can the machine take?	Check what tolerances and surface finish the AM-machine can make. However, the tolerance and surface finish depends on many factors; see 4 *Design rules and guidelines*. Note: If not satisfying then consider another manufacturing method or the cost for post-processing.
What are the design limitations of the machine?	Wall thickness, smallest/biggest hole, smallest square, radiuses etc. depends on what material and machine is used but is constantly being updated. Make sure to use the manufacturing company's knowledge as much as possible. There are some general guidelines in Chapter 4 *Design rules and guidelines*.
What materials do you use?	Make sure that they have what you need.
How do you test the quality of the prints?	There are no international standards for testing AM prints yet so it is good to know what the manufacturer test and how often. If this is not up to your standards then more tests need to be booked.
What information does the manufacturer need from the designing company?	This also depends on the requirements for the product. An example of things they might need: Material requirements, surface finish, cleanliness specifications, build orientation, tolerances, test specifications and standards to follow.
Do you take care of the machine setup or should we?	Communicating what machine setup that is required is important for repeatability and possibly the cost and quality of the finished product. When designing for AM orientation needs to be kept in mind from the beginning. See guidelines on placement and orientation. Note: Discussions about print orientation needs to be discussed in early stages of development.
How much shrinkage can we expect?	This depends on the thickness of the section, the material and so on but still good to ask so you have a general understanding. If the part is small enough it might not even matter.
Does it matter where on the build platform the part is placed?	The technology is continuously improving and this is one of those aspects that changed considerably over the last years. Since the quality can differ depending on where on the build platform the part is being built it is important to find what applies to the machine the part will be manufactured with.

If the build platform is filled, how does this affect the stress and heat transfer?	A part can be corrupt if there is too much heat in the build platform. There are software that can simulate this, such as Netfabb. Depending on the answer, this can affect the decision regarding the orientation, see Chapter 4.1 *Placement and orientation*.

3.3 Design for post-processing

Questions about the post-processing are found in *Table 4* and whom to ask these questions will vary depending on the product and the answers on the questions in Chapter 0 *Design for function* and 3.2 *Design for manufacturing*.

Table 4. Questions to ask regarding the post-processing.

Question	Reason
What types of post-processes are the part going through?	If you are planning to have some kind of post process of the part, make sure to prepare for that in the design. For instance, if a hole will be drilled afterward or any type of machining is to be used then consider adding fixture points. See guidelines on holes and post process. Note: Printed parts are more often than not heat treated after printing to release stresses inside the parts and/or to increase the mechanical properties. If you are not planning to heat treat the part check with the manufacturers what implications this might have on the part if the material used does not specifically need it.
What tolerances can the machine take?	To know how much extra material you have to add on the surfaces that are going through post-processing.

4 DESIGN RULES AND GUIDELINES

There are many things to think about regarding the design and the geometries used when a product will be manufactured using AM. To make it easier the guidelines are divided into categories. The guidelines are ordered in how much the rules will affect the design process if optimized, and the further down you go the easier it gets to change things at a later stage. To give an example of this: changing the orientation of the part, Chapter 4.1 *Placement and orientation*, will most likely lead to a total redesign compared to changing hole sizes, Chapter 4.9 *Holes*.

Apart from the question in Chapter 3 *What to know before designing* there are a few things to think about because of the technology that is used.

- During the designing keep in mind what build direction the product will have because many of the design rules are dependent on the build direction. In turn, it will limit the need for a support structure, which saves time and money and it is easier to predict the surface quality. See Chapter 4.1 *Placement and orientation* to better understand how orientation affects the print in more ways than quality.

- Before starting it is essential to consider if more functions can be merged into one product because this is one of the most common ways to make AM a viable alternative, the cost saving can be huge if the number of components can be reduced and thereof also reducing the number of fixtures and tools.
- Try to keep good communications between all partners in the process, like the manufacturer and post-processer, so problems and new inputs can be dealt with early on in development.

4.1 Placement and orientation

Placement on the build platform can affect the quality of a print. The best results can be expected in the center of the build platform and gradually decrease towards the edge because of the angle of the laser. How much placement affects the quality depends on the machine and setup so check with manufacturer how placement will affect your design. Depending on the design and what the part is used for the placement might not be of importance at all but corruptions in one part of the build platform can affect the rest of the print.

Since build orientation is of large importance this information needs to be linked with the product in some way so make sure to make notes in the 3D-model, attached documents or on the drawing. When choosing build orientation note that because of the layer by layer build process the Z direction will not necessarily have the same mechanical properties as X and Y, see *Figure 4*. There are generally three ways of optimizing a build: by cost, buildability or quality. Usually, the strength in the Z direction is lower than X and Y but if possible ask a person with material knowledge for consulting because of the differences in anisotropy of each material.

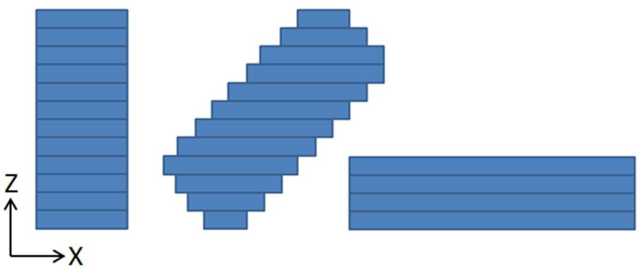


Figure 4. Illustration of how a rectangle is translated into layers when printing, the layer thickness is exaggerated.

As seen in *Figure 4* angles in the design will lead to a so-called “staircase effect” which means rougher surfaces. The surfaces roughness can be managed by changing the layer thickness but will then lead to higher costs because of longer manufacturing time, see Chapter 4.2 *Layers*. Other aspects that affect the tolerances and surface roughness are the size of the metal powder and the width of the laser beam.

When deciding the orientation there are three main properties to consider, which are presented below.

4.1.1 Cost

By shortening the time it takes to print each part and the time it takes to remove supports a lot of money can be saved. By "nesting" parts together (see *Figure 5*) on the build platform you can print more parts each time the machine starts and if as little support as possible is used the time for post-processing a part reduces. However, there could be problems with the heat transfer if too many parts are built on the same platform and the outer edges tend not to produce with as high quality, see the beginning of Chapter 4.1 *Placement and orientation*.

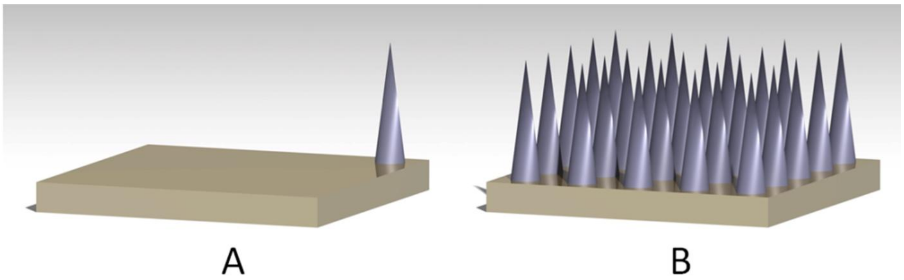


Figure 5. A: Only one part is printed which makes it expensive, B: Build platform is fully used which takes down the cost for each part.

4.1.2 Buildability

With enough supports, almost anything can be printed but if things are not positioned well enough failures may occur. The most common failure is when the recoater hits the part while adding a new layer of powder because it comes in at a zero degree angle. By placing the part in an angle failures are less common. It is recommended to place parts at an angle of 30 degrees or greater. If not possible place it so the thinnest part hits the recoater first, see *Figure 6*. A rule of thumb is also that a part should have an aspect ratio of 8:1 (height:width) and to bridge tall structures close to each other to avoid problems, see *Figure 7*.

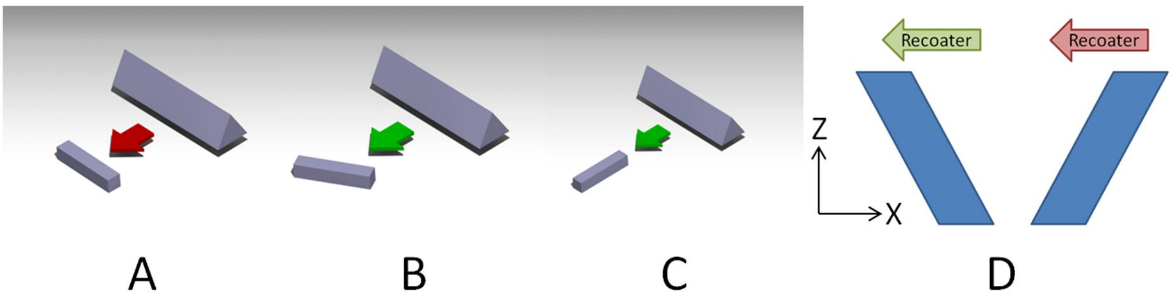


Figure 6. A: The recoater is coming in at a bad 0 degree angle, B: The recoater is coming in at a good 30-degree angle, C: The recoater is coming in on the parts thinnest side, D: Side view showing good and bad part positioning (Green = good, Red = Bad), if the recoater hits the left one the part will be forced down without machine failure, if the recoater hits the right one the part will be forced up and risk machine failure.

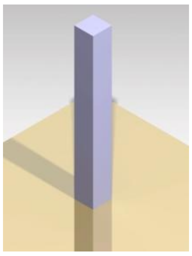


Figure 7. Picture showing a part with an aspect ratio of 8:1.

4.1.3 Quality

Good orientation can make post-processing easier or not needed at all. One way of doing this is to position it in a way that makes supports easier to remove, preferably designed and not automatically generated, putting crucial surfaces horizontally to avoid step effects and to make the print as accurate as possible, see *Figure 8*.

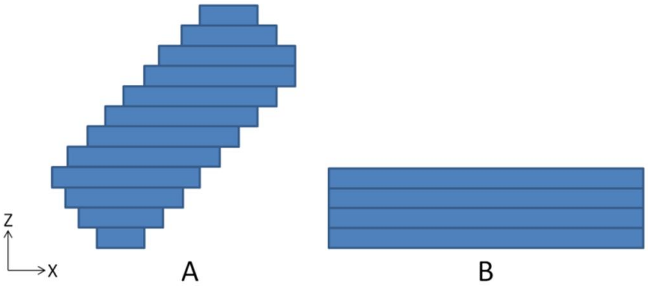


Figure 8. A: Part printed at 45-degree angle, surfaces will have a “staircase”-structure, B: Part printed at a 0-degree angle, top- and side surfaces will have a better quality than A but bottom needs post-processing because of supports.

4.2 Layers

AM-machines can print with different layer thicknesses from 20 to 100 [µm]; thicker layers means shorter total print time but will also affect the build quality negatively. Thicker layers mean higher surface roughness and “staircase effect”, see Chapter 4.1 *Placement and orientation*. Also, make sure that the height of the product is within the set tolerance, see *Figure 9*. This is especially important to think about if areas of the part will not be post-processed.

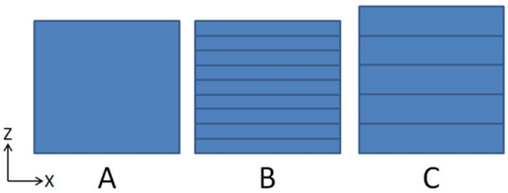


Figure 9. A: Part that will be printed, B: Printed part with a good layer thickness, C: Printed part with a bad layer thickness (it is thicker than it should be).

4.3 Split parts

When a part is too big and does not fit into the machine it needs to be split into smaller pieces, see *Figure 10*. This means that the design has to be made so that no advanced internal geometries are affected by the split line and that some kind of design for alignment, like pins and holes, are implemented. If possible try to isolate the functions that need to be printed, make the rest of the part in a conventional way and then join them at a later stage.

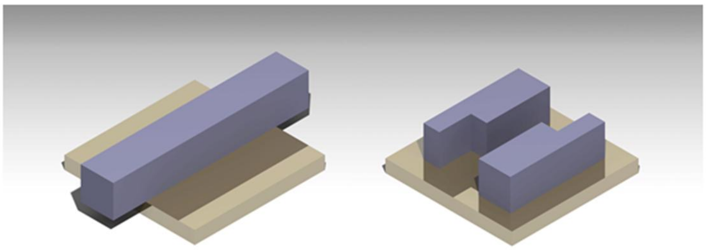


Figure 10. An example of how to split a big part.

Splitting parts mean that they need to be joined again at some point with the consequence of added costs for surface processing and the joining process itself. The way each layer is made with AM resembles welding so when joining the two parts welding is a good option. Always consider that if a part is too big for the AM machine then it might be too expensive and another manufacturing method should be considered.

4.4 Volume

Just like in casting, stress easily builds up in thick sections and can result in cracks and faulty parts so hollow structures are recommended. AM has the unique ability to create internal structures so by making a section hollow and then add lattice structures the part can be made lighter but still be able to take about the same amount of loads, see *Figure 11*.

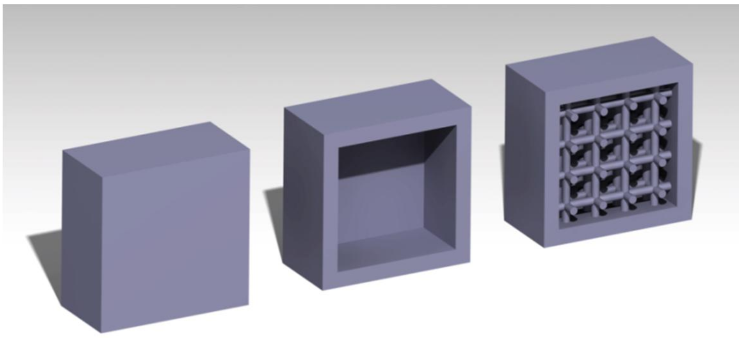


Figure 11. From left to right, a split cube that is solid, hollow and hollow with internal lattice structures.

4.5 Powder removal

When designing something that will be hollow you have to think about how the excess powder can be removed in post-processing. If an area is hollow you should have at least one hole/gap, or more, to ensure that all the powder can be removed, see *Figure 12*.

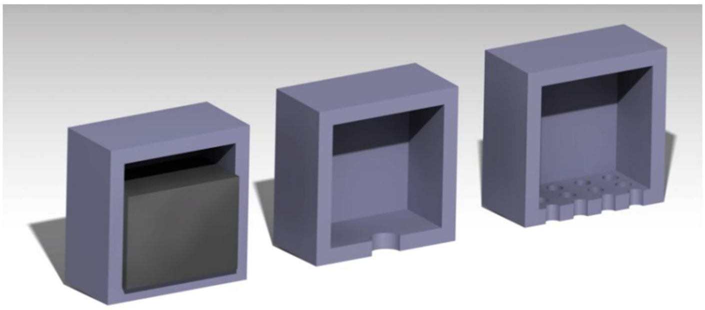


Figure 12. Split cube with different amount of holes. The left one with no holes still has powder in it.

One hole can be sufficient but if the geometry is advanced or have pockets several holes in different places might be needed to make sure that all the excess powder can be removed or there is a risk of powder nesting, see *Figure 13*. It is recommended to have holes and gaps sized at a minimum 0.2 [mm]. Smaller holes and gaps can be used but the risk of powder adhesion gets bigger as holes and gaps get smaller, check machine and powder specifications first.

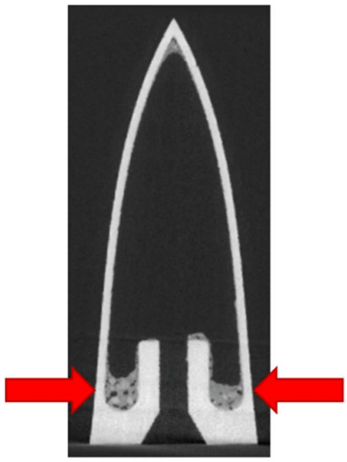


Figure 13.A scan of a BOR-element showing powder nesting from ETAM thesis (see Chapter 8.3 *Articles/thesis*).

4.6 Corners

It is very important that all corners have some radius because of the risk of cracks and stress buildup, see *Figure 14*. Recommended is to have at least a radius of 0.1 mm (REF Karolina, Lasertech).

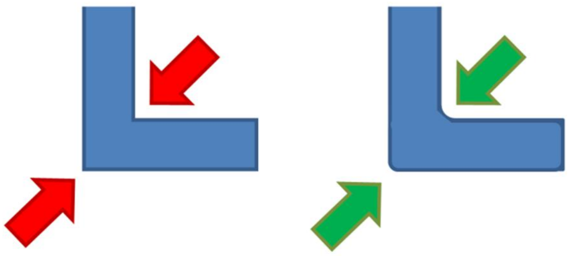


Figure 14. On the left is a sharp corner that has a high risk of cracking during print compared to the right one.

4.7 Walls

As stated earlier in Chapter 3 *What to know before designing* the minimum wall thickness is dependent on material and machine so this needs to be checked before designing. It is important to know that the minimum wall thickness is dependent on the height of the wall and material used. This means that the higher a wall gets the thicker it also needs to be. Thin walls also run the risk of vibrating when hit by the recoater, moving the powder surrounding it, and therefore run the risk of failure or corruption in the design.

4.8 Horizontal segments

All types of horizontal segments like overhangs and bridges will need supports structure or support built into the design. Without these, the part cannot be built and will fall apart during print, see *Figure 15*.

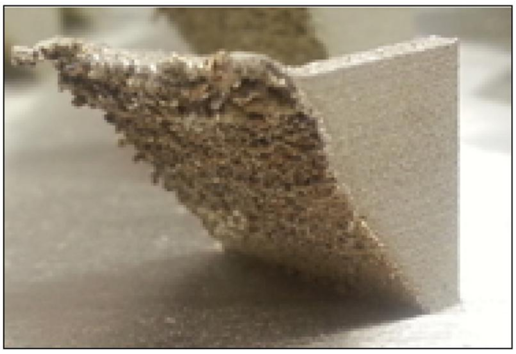


Figure 15. Picture showing how unsupported structures can look, picture from EPMA.

When it comes to angles the rule of thumb is that 45° angles can be built without the need of support structure. Depending on the material used the angles can be smaller, see *Table 5* and *Figure 16*.

Table 5. Data of minimum angles without the use of support structure from Crucible designs.

Material	Minimum angle (α) in degrees
Stainless steel	30
Inconel	45
Titanium	20-30
Aluminum	45
Cobalt chrome	30

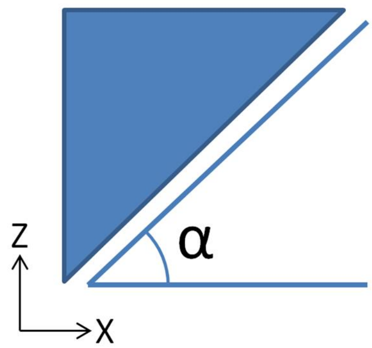


Figure 16. Illustration showing angle referred to in *Table 5*

Support structure will have to be removed so if possible make the supports part of the design. Examples of shapes that are self-supporting are angles, Gothic arch's or drop shapes, see *Figure 17*.

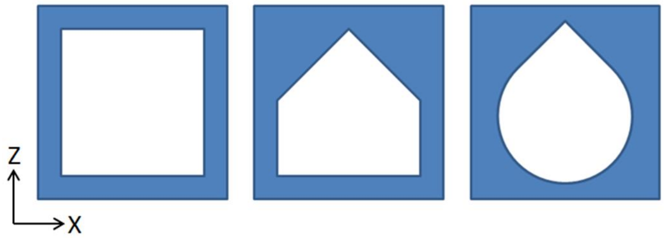


Figure 17. Showing structures where the left one needs support during print but not the others who are self-supporting.

4.9 Holes

When a hole is present in the design: think about what the hole will be used for because the roundness of the hole depends on the orientation and how much support material is used. The best result is achieved when it is built in the Z-direction. Just like with walls, after a certain height, it will start to sag that, for instance, can cause problems when it comes to perpendicularity requirements, see *Figure 18*.

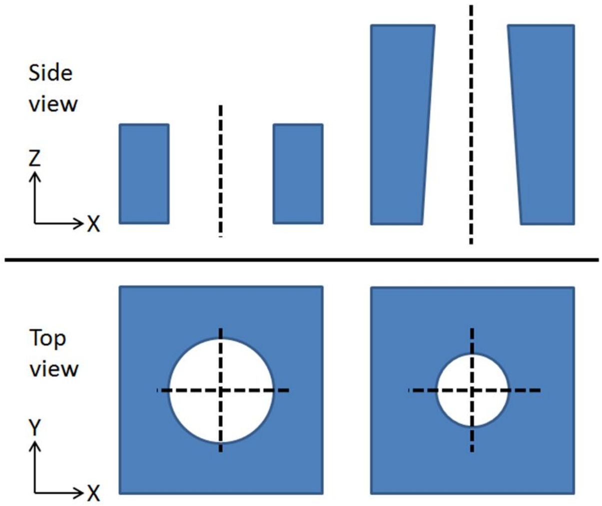


Figure 18. Two same sized holes built in Z-direction where the right one has started to sag.

A rule of thumb is that holes with a diameter smaller than 10 [mm], 12 [mm] for Titanium, will be round and if any bigger defections will be present. But like with almost everything else this depends on the material and machine so make sure to consult the manufacturer about it. If holes in the design are critical for the end function it is recommended to have them drilled afterward. This means that holes can be excluded during print and to be drilled afterward. Alternatively, make the hole smaller/teardrop-/square-shaped to minimize the use of material, see *Figure 19*.

Figure 19. An example of how to design a hole for AM. The left one will be defective if larger than 10 [mm], the other ones will not.

Do not forget that holes need a flat surface to be drilled so if a hole goes in at an angle it is recommended to print a part of the hole as a guide for the drill or another type of solution. Holes do not have to be round, try to think about what function the hole has and design it from that.

4.10 Support structures

In the powder bed fusion machines, the support structure is made of the same material as the part itself. The support structure has many uses, for example, making sure that the part keeps its form during print and to transfer heat. Understanding how to combine design and orientation in the machine can lead to a minimum amount of supports, which will lead to less material used, lower costs and less need for post-processing. Alternatively, the part can be designed in such a way that the support structure can be left or the design is self-supporting.

The support structure cannot be completely avoided because of the heat that needs to be transported away from the product and it needs to be removed from the build platform. Therefore, the bottom of the product will be attached to the build platform with a support structure. In turn, this means that the surface finish will not be very good unless some post-processing is made. There is also a risk of small cracks appearing where the support structure was located after removing it.

Support structures are often automatically generated in the same software that is used for setting up the build orientation but it is sometimes more efficient to design supports that are unique for the part. This can make the print and post process more effective and less expensive but it also means that the designer has to have a good understanding of the process and communication with the person setting up the machine. As you get better and gain more knowledge about AM you can start to design your own supports. When designing supports it is recommended to include breaking points in the design to ease removal, see *Figure 20*.

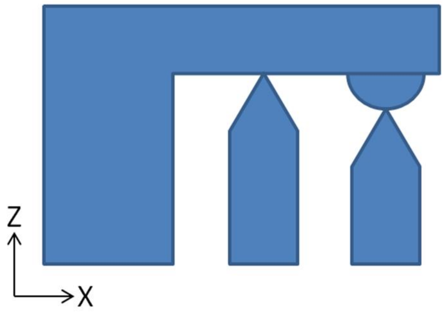


Figure 20. Supports made with breaking points that ease removal.

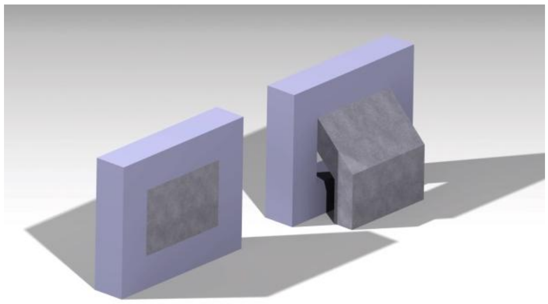


Figure 21. The right model shows an example of support structure offset from part to make it more accessible, compared to the more common way.

When supports are added to a design or before printing make sure to think about how accessible it is for the different tools like clippers, pliers, and files needed to remove it. One example of easy removal of supports is by offsetting it from the part, see *Figure 21*. This makes sure that it will be accessible for post-processing and surfaces close to the support will not be of lower quality. Also, remember that supports can sometimes be left on the design as a form of a lattice structure.

5 PRE- AND POST-PROCESSING

As described earlier in the document there are some processes before and after the printing process. These processes need to be taken into consideration while designing to make sure that the part is fully optimized for processing/machining.

5.1 Preprocessing

Before the CAD-model can be manufactured in the AM machine it needs to be converted to a universal file format. At the moment it is most common to use the STL format but many of the interviewees pointed out that they would prefer a more detailed format, preferably the original format. There are new formats on their ways, such as AMF and 3MF and both are able to contain more information than the STL format. STL still has the advantage of being the format most machines accept with the disadvantage sometimes making geometries too simple. Companies are also working on a way to use unconverted CAD-files in the setup phase but until then designers will have to keep working with converted file formats.

As of now the most used is STL, which means that it is important to point out a thing that needs to be considered. The best result is achieved if the person adding the support structures also does the converting to STL otherwise there could be problems with the resolution and setup of supports.

5.2 Post-processing

After the product is finished in the AM machine it needs to be removed from the build platform. If the product is removed with cutting there might be other geometries that need to be cut out. There are two ways to remove the product from the platform; wire-EDM (wire-electrical-discharge machining) and band saw. At a later stage, some support structures might need to be removed by hand since it is often complicated structures that need support. This is a reason why you would like to integrate the supports in the design as much as possible. If a cutting machine is used then having a fixture for the build platform is necessary and also considering how the parts are placed, if there are multiple parts on the same platform, is essential because they could hinder the cutting process and result in a poor result.

Since AM enables internal structures that were not possible before it also requires the designer to think about adding visual aid for people handling the part. This is only a problem if the outside is symmetrical whiles the structure inside is not, see *Figure 22*. There are a lot of ways to make visual guides but physical pins, holes or gaps might be the best. If this is not possible numbers or text can be written on the surfaces to understand what is up and down, right or left. The risk of wear and tear or people forgetting to add text directly after the print is then greater.

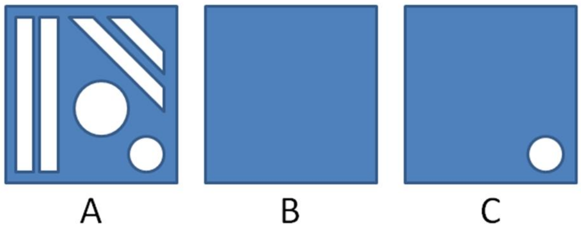


Figure 22. A: Cube split in two showing internal geometry, B: Outside view of the cube with no way of knowing how the inside looks, C: Outside view of the cube with a visual guide to understand how the inside looks.

There are several kinds of post processes that the product could go through after the manufacturing, which involves different kinds of machining, coating and heat treatment to reduce internal stress and pores. Often the post-processing has to be kept in mind when designing since it could be necessary to add, for example, fixtures or ensure that all surfaces can be coated. Threaded holes can be printed but it is recommended to add threads during post-processing to make sure that the mechanical properties are good enough. The surface finish is relatively poor and therefore the part might be machined afterward so it is recommended to add 1 [mm] to these surfaces. Manufacturers can sometimes do this by themselves but it is recommended that the designer do it to make sure that all the documentation is up to date and that the added material do not cause any problems. But if possible try to keep surfaces unprocessed after print because this will save both time and money.

5.2.1 Testing

Quality assurance and testing, both destructive and non-destructive, will be a big part of AM until standards are released on the subjects and companies gain more experience using it in their production. So until this happen companies have to define what tests need to be done before sending out a product. At the beginning, over testing might be costly but necessary to build up a database and understanding the limitations of the process. But testing cost money and non-destructive testing like CT-scan and ultrasonic testing, for internal geometries, are expensive so as time goes by and companies start to trust the technology less testing will be needed.

6 EXAMPLES

This chapter is here to encourage the reader to add to the document once there are examples in the organization that is useful for other to see.

7 FUTURE WORK AND NOTES

This document is meant to be the start for designers and developers that want to explore additive manufacturing as a viable manufacturing process. There are a lot more to AM then presented here so the next step is to keep working and learn more about the process. AM is vastly different from all other ways of manufacturing and there are still a lot to learn and to understand so if something new comes up or if you learn something new; write it down or document it in any way for your colleagues or yourself. The best way is still “learning by doing” so keep trying and working with it, no one becomes an expert at something after reading 20 pages.

The material properties are created during the creation of the product, which means there is a shift in responsibility for the material quality and new ways of measuring it. To investigate and try out new materials takes time because the properties have to be researched and the parameters for the machine needs to be tried out and tested thoroughly. This process can take anywhere between months to years (Klas Boivie, personal communication 2017-03-06).

The earlier in the design process that the manufacturing method can be decided the better the product can be optimized for AM. The more the product can be designed for AM, the more value can be gained from the chosen manufacturing method. If the number of components can be reduced, also the number of joints and tools will then be reduced. Even when the limitations with AM are considered a lot of products that are manufactured with other methods are possible to make with AM. But as a wise man once said: “Just because you can doesn’t mean you should” (Jeff Goldblum, Jurassic Park, 1993).

8 RECOMMENDED READING

To get a deeper understanding of AM and its benefits here are some literature, articles, and websites that might be of help. More is coming every day so it is recommended to make a web search on keywords such as Additive Manufacturing, Rapid Prototyping, 3D-printing with metal, and powder bed fusion. The best thing is to consult people with knowledge and ask them for good sources as this list might soon be out of date.

8.1 Standards

- ISO/ASTM 52900
    - Focus on the terminology within AM.
- ISO/ASTM DIS 52901.2
    - Requirements for purchasing AM parts.
- ISO/ASTM DIS 52910.2
    - Still a draft but focuses on what AM is and recommendations on what to do and not do when designing for AM and it contains some terminology.

- ISO/ASTM 52921
    - Terminology with a focus on coordinate systems and setup.
- ASTM F2792 - 12a
    - Similar to ISO/ASTM 52900, it contains terminology.

8.2 Books

Additive Manufacturing Technologies – 3D printing, rapid prototyping, and direct digital manufacturing, Authors: Ian Gibson, David Rosen and Brent Stucker

…

8.3 Articles/thesis

Olsson Pamelina, Hedström Kuosmonen Linn. 2015. *Evaluation and transformation for additive manufacturing (ETAM)* (Master's thesis, Chalmers University of Technology, Gothenburg, Sweden). Retrieved from: http://studentarbeten.chalmers.se/publication/229803-evaluation-and-transformation-for-additive-manufacturing-etam-a-method-for-conversion-of-high-techno

…

8.4 Websites

European Powder Metallurgy Association (EPMA) (https://www.epma.com/)

http://canadamakes.ca/designguide/story_html5.html

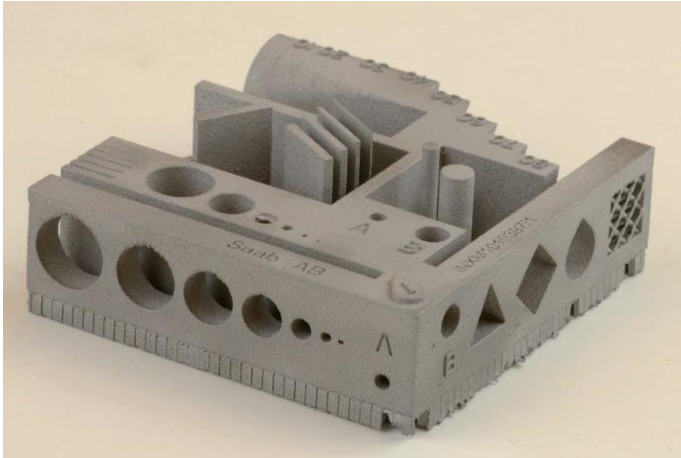
…

8.5 Guidelines

Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4, Authors: J. Kranz, D. Herzog, and C. Emmelmann

Design guidelines for direct metal laser sintering (DMLS), Authors: Crucible design (https://www.crucibledesign.co.uk/guides/)

APPENDIX N – BENCHMARK MODEL PAMPHLET



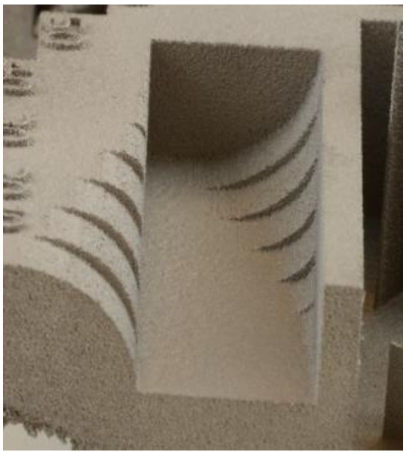
This pamphlet shows the features on the benchmark and what can be learned from them.

Angles

The eight angles presented on the benchmark model illustrate how "as built" surfaces will look after print without supports or post-processing. The angles go from 10 to 80 degrees, in steps of 10, measured from the build platform.

This information can be used during design to understand when supports are necessary and how angles affect surfaces. Observe that from angle 30 to 10 the surface goes from bad to corrupt.

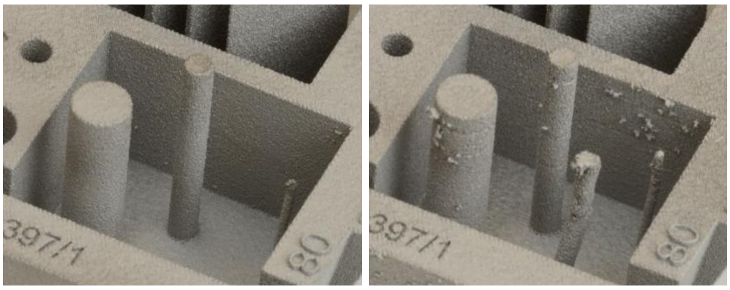
Radius



The benchmark model has 16 angles showing how prominent the "staircase effect" is in corners and on edges. The rule is to always have a small radius in corners to avoid stress build-up and reduce the risk of cracks.

The radiuses range from 0 to 10 [mm].

Aspect ratios



The four pins illustrate how aspect ratios will affect the buildability of a model. The four pins have the ratios 4:1 (thickest), 8:1, 12:1 and 24:1 (thinnest).

The rule of thumb is to have an aspect ratio of 8:1 but this depends on the machine and material. As seen in the pictures ratios 12:1 and 24:1 do not always work.

All pins are 24 [mm] high in the CAD-model and diameters go from 6, 3, 2 and 1 [mm].

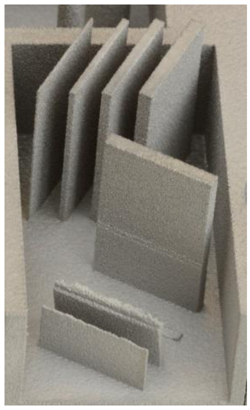
Gaps

The six gaps on the benchmark model have several functions. These things are: showing how small a gap can be without corruption, powder adhesion and powder removal from tight spaces.

The smallest gap of 0.1 [mm] is too small to notice powder adhesion without the use of a scanner or feeler gauge.

The gaps range from 0.1 to 0.6 [mm] in the CAD-model, however, they are smaller in the printed part.

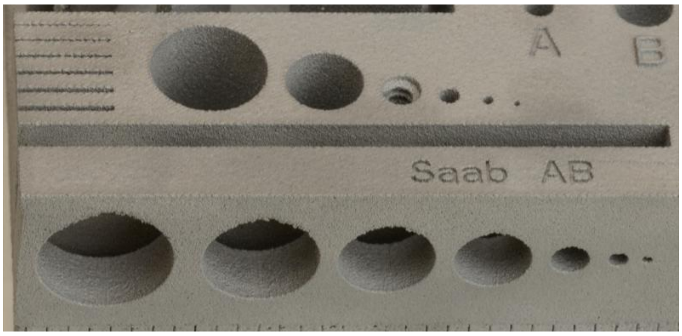
Walls



The walls located in the middle of the benchmark model have the same height but different thicknesses and angles towards the recoater. The walls range from 0.5 to 2 [mm] in thickness and half are made to hit the recoater at a 0-degree angle and the other half at 90 degrees.

Observe that walls positioned at 0 degrees have failed and the others are still standing.

Holes

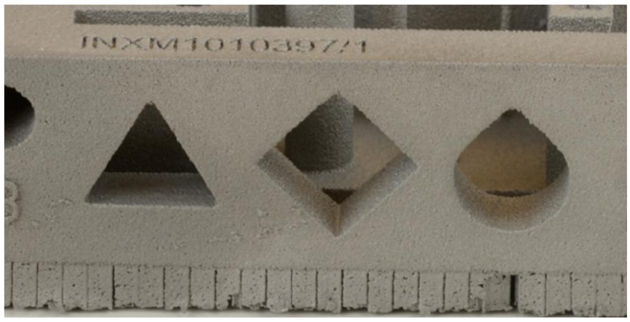


On the top of the benchmark model, there are six holes ranging in diameter from 0.5 to 12 [mm]. This is to show the quality of holes in ranging sizes built in the Z-direction.

On the side are holes ranging in diameter from 1 to 14 [mm]. This is to show how some holes can be printed in XY-direction and still keep their shape and some cannot.

Observe how the holes become less circular the bigger they get on the side, specifically 14 and 12 [mm].

Shaped holes

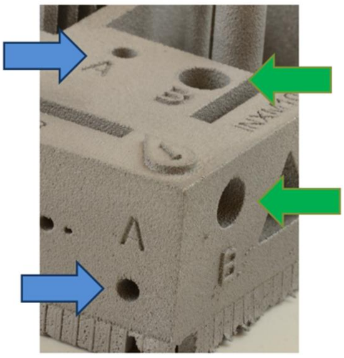


A hole does not always need to be circular so if possible self-supporting holes can be used to make holes bigger than 10 [mm] if they would be circular.

On the side are some holes shaped in different ways to show examples of how one can make these self-supporting holes.

Observe how all holes are built with angles equal to or above 45 degrees.

Channels

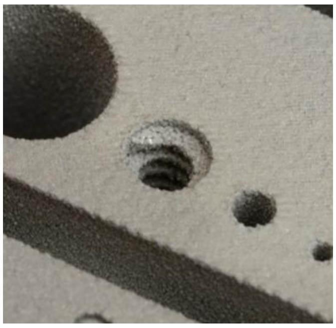


The four holes marked with the letters A or B are channels connected A to A and B to B. The difference between the two is that A is 3 [mm] in diameter and B is 6 [mm] in diameter.

This is to show AM:s unique ability to integrate channels into a component. Earlier the only option was to connect two holes by drilling two straight lines.

Blow into one hole to test it yourself.

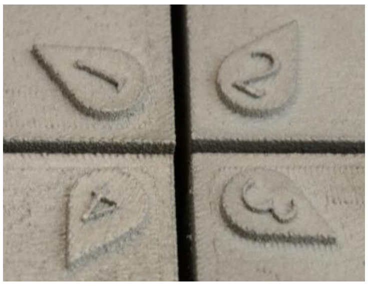
Lattice structure and threaded hole



On the side of the benchmark is a square-shaped hole with an auto-generated lattice structure. This is something very unique to AM.

Another feature that is possible with AM is a threaded hole located on top of the benchmark inside one of the Z-direction printed holes.

Extra



The last shape on the benchmark model is a drop-shaped arrow on the top of the model. This is only there as a visual guide for the manufacturer to see how it should be placed on the build platform.

The arrow shows the angle the recoater should come in to add new layers of powder. This angle is 30 degrees.

The arrow is drop-shaped because if it was shaped like a traditional arrow the recoater would come in at a 0 degree angle and the risk of the recoater hitting it would increase.