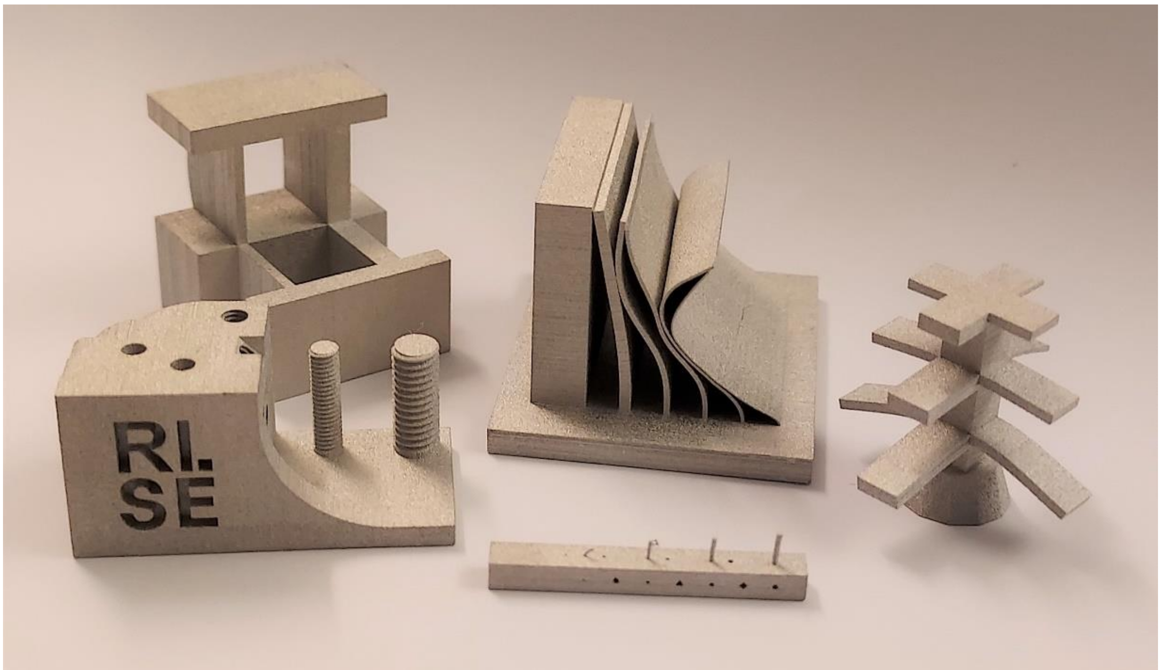

Evaluation of Part Dimensions for Additive Manufacturing, Metal Binder Jetting

Foundation for a design guideline within Additive Manufacturing

Bachelor's thesis within the university engineering program, Mechanical engineering

Louise Andersson
Emilia Hall

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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A photo of five components manufactured with help of Metal Binder Jetting. More about the artifacts can be found in *chapter 7*. Hall, E (Private).

Chalmers Reproservice,
Gothenburg, Sweden 2021

Evaluation of Part Dimensions for Additive Manufacturing, Metal Binder Jetting

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Abstract

The concept of Additive manufacturing (AM) was introduced already in the 1970's as mentioned in (Wholers et al., 2016) and the first commercial system were introduced in the late 1980's, this type of manufacturing is relatively new. When using AM technology, the components are manufactured by adding the material layer-by-layer and selectively where needed. Plastic materials were first used and since then, several AM-technologies has been launched with a larger selection of materials.

This bachelor's thesis was made at Research Institutes of Sweden (RISE) IVF AB.
The main purpose of the thesis was to set the base for creating a design guideline for one of the additive manufacturing technologies, specifically Metal Binder Jetting. Literature review was used as base for the information around the technology and existing guidelines, but we have also performed interviews as well as discussed directly with one machine and service provider, Digital Metal AB. Most of the information as found with respect to the design guidelines were of general character. The information is intended to be compiled into a guide with the initial purpose of designers with low or limited knowledge of design for MBJ.

Therefore, it was decided to print artifacts with help from Digital Metal AB to be able to set the base for what is viable and not, connected to the design rules. The printed parts were evaluated with manual inspections.

The timeframe of this work was from January 2021 and ended June 2021.

Keywords: *Additive manufacturing (AM), design guideline, metal 3D-printing, 3D-scanning, Metal Binder Jetting (MBJ), ISO-standards*

Sammanfattning

Konceptet Additiv tillverkning introducerades redan på 1970-talet, och det första kommersiella systemet introducerades sent 1980-tal, därav är denna typ av tillverkning relativt ny. När man använder sig av additiv tillverkning så tillverkas komponenterna genom att tillföra materialet selektivt och i en lager-på-lager princip. Det första materialet som användes inom AM var plast och sedan AM introducerades har antalet AM-teknologier ökat och det finns ett numera ett bredare utbud av valbara material.

Detta arbete gjordes hos Research Institutes of Sweden (RISE) IVF AB. Huvudsyftet för rapporten var att lägga grunden för skapandet av en guideline för en av de additiva tillverknings teknologierna, mer specifikt Metal Binder Jetting. Litteraturstudier agerade som bas för informationen om teknologin och existerande guidelines, men vi har även utfört en enkät, informella intervjuer såväl som diskuterat direkt med en maskin- och tjänsteleverantör, Digital Metal AB. Den information som hittades och avses att implementeras i en guideline var av generell karaktär, med huvudsyftet att konstruktörer eller designers med låg eller begränsad kunskap inom design för Metal Binder Jetting ska på ett enkelt sätt kunna sätta sig in i processen.

Det bestämdes att printa 6 olika artefakter med hjälp av Digital Metal AB för att lägga grunden för vad som är genomförbart och inte, kopplat till designreglerna.
Det printades 6 olika artefakter med hjälp av Digital Metal AB. De printade artefakterna studerades med manuella inspektioner.

Tidsramen för detta arbete vårterminen 2021 som sträcker sig från januari till juni.

Acknowledgments

For the development of this bachelor's thesis, we would like to thank everyone who has been involved and helped us during this work. We would especially want to thank our supervisors, Peter Hammersberg (examiner), Seyed Hosseini at Chalmers University of Technology and Tomas Vannucci from RISE IVF.

We would like to thank RISE IVF for providing us this opportunity, and specially the AM-team for their support and engagement. The specific support from Anton Dahl-Jendelin and Patrik Hallberg are highly appreciated. Finally, we would like to thank Martin Pfern and Hans Kimblad at Digital Metal AB for their help and support with respect to sharing their know-how and knowledge in the field as well as providing the requested parts. The bachelor thesis was performed in the frame of Competence Centre for Additive Manufacturing – Metal (CAM^2).

Terminology

AM	*Additive Manufacturing*
CAD	*Computer Aided Design*
MBJ	*Metal Binder Jetting*
ISO	*International Organization for Standardization*
3D	*Three-dimensional*
SL	*Stereolithography*
SLA	*Stereo Lithography Apparatus*
L-PBF	*Laser Powder Bed Fusion*
FDM	*Fused Deposition Modeling*
MIM	*Metal injection molding*

Table of Contents

1. Introduction

In this chapter are background, aim and demarcations presented.

1.1 Background

Additive Manufacturing (AM) is defined by the SS-EN ISO/ASTM 52900 Standard (*SVENSK STANDARD [SIS], 2015*), as the process of joining materials to make three-dimensional objects from a three-dimensional model data (3D-CAD). When using this technology, the components are manufactured by adding the material layer-by-layer and selectively where needed. The AM-technology enables near-net-shape manufacturing with minimum material waste, which can be compared to traditional manufacturing methods involving rolling, forming and followed by several subtractive processes to reach the final geometrical shape and dimensional accuracy. The concept of AM was introduced already in the 1970's as mentioned in (Wholers et al., 2016) and the first commercial system were introduced in the late 1980's. This initial use of AM was with stereolithography (SL) from 3D Systems. The process uses a laser to solidify thin layers of an ultraviolet light-sensitive liquid polymer. A beta test system called SLA-1 was the first commercially available AM-machine in the world. Since then, several AM-technologies has been launched and today AM is divided into seven large groups which is further divided in subgroups considering the material feedstock, power supply etc. These are listed in the same standard *SIS (2015)* as:

1. Binder Jetting, BJ
2. Directed Energy Deposition, DED
3. Material Extrusion, FDM
4. Material Jetting
5. Powder Bed Fusion, PBF
6. Sheet Lamination
7. Vat Photopolymerization

These technologies have different benefits and various tolerances. Which is the reason why not all techniques work with all materials as the techniques varies in speed and provide, among other things, different mechanical properties (Bournias-Varotsis, n.d.).

RISE IVF has been active in AM since late 90's, starting on the development of Metal Binder Jetting (MBJ). Today RISE IVF works with several AM-technologies like laser powder bed fusion (L-PBF) for metals, fused deposition modeling (FDM) for polymers and Vat-photopolymerization for ceramics as well as working along the eco-systems for AM. To further expand the portfolio with MBJ, this Bachelor of Science thesis will address the start for creating a guideline for the MBJ process. The guideline will consist of construction rules specific to the MBJ process, the ideal goal with this guideline is to achieve "first-time- right" printing. That means the first print trial acquires a part with the expected properties and dimensions without defects.

1.2 Aim

The aim of this thesis is to describe the MBJ-process more in detail and understand how the different process steps could potentially affect the dimensional accuracy of the component. This thesis will form the base for a future guideline. The future guideline will be suited for design engineers and the guideline will consist of compiled information about the process and present them in several sub-steps. To better understand the time span needed for planning, printing, and evaluating, this work is divided in several parts, which involves both a theoretical and a practical part. In addition to better understand how such a guideline could be used and how much it could potentially help the industry; A survey will be created, that will be sent out to selected industrial companies. The results will be presented in the thesis and serve as a support tool in understanding the use and content of the guideline. A good planning is of great importance for this work since all printing will be carried out at an external company.

The entire work will be based on relevant geometries, where the found theoretical basis for the technology will be translated into a component with various features. The ambition is to evaluate the potential of the technology with the identified and created features. The features should identify the opportunities and boundaries along the entire eco-system for the technology, which includes printing, drying, curing, cleaning, and sintering. All this will be examined and explained in this fundamental research of what belongs in a guideline for MBJ so anyone can understand and follow each step in the process and learn how to avoid design problems. The main purpose with the guideline is to help RISE IVF get a deeper insight when it comes to the MBJ-process to boost the adoption of the technology.

1.3 Aim of The Thesis

The following questions below are constructed from the Aim 1.2 and will be used to clarify what will be examined throughout the project.

- For whom is the guideline most useful? What should a useful guideline contain, and how can one measure the level of usefulness of the guideline?
- What are the opportunities and limitations of the MBJ-technology in terms of geometrical features?
- What is the dimensional precision of parts produced via the MBJ-technology?
- How can deformations in the component's geometry be controlled?
- In what way can a reference part be used to test the capacity of the MBJ process?

1.4 Demarcations

In this report only the AM-process Metal Binder Jetting, MBJ, will be examined. The report will only consider the changes in the detail's geometry throughout the process and changes in the microstructure and material properties will be excluded. Part size was excluded, that means that no emphasizes was put on the maximum part size.

The analysis will not consider the economic and commercial value of a printing service, but merely explore the capability of the application and requirements on the guideline relative the existing in-house procedures and organisation.
Due to the occurring pandemic, Covid-19, physical visits to the companies and in person interviews is not possible.

2. Method

To deepen the knowledge in AM for this thesis, literature studies will act as the primary source for information, followed by a survey and virtual visits to a machine and service provider of the Metal Binder Jetting technology. All this information will be evaluated and brought together in order to create the base of a manufacturing guideline for MBJ.

With the compiled information and with the help of Catia V5 (Dassault Systèmes, n.d.) Artifacts will be produced to test the opportunities, limitations and difficulties that can occur in the MBJ process. GOM Inspect Suite (ZEISS Group, n.d.) will be used to evaluate a cube with similar features as the printed artifacts. The test artifacts mission is to verify the design rules that will form the foundation for a guideline of the MBJ process. The artifacts will be constructed and realized with the help of Digital Metal AB in Höganäs Sweden.

2.1 Literature Study

Metal AM are in general a new method and is still in the evolution phase in terms of many new developed processes such as the MBJ-process. Therefore, it’s necessary to search about not only the process itself but also everything related to the process to expand the knowledge about the topic. The focus area is to collect information about metal AM and not polymers because they are slightly different, but the design guidelines will also be evaluated for polymer AM just to get an understanding about the basic process. The novelty of Metal Binder Jetting makes documentation and information sources scarce. The difficulty of finding in-depth knowledge and information is also partly due to the fact that most of the knowledge is company “know-how” and is not publicly shared. On the upside, the literature is mostly fresh it doesn’t lead to outdated information.

2.2 Survey

In addition to better understand how a guideline for Metal Binder Jetting could be used and how much it could potentially help the industry to rapidly adopt the technology, a survey will be conducted to gather information from various companies. The survey will help to map the current state of knowledge and act as a base for understanding the use as well as the content of the guideline. The survey will be evaluated with help from the two first tools of the 7 management tools as described in (Bergman & Klefsjö, 2020).

2.3 Virtual visit, Digital Metal AB

Given the current situation with respective to COVID-19, a virtual visit to Digital Metal AB was offered to take a closer look at the process. The virtual visit will take place sometime in the middle of the thesis work and be hosted by Martin Pfern, Product Design Engineer at Digital Metal. The expectations of the visit are to get answers to eventual questions and to get information directly from someone that works closely to the process.

2.4 Artifacts

To test and evaluate the information generated by literature studies, the survey, and the virtual visit to Digital Metal, an artifact will be created. The artifacts purpose is to test different geometrical to see how, where and why the printed object are successful or not. As mentioned earlier Catia V5 (Dassault Systèmes, n.d.) will be used to create the CAD-file that later will be sent to Digital Metal AB for printing.

2.5 Evaluation of Artifacts

Manual measurements with calipers and visual inspections will be used in the evaluation of the artifacts. The evaluation of the artifacts main purpose is to verify the information of the

MBJ-process, and from that draw a conclusion of what belongs in the guideline. An opportunity to evaluate a 3D-scanned cube with similar geometrical features as the artifacts was presented. The cube will be scanned with the system ATOS III Rev. 02 and evaluated with the computer software GOM-inspect (ZEISS Group, n.d.) to see how and where the MBJ-technology potentially can encounter manufacturing defects. The scanned model will be cross checked with the original CAD-file to pinpoint where deformations might occur.

2.6 Validation of Data/Information

Cross-validation of information of collected data between methods and application will be made in order to identify uncertainties and sort out strongly and weekly confirmed aspects. Developed guidelines, proposals and recommendations will be evaluated from sustainable and ethical perspectives.

3. Survey

This chapter will describe why and how the survey was conducted and used to highlight the most important aspects when gathering information to the guideline.

3.1 Purpose With The Survey

To better understand how a guideline for MBJ could be used and how much it could potentially help the industry, a survey was created with the primary purpose to map the current state of knowledge, use and the opportunities that a guideline for MBJ could contribute with. The survey consists of ten questions (Appendix A) which was sent to several companies representing different industries. Since all the answers were anonymous, the questions with all associated answers are compiled and listed in Appendix B. The evaluation of the answers is described in subsequent sections.

3.2 Evaluation of The Survey

By systematically evaluating the answers with the two first tools of the 7 management tools as described in chapter nine by (Bergman & Klefsjö, 2020) some of the underlying difficulties with the creation of a guideline for MBJ will come forward. This method is used to help pinpoint the most challenging aspect of the guideline. The survey was made using Google forms (Google LLC, n.d.), and it was sent out to the companies with one-week deadline to participate.

3.2.1 Structure of Data

The selected approach is used to find the most challenging aspect with the creation of a guideline, therefore the main question for the evaluation of the survey was set to “What is the most challenging when creating a guideline for Metal Binder Jetting”. The answers from the survey are then examined and sorted into groups that shows a relation to the main question.

In order to divide and structure the amount of data the survey generated all the answers were separated from the initial questions and later transferred to yellow sticky notes. Similar or identical answers were combined into only one note, this is step one in figure 1.

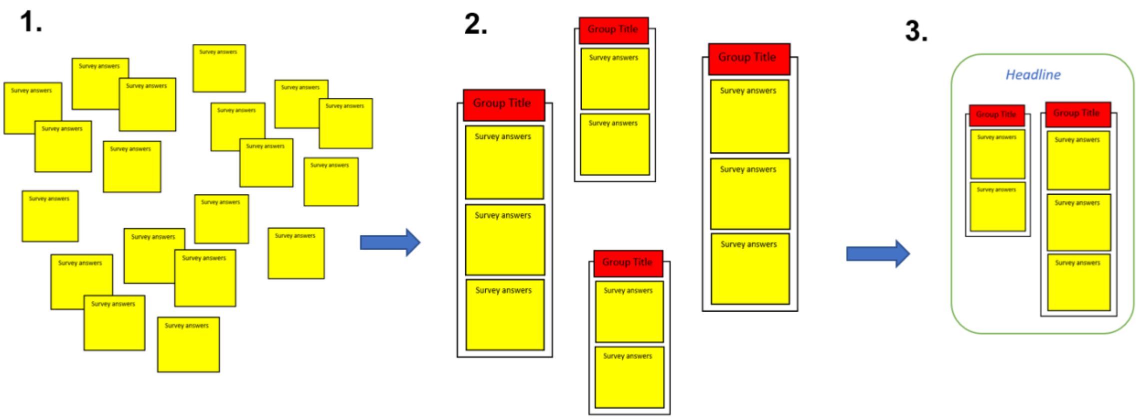


Figure 1. Describes the structure of data generated from the survey. Hall, E (Private).

Step two, all the notes are examined and formed into smaller groups of three or less notes. When there are no more single notes left, the next in the evaluation is to summarize the notes in each group with a title that explains the meaning of each group. These titles are the red notes seen in figure 1.

In the third step, the whole procedure is done again but this time the titles with corresponding yellow notes are examined and formed into larger groups off three or less. And as previously for the yellow notes, these new groups are given a headline that shows the relation between the minor groups and is also connected to the main question, the main question is found in the upper left corner in figure 2.

3.2.2 Relations

After the evaluation of data is complete, the relations between them are examined. Large arrows are drawn to show how the groups are related or perhaps dependent on each other.

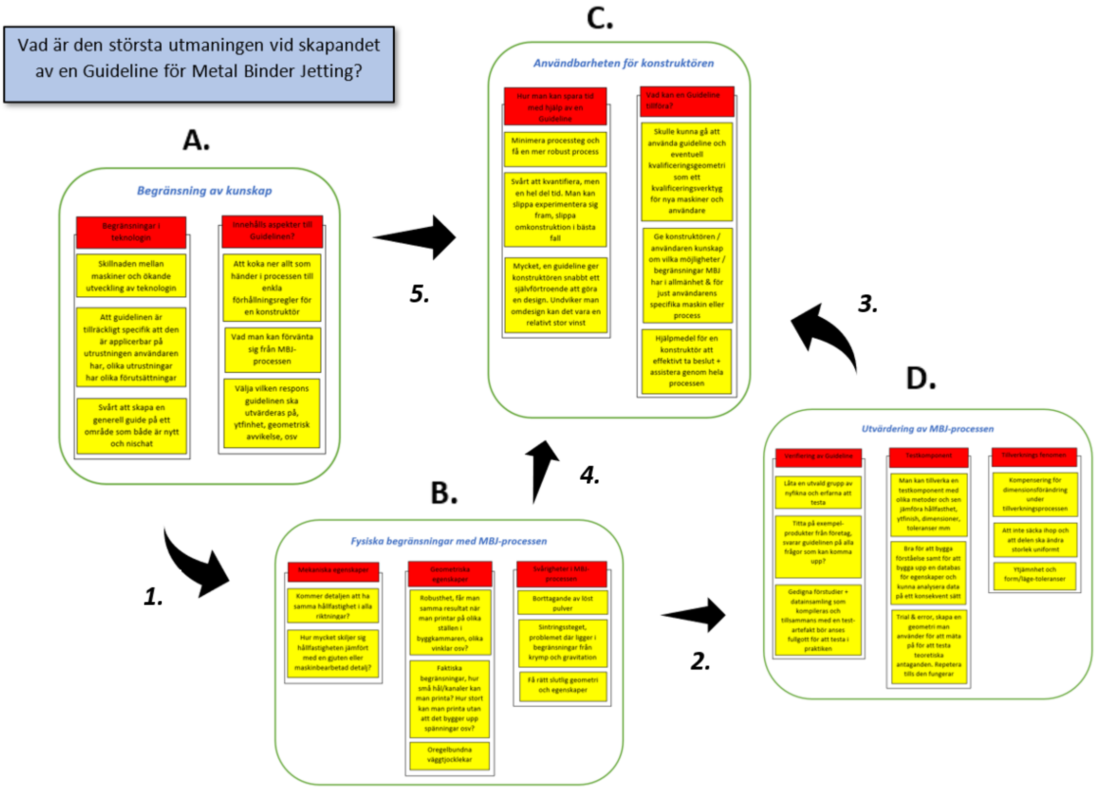


Figure 2. Evaluation of the structured data. Hall, E (Private).

As seen in figure 2, the arrows starts out from group A and then arrow 1 points to group B while arrow 5 points to group C. From group B, arrow 2 and 4 points to group D and C. the last arrow (arrow 3) points from group D to group C. there are no arrows pointing out from group C. To understand the placement and meaning of the arrows they will be described separately.

<u>Arrow 1</u>

To interpret the meaning of the arrows, start at the group named “Limitation of knowledge” (group A), arrow 1 points to the group “Physical limits with the MBJ-process” (group B) this relation says that if there is a lack of knowledge in the subject there might also be more likely to encounter physical limitations in the process itself.

<u>Arrow 2</u>

To continue with the arrow that point to the group “Evaluation of the MBJ-process” (group D) it says that if there are physical limitations in the process (that already might origin from the lack of knowledge, group A) there can be difficult to know how to correctly evaluate the process and bring the right information further into the guideline.

Arrow 3
This trail of arrows ends with arrow 3 that point to the "Usability for the constructer" (group C). Arrow 3 shows how the process is evaluated, based on the possible former physical limits will affect how useful the guideline can be for the person using it or even for a whole company.

Arrow 4
Another arrow that needs explaining is arrow 4 that points from "Physical limits with the MBJ-process" (group B) to the group "Usability for the constructer" (group C). This arrow explains that a challenge for the guideline to be useful is that is based on to which degree the physical limitations in the process affects the final outcome. And as previously the physical limitations can come from the limitation of knowledge of the process (group A).

Arrow 5
The final arrow shows directly that the usability of the guideline is founded in the level of knowledge about the process.

3.3 Conclusion of The Survey

The previous relations between the groups results into the final conclusion that the biggest challenge with the creation of a guideline for MBJ is based in how useful the guideline will be for anyone who wants to implement it in their set of tools.

An important aspect of this newfound knowledge is that in order to make the guideline useful, the most effective way is to investigate the effect the underlying causes such as "how much is known about the technology, the level of knowledge today", "what are the physical limitations in the MBJ-process?" and "how can the MBJ-process be evaluated?" (group A, B, D in figure 2) have on the final guideline. It can thereby be profitable to investigate for example the limits of the technology and how to evaluate it first and then based on the findings pinpoint the guidelines' usability.

To keep in mind when executing this method of analysing data is that the method is in fact meant as a group activity, and a version of the original method described in (Bergman & Klefsjö, 2020) is used in this thesis. It is not ideal, but it presented a satisfying result at the end that will contribute to understand how the state of knowledge is today. This will give the thesis a good insight at what challenges the guideline may encounter and how to deal with the collected information.

The survey was sent out to a small group and received a total of five answers from people where their precise knowledge and background in the subject of additive manufacturing is unknown. This brings a level of uncertainty to the received data and to get a more accurate picture of the state of knowledge the survey should be sent out to a larger group.

4. Virtual visit, Digital Metal AB

The virtual visit took place 15/4 2021 on the platform Teams (Microsoft Corporation, 2021) and was hosted by Martin Pfern as predetermined. He showed the different process steps and introduced all steps in a comprehensive way. The tour started in an office environment where the preparatory engineering steps take place and then continued down to the factory.

Down in the factory, components were about to be manufactured, which made it possible to follow the different process step for the specific component. Martin explained more in detail about the different steps, showed what it could look like and answered questions about the process during the visit.

5. Additive Manufacturing

This chapter provides a brief introduction to additive manufacturing as a manufacturing technology with a focus on the Metal Binder Jetting.

5.1 Introduction

Additive Manufacturing (AM), also known as 3D-printing, refers to a new category of manufacturing methods. Unlike traditional manufacturing methods, like drilling and milling that usually removes material, AM uses a layer-by-layer technology to build up a component with help of a computer program. This method makes it possible to handle even more complex designs regarding geometries compared to the traditional manufacturing methods. Given the nature of the AM-process, layer-by-layer approach, there are still some challenges that needs to be addressed. For example, in the case of metal-AM the porosity that is built-in in the specimens and the stresses with consequential distortions.

Today there are a few larger corporates that are using AM as a production method, the general state of the industry is still that the technology is expensive and mostly used for prototyping. The lack of wider adoption of the technology is partly connected to the production speed, robustness, large number of variations and that in many cases the batch series are too large to be suited for AM. Also, todays mass production involving traditional manufacturing technologies often handle simpler geometries that are assembled, welded or joined into more complex shapes. This partly reveals that lack of knowledge around the capability of AM and its design freedom that can enable massive weight reduction, part consolidation, etc. However, there has been a growing interest of AM over the last years. Given the layer-by-layer approach and adding material selectively where it is needed, when combining topology optimization with AM, it possible to take a major leap toward massive weight reduction. Topology optimization is a method where the parts design can be optimized based on the loading condition, hence unnecessary material is removed and hence output a weight optimized part (Wholers et al., 2016). Industries who benefit from the lightweight construction are for example the automotive industry and the aerospace industry.

5.1.1 General Process Steps In Additive Manufacturing

According to (Gibson et al., 2021) the generic AM process may be sorted into eight overall steps:

1. CAD
2. STL convert
3. File transfer to machine
4. Machine setup
5. Build
6. Removal
7. Post-processing
8. Application

The first step, CAD - (Computer-Aided Design), is to make the design of the part suitable for that specific AM-process of interest. The second step, STL converter, is to convert the 3D-CAD file to a STL-file, which is normally the file format acceptable for most AM-systems. The third step included part orientation, part positions in the build envelope, printing strategy involving how the material is to be joined (laser, electron beam etc.), layer thickness etc. The fourth step involves file transfer to the machine and potentially prepare the machine to be ready for printing. Step five, being the actual printing process involves realization of the 3D-cad file into an actual product. The sixth step is part removal from the machine and potentially also from the build plate (if such is used) to make the part available for the assigned post-processing steps, which is the seventh step in the eco-system for AM. Depending on the AM-process that has been used, there is major difference in the post-processes that are required to finalize the part. Finally, the eight step is to potentially test and verify that the part works as intended at service (Gibson et al., 2021).

5.2 Metal Binder Jetting

The paragraphs below describe the Metal Binder Jetting (MBJ) process to get a better overview of the process and understanding of the upcoming guideline. The process is separated into 6 main stages, Computer-aided design, Machine setup, Printing, Curing, De-powdering, De-binding, and Sintering, note figure 3.

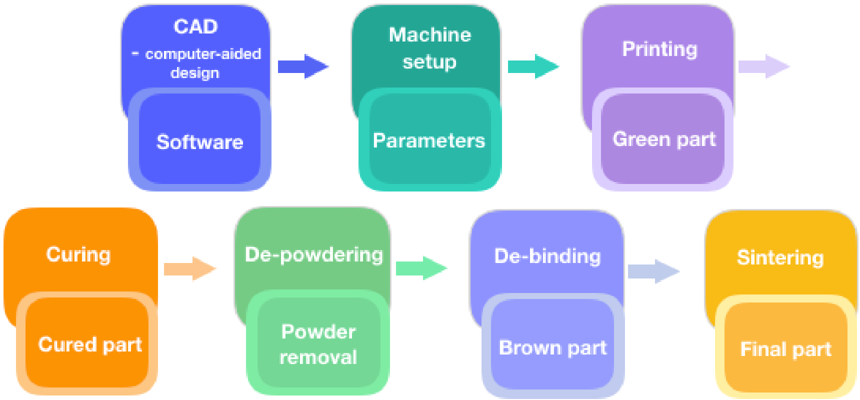


Figure 3. The Metal Binder Jetting process. Andersson, L (Private).

5.2.1 CAD - Computer-Aided Design

The first step is to design the part suitable for the technology after which it will be converted into the *.STL format. If the 3D-cad file already exists, the file needs to be converted in the *.STL format prior to be able to take the next step. Indeed, AM enables impressive part designs with extremely complex shapes, however, here the manufacturing constrains (layer thickness, overhang, internal cavities, etc.) need to be considered, which also includes the post-processes to ensure a viable production.

5.2.2 Machine Setup

Once the 3D-cad file is finalized and converted into *.STL-file format, the file will be forwarded in many cases to a slicing program where also the printing strategy is assigned, also involving part orientation, support structures, etc. To be able to assign the needed printing strategy for the specific part, one need to have the machine specific build processor which enables that the part can be prepared for printing and a machine specific file can be created. An example of such a program that allows these kinds of actions are a Materialise software. It's also possible to take care of shrinkage with help of the Materialise software (Materialise NV, 2020) which in the case of Metal Binder Jetting is in the order of 20%.

5.2.3 Printing Process

The binder jetting system typically consist of a build box, powder supply platform, binder printhead and a levelling roller (Li et al., 2020). As mentioned in 5.2.1 a model of the part is evaluated with help of a CAD software and then sliced and divided into layers of the selected thickness. The roller then spreads a layer of metal powder across the build platform and the binder printhead then deposits the liquid bonding agent on selected areas to bind the loose powder particles together within the cross-sectional area of the selected part. When the binder printhead has finished one layer the build platform descends the same distance as the already selected thickness of each layer. This process is repeated until all the layers are done and the entire part, in this stage called the green part, is printed, note figure 4. The green parts are not sufficient to sufficient to achieve sought after mechanical properties set on the final part. Thereby some post-processes are necessary to obtain the targeted density and the mechanical properties.

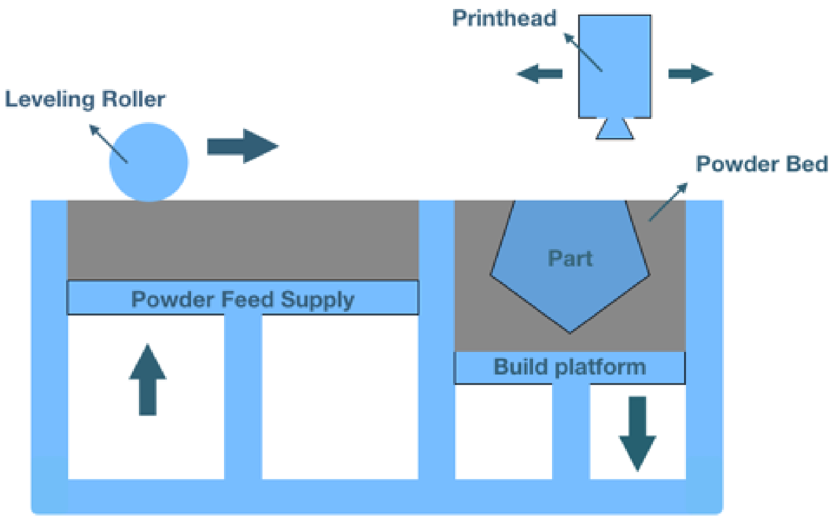


Figure 4. Shows how the MBJ technology works. Andersson, L (Private).

5.2.4 Post-processing

Post-processing is necessary for most of the AM processes, and especially for Metal Binder Jetting. For example, before removing the loose powder, particles surrounding the green part (de-powdering), drying and curing are usually done to slightly strengthen the green parts to prevent them from breaking during the de-powdering stage. (Li et al., 2020). The subsequent sections will describe the post-processes for the MBJ in detail.

5.2.4.1 Curing

When the printing step is completed, most parts require a post-cure in order to dry the binder in the green part and thus increasing the strength of the part. This step is described by (Mostafaei et al., 2020), it is done by removing the powder bed from the printer and heat treating it in a low temperature oven (usually somewhere up to between 180-200°C) for several hours to dry out the binder as much as needed so the green parts can be manually removed from the powder bed and brought to the next step that is de-powdering. How long the curing process takes is based on the volume of the build platform and the characteristics of the chosen binder.

5.2.4.2 De-powdering

When the green parts are cured and have enough strength to be handled manually, they are moved to the de-powdering station. In this step, the loose powder in the build platform is removed by vacuuming and careful brushing done manually by an operator in an air-tight chamber. The chamber has two thick gloves inside and a glass window which makes it possible for the operator to remove the powder without interacting with the loose metal powder particles. To clean the individual parts, a brush can be used for the surface. For parts printed with internal details they can be gently vacuumed or air-blasted, also done by hand. While handling printed parts with overhang structures or small features they are more likely to break, thereby extra caution while handling is necessary. After the de-powdering stage, the loosely bound green metal parts are densified by further post-processes such as de-binding and sintering. Both that sometimes are done separately or in a single phase. The parts are sintered to achieve full density, the parts can also be infiltrated with another material to achieve its full density along with desirable mechanical properties. (Mostafaei et al., 2020).

5.2.4.3 De-binding/Sintering

After the two previous steps, curing and de-powdering, the relative density of the printed green parts is typically about 50-60%. Viewed in a microscope, the individual powder particles at this stage can be observed and are simply bound together at the particles contact points. As mentioned in the de-powdering stage, to achieve the desired density and mechanical properties, further densification methods are needed. Regardless which method is chosen a step where the binder is burned out is necessary, this is done to fully pyrolyze the binder before infiltration or sintering can occur. This step is called de-binding and is done by heating up the green parts to a temperature of ~600-700°C. To reduce the proportion of support structure, it may be advantageous to use ceramics. In mass production, some companies use ceramic boxes with silica sand to support the green parts. After the de-binding step the parts are no longer called green parts, they are instead called brown parts. (Mostafaei et al., 2020)

Before the post-processing stage, it's good to know that different materials have different properties when it comes to sintering. For example, ceramics have a lower risk of densification and a higher temperature during sintering in general than metal powder. Sometimes a component doesn't need any support structure in the printing stage but needing support during the sintering. Therefore, it is important to review the design of the component before beginning the process. Section size and binding removal technique are two important factors that must be checked before the process begins. Another important thing to keep in mind is gravity and that the direction of gravity is directed downwards in the sintering step, which means that the orientation of the part is of great importance.

6. Designing

This chapter considers different aspect when it comes to the design for Metal Binder Jetting involving designing for functionality, manufacturability, and post-processing. Other general design guidelines for metal printing are also addressed here along with some rule of thumbs.

6.1 Before Designing

As mentioned in Section “Additive Manufacturing”, the technology includes several steps, all being linked, why for a successful print, one needs make sure that the steps are connected, and their limitations brought into the design phase.

Additive manufacturing can be used to manufacture parts with a variety of purposes, ranging from visualization purposes, functional prototypes, or full-scale production. This means that a part may carry loads close its physical strength, or being static or dynamically loaded, or being in motion at service, hence by considering the function of the part in the design, it will be called Design for function. Moreover, Design for manufacturing includes knowing the limitations and difficulties of the manufacturing process, is the components realizable or are the design too complex for the process? Designing for post-processing, can for example be factors such as creating a support structure to make sure the part does not break in the sintering stage or making sure the component can be fully clean from loose powder. The design aspects mentioned in (Sönegård & Warnholm, 2017) are further presented down below:

Design for function:
AM makes it possible to create small parts with great complexity and it’s highly requested to have as many functions as desired. There are a lot of aspects that should be checked when it comes to the functoriality of the part. For example, questions like: Which tolerances and surface finishes are required? What material is going to be used? What should the part be optimized for, weight, assembly, etc.?

Design for manufacturing:
Various AM-technologies have different design rules and possibilities to print certain materials. When designing for manufacturing it’s preferable to have knowledge of the various post-treatment processes in the supply chain, as they might for example lead to difficulties such as removal of the loose powder from internal channels. The design should be created in a way so all the powder can get removed after printing. The mechanical properties can also differ depending on direction because of the anisotropy. Aspects like building volume, tolerances of the AM machine, quality of printing etc. should be considered.

Design for post-processing:
Even though the AM process is mostly automatic the finishing steps are often taken care of manually. The removal of powder and support structure are the most critical stages, if the powder is not fully removed it may lead to failure of the part later in the process. The main question here is what post-processing are going to be used for the specific part and is it necessary to re-design the part for post-processes?

6.2 Design Guidelines and Rule of Thumb

General design rules for MBJ are necessary to know when creating a part. The general rules make it easier for the manufacturer, the person that is going to make the part in production and knowing the limitations of the process saves time and effort. For example, if someone wants to print a part that has an overhang, and a lot of complex features the manufacturer should know if the part is possible to create or not within the process limitations and what difficulties that might rise. (PACIFIC RESEARCH LABORATORIES INC, n.d.)

When the manufacturer, the person that is going to produce the part (production), has knowledge of the tolerances and limitations of the process it will become easier to make the parts with higher quality and potentially eliminate or at least reduce the production errors. This becomes even more important in case of assembly of several AM-parts. Understanding these tolerances are important, although it can take a long time to map the source of errors and control them to reach the set tolerances of the targeted product.

6.2.1 Shrinkage

Given the major impact of shrinkage on the final part shape from the post-processing operations for the MBJ process, the initial part design plays an important role in defining the part accuracy and tolerances. As mentioned in chapter 5.2.2 and further explained by (Bournias-Varotsis, n.d.), a component can shrink of about 20% in the sintering step.

The shrinkage in sintering is as mentioned in (AMPOWER GmbH & Co. KG., 2021), not entirely uniform in all directions, see table 1 for comparison of shrinkage at the sintering stage with alternating printing axis. This anisotropic shrinkage can be caused by a number of factors such as:

- Green part density
- Gravity
- Friction between platform and part
- Powder contamination
- Bending of unsupported structures

To avoid the influence from the factors just mentioned, the printing orientation and the sintering orientation should be the same. Given the major impact of shrinkage on the final part as produced by MBJ, it is important to secure the correct design (shrink compensation) to reach the part accuracy and tolerances.

Table 1
Comparison of shrinkage in X-,Y-,Z-axis

Printing Axis	Shrinkage [%]
X	16,5
Y	16,5
Z	20,5

Note. Values From “Design guideline for sinter-based Additive Manufacturing,” of (AMPOWER GmbH & Co. KG., 2021)

The part can be compensated for the shrinkage in the machine software and sometimes the CAD-file is altered so the part will obtain its requested shape. Shrinkage also acts different regarding which material is used and individually for each part and can therefore not be generalized. If part shrinkage is not considered in detail, it can cause major issues and in the worst-case scenario leading to manufacture of exclusive waste.

6.2.2 Orientation

The orientation in which the part is printed can have a huge impact of the resulting components outcome. As mentioned by (Tyson, 2018), the most important factors to have in mind when printing a part are the following:

- Ensure best possible surface accuracy
- Minimize support structure
- Maximize strength

General orientations for AM:
Sometimes it is not possible for all the factors to be achieved at the same time and this can lead to compromises. However, it's necessary to know how the different orientations will affect the part and the properties of the part. Note that the mechanical properties can vary depending on building orientation, for example doesn't the mechanical properties in the Z-direction need to be the same as the ones in X- and Y-directions. The Z-direction often tend to be the weakest orientation as described by (Redwood, n.d.). A rule of thumb is to reduce the height in the Z-direction when setting up the orientation of the part. This is due to the direction of the anisotropy which always are in the vertical direction of the printing.

Orientations for MBJ:
However, parts made by the MBJ process are isotropic, which means that the tensile force is the same regardless of direction, this is due to the high dense and compactness of the part that occurs when loose powder are used.

6.2.3 Layers & Surface Accuracy
When the part is placed as in Figure 5 it often leads to rougher surfaces, this is called the *stair-case effect and* often wants to be avoided. For example, when holes are orientated in the horizontal direction, they will become a bit elliptical due to the *stair-case effect.* Instead, holes should be printed in the vertical orientation to avoid this phenomenon. However, it's possible to create smoother surfaces by having a finer layer thickness but this will create a longer printing time and the cost of the printing will become higher. Even the size of the metal powder has a significant role when it comes to surface roughness and it's better to have as fine-grained powder as achievable.

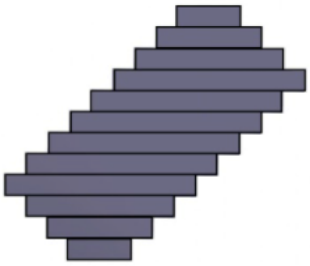


Figure 5. An illustration of the stair-case effect. Andersson, L (Private).

6.2.4 Build Volume
The maximum build box size of MBJ is close to 730 x 380 x 360 mm (29" x 15" x 14.25"). MBJ are often suitable for the manufacture of small parts, in some cases, components can be smaller than 10 x 10 x 10 mm.

The MBJ process is often tempting due to the ability to create robust parts with low weight. To minimize the weight of a component it's sometimes possible to make the part hollow, this also means that the cost of the components becomes lower when less material is used. It's also possible to use a so-called lattice structure, which both minimizes weight and gives control over some characteristics of the component. These are used to minimize weight while maintaining the strength.

6.2.5 Powder & Removal
The most common powder used are MIM-powders. Up to 99% of the powder used in the process can be reused and all the binder needs to be removed before the green part can go to the next step, which means that the binder is removed from the powder during the post-processing step. Moreover, during the cleaning process (de-powdering step) the powder is either removed with a brush or with help of pressurized air. One of the most difficult aspects

of removing powder is from hollow parts. This can prevent the powder from fully being removed and lead to extensive consequences later in the post-processing and parts deviating from the set tolerances. Depending on the design of the part, it might be necessary to add additional holes or cavities to be able to remove the loose powder from the part. It's important to remove all loose powder before moving on to the sintering stage otherwise the part runs a great risk of becoming deformed. To be able to make sure the component can be cleaned from all loose powder, holes and gaps should be around 1mm in diameter (Xometry Europe GmbH, 2020), but this can vary depending on which powder and machine that are used. However, creating additional holes or cavities leads to extra work and it can be difficult to fill in the holes afterwards to get back to the original shape.

6.2.6 Overhang & Angles

For AM in general, overhanging structures needs to be supported in some way to avoid the part from breaking in the de-powdering stage or later in the sintering process. Overhang structures with angles that are less than 45° from the horizontal plane have a high risk of breaking if there is no support structure, sometimes even steeper angles need supporting due to volume and aspect ratio of the overhanging structure. Figure 6 illustrates an overhanging angle of 45°C. (AMPOWER GmbH & Co. KG., 2021). The support may be built into the part or as support structure built onto the building board.

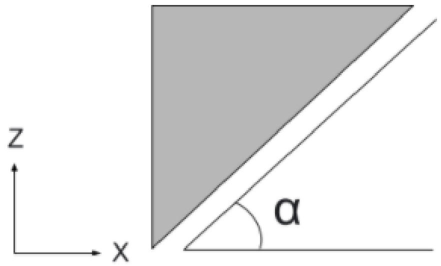


Figure 6. An illustration of overhanging angle. Andersson, L (Private).

6.2.7 Edge

Designing with sharp edges can lead to some difficulties during the MBJ-process, problems such as stress concentrations might occur. The sharp edges can lead to cracks and chips which is something that every manufacturer want to evade. The best way to avoid this from happening is to use fillets since stress concentrations can easily appear in a part if fillets aren't used to make the parts structure stronger. This phenomenon can cause distortion of a part in the sintering process and the stress can remain in the structure if it's not taken care of. Which size the fillet should have differs from source (Inovar Communications Ltd, 2020) to source, (Materialise nv, n.d.) so a fillet size of 1-0.5 mm minimum can be used. If the finished component needs to have sharp corners, it's possible to reconstruct those in the post-processing stage.

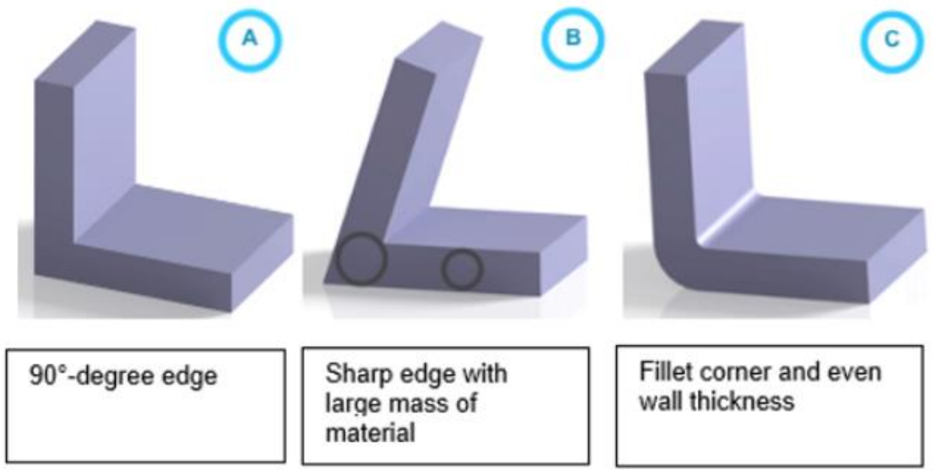


Figure 7. Shows situations A, B, C of typical corner cases. Andersson, L (Private).

The figures above show different situations with typical corner cases. in Figure 7, (Type A) shows that stress cracks are most likely to appear because of the 90°-degree sharp edge, internal corners are often the reason why stress cracks. If using an angle less than 90°-degrees, it's going to create an uneven wall thickness because the corner will get a larger mass of material than the sides of than walls, see Figure 7 (Type B). This causes the walls to distort because of the residual stresses. Figure 7 (Type C) indicates how a part should be treated using fillets to eschew the problem with stress cracks and chips.

6.2.8 Walls

Depending on the material and specific machine the critical wall thickness may vary. A wall created with the MBJ-process is either supportive or non-supportive. In general, supportive walls can be thinner than non-supportive walls, due to the risk of a non-supportive wall breaking is higher in the handling stages. If a wall is supportive or non-supportive depends on where the wall is located and connected to other walls. A wall is supportive if it's fixed to at least two sides of the wall and if not it's non-supportive. When designing parts with variable wall thickness it is important to be aware of that thicker wall sections connected by thin wall sections can cause unexpected deformations of the part. It may even affect the part tolerances. (Xometry Europe GmbH, 2020) The underlying cause to this phenomenon is the cooling rate, after the part is removed from the furnace the thicker sections will have a much slower cooling rate and this can cause the part to warp.

6.2.9 Holes

When printing components with holes it's vital to know tolerances for the design of the hole and it can help to answer the following two questions below:

1. If the diameter of the hole is increased or scaled down, how much can the hole be enlarged or reduced before the properties of the hole gets affected?

2. How much variation is possible in X-, Y- and Z-dimensions of the hole to still make the component work in the wanted way?

The minimum diameter of a hole with MBJ is mostly limited by the powder removal process and the design should thereby support manual removal of the loose powder in holes and cavities. As mentioned in (AMPOWER GmbH & Co. KG., 2021) the depth of the hole is also connected to its diameter, see table 2.

Table 2
Depth and diameters of holes in MBJ

Minimum Diameter [mm]	Hole depth [mm]
0,2	0,1
0,5	1
1	5
2	10
5	30

Note. Values of minimum diameter with corresponding recommended depth. From "Design guideline for sinter-based Additive Manufacturing," of (AMPOWER GmbH & Co. KG., 2021)

Curved holes can be particularly hard to clean out the additional loose powder from. A good rule of thumb is to be able to see through the hole from one side to the other to make sure the hole will be easy to clean in the post-processing stage. If the hole isn't completely cleaned the process will fail and the hole will become totally solid instead. Material shrinkage often affect small dimensions of holes and the circularity have a high risk of disappearing.

6.2.10 Support Structure

The MBJ process involves loose powder that surrounds the printed parts, this means no support structures are needed in the MBJ printing process. However, there are still some design features or structures that could lead to breakages, when the part is handled in the green stage. To minimize this risk, some certain actions can be considered, which is the use of self-supporting structures like ribs, arches, and fillets to get a more stable structure.
If no self-supporting structure are used the risk of the part breaking during the de-powering phase increases, which means that overhang and walls being not self-supporting are more dependent on support structures. If a part runs a high risk of breaking the easiest way to fix the problem is by making sure the dimensions are not too small. If the part is too weak, it's possible to add extra support structures to the design to make it stiffer. These extra support structures are often removed after the sintering process. The two kinds of support structure that can be applied is:

- Ceramic supports
- Printed metal supports

The ceramic supports are reusable and often used when support is only needed in the sintering stage. The printed metal supports have the same shrinkage as the part itself. (AMPOWER GmbH & Co. KG., 2021)

6.3 Pre-processing

The pre-processing stage begins when the design is finished but before the machine is running. Depending on manufacturer this stage may look different, and some manufacturers prefer a raw format CAD-file instead of the commonly used STL-file (Sönegård & Warnholm, 2017). All the necessary data should be presented in this step, such as material and tolerances. Sometimes support structure are used in pre-processing and if it's the case it should be removed in the post-processing step.

6.4 Post-processing

In the post-processing step both support structure (if any are used) and unnecessary powder are removed. The powder that isn't used can be reused up to 99% when using the MBJ-process (3D Print Pulse). A disadvantage of most AM processes is that the surface finish is often inferior to traditional manufacturing methods. Post-processing can be made with a various of method and some of them require preparatory work (Sönegård & Warnholm, 2017).

7. Artifacts

This section describes the designed and manufactured objects, called artifacts. The artifact enables to test and analyze, in this case, the design rules and features mentioned in the previous chapter too see which exact rules to implement in a future design guideline.

The artifacts are produced in one machine which means that the variations that could potentially come because of using several machines are eliminated hence variables such as the layer thickness, pack density, ink-quality, are reduced. An artifact may be tested to investigate a certain part of the entire supply chain, that means a single process step or multiple process steps (NIST, 2017). Since each print trial is costly, it is important to find various approaches to reduce the costs connected to the manufacturing of the artifacts. In this case, focus on adding several interesting features in one artifact which enabled to print, evaluate and study several features in one component was of importance, as the manufacturing of the artifacts were made externally by Digital Metal AB.

Only relevant design aspects that have been brought up in chapter 6 are going to be printed in this thesis. The reason for this is that it would take too much time and become too costly to evaluate all aspects. As previously mentioned in “Demarcations” chapter 1, the maximum part size is excluded.

7.1 Features

With help of Digital Metal, it was possible to produce, test and evaluate the Metal Binder Jetting technology with several of the identified artifacts. The artifacts purpose is to verify the process and identify problems and limitations that may occur as mentioned in chapter 1.3. The artifacts are as mentioned earlier created in the CAD-program, Catia V5 (Dassault Systèmes, n.d.) and are based on the information collected in this report. It was decided to create challenging artifacts to be able to find the opportunities and challenges in the process. When the CAD-files were completed, they were transferred to STL-files and sent to Digital Metal for printing. All artifacts are printed in stainless steel 316L.

The features were sorted into groups depending on what parameters to evaluate. The geometries were also discussed with RISE IVF to get their point of view and to compile which tools are suitable to use when evaluating the artifacts.

There was a discussion about doing some hollow parts to see how well the powder removal worked. However, this was decided not to be included because Digital Metal does this in their factory and is therefore difficult to evaluate. The final geometric features that were decided to be evaluated were walls, channels, holes, radiuses, protrusion, gaps, threaded features, overhang, text font, angles, and shaped holes. The result of the discussion and geometries is listed in table 3 and the final artifacts are listed below, notice figure, 8-13.

Artifact 1

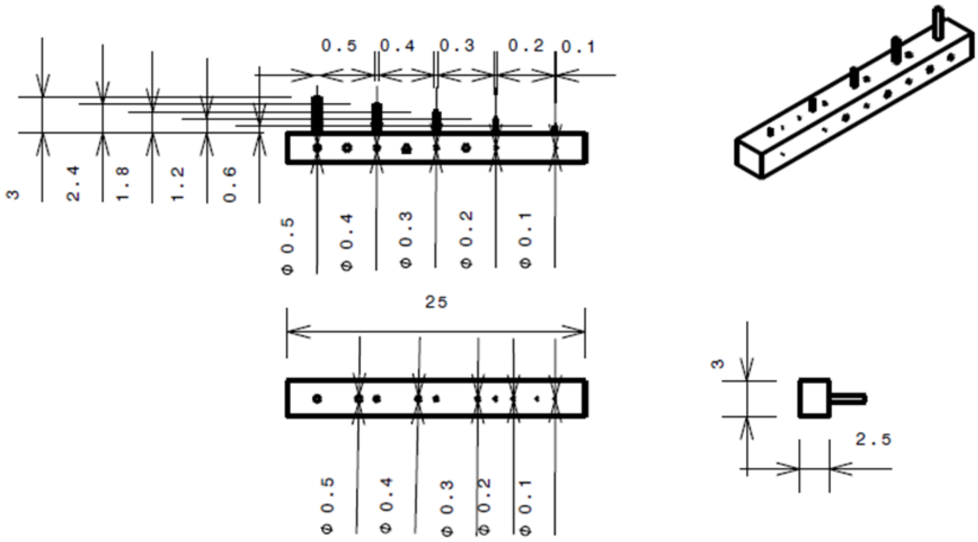


Figure 8. Drawing of artifact 1, all measurements in millimeters. Andersson, L (Private).

Artifact 2

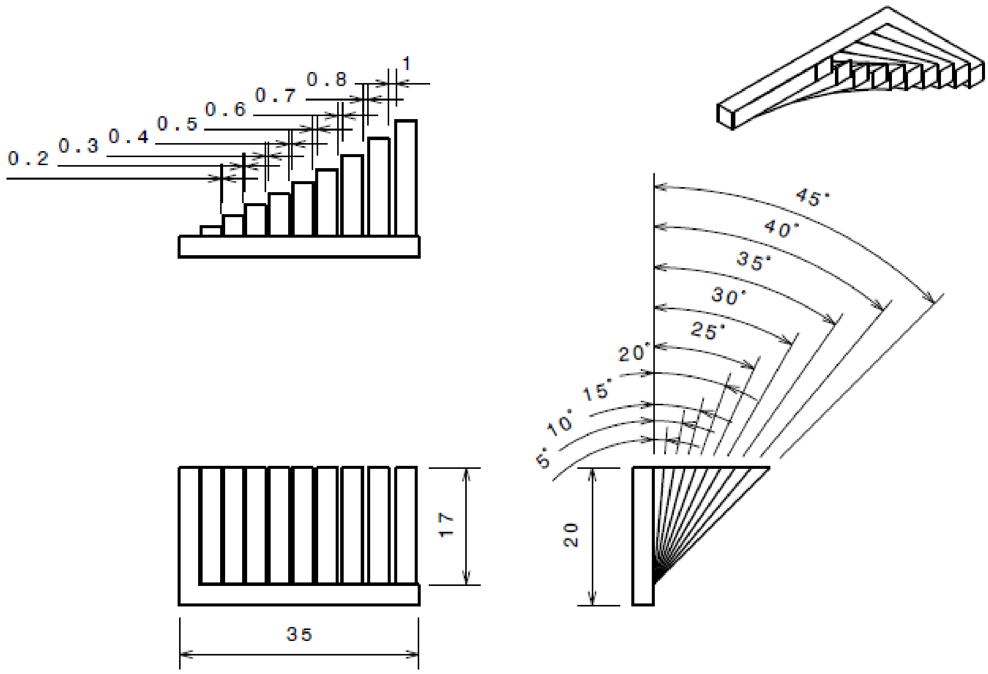


Figure 9. Drawing of artifact 2, all measurements in millimeters. Andersson, L (Private).

Artifact 3

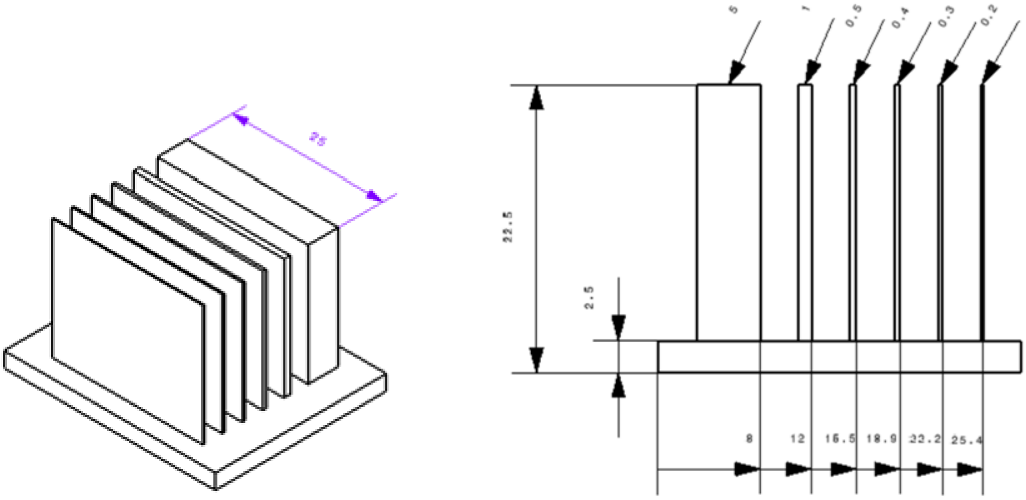


Figure 10. Drawing of artifact 3, all measurements in millimeters. Hall, E (Private).

Artifact 4

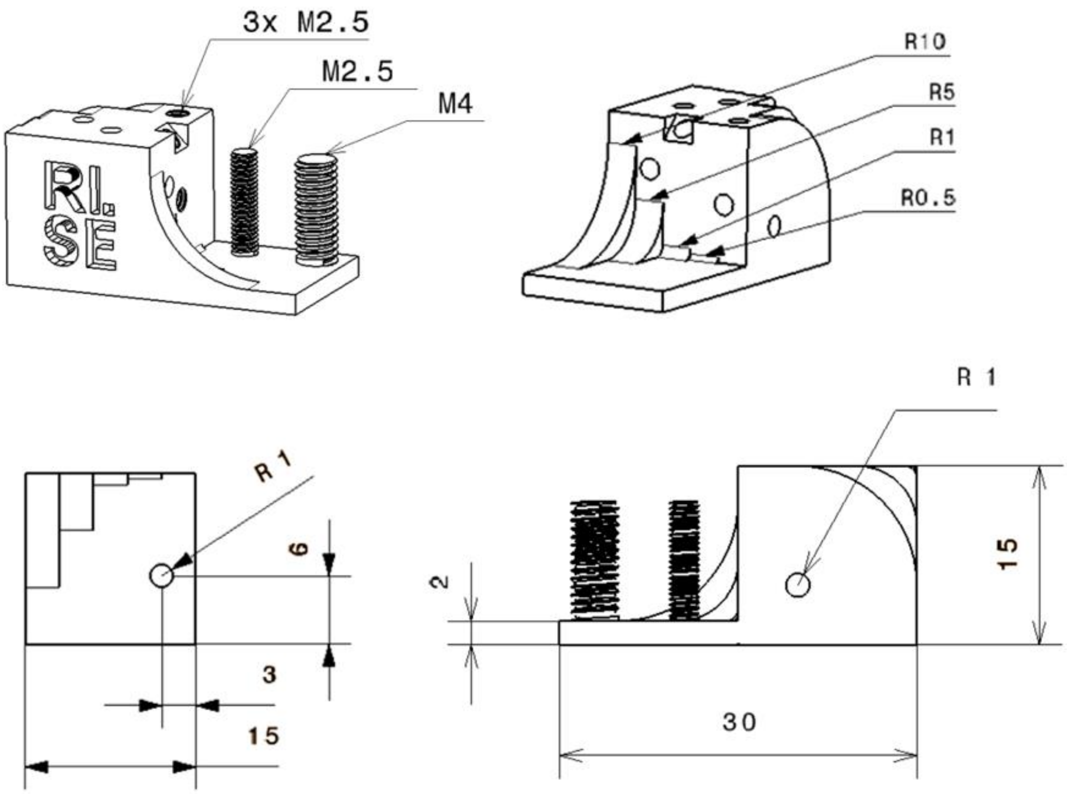


Figure 11. Drawing of artifact 4, all measurements in millimeters. Hall, E (Private).

Artifact 5

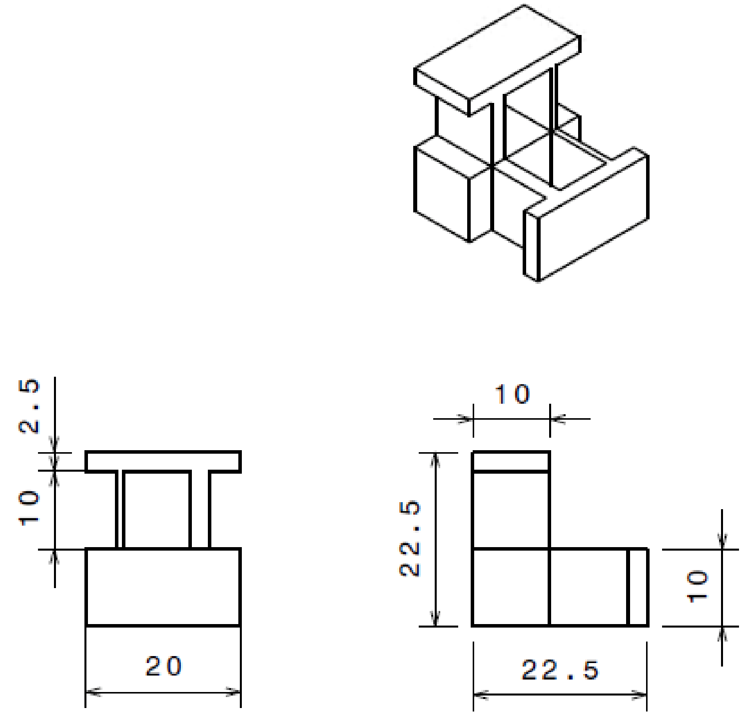


Figure 12. Drawing of artifact 5, all measurements in millimeters. Andersson, L (Private).

Artifact 6

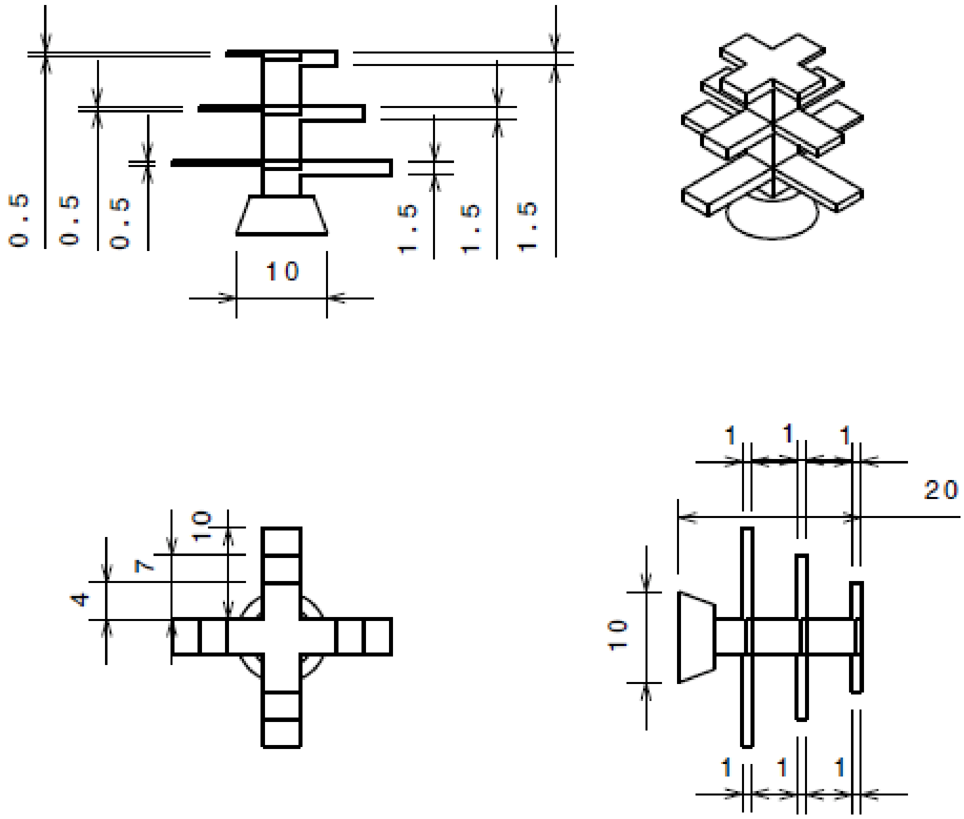
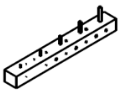
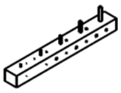
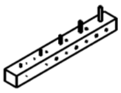
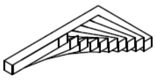
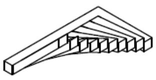
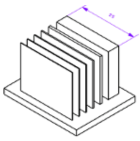
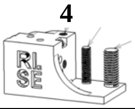
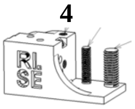
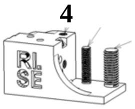
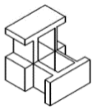
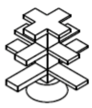


Figure 13. Drawing of artifact 6, all measurements in millimeter. Andersson, L (Private).

Table 3

List of geometries and how to evaluate them.

Artifact	Geometries	What should be evaluated?	How to evaluate?
1 	Holes	How the roundness is affected by the holes in both the X-, Y-direction and the Z-direction and accuracy	(3D-scanner, Concentricity, Cylindricity) Visual analysis
1 	Diameters	Buildability, roundness, diameter, perpendicularity	(Cylindricity, Caliper / 3D scanner) Visual analysis
1 	Shaped holes	The complexity (resolution)	Visual analysis
2 	Overhang	How much overhang can you have before it breaks? Want to see when it collapses and when it lasts to know when support structure may be needed.	(3D-scanner) Visual analysis
2 	Angles	Straightness of the plane at different overhanging angles, surface finish on the surface at different overhanging angles. Angularity	(3D-scanner) Visual analysis
2 	Gaps	Show how small gaps you can have so that there is no corruption and if it is possible to remove the powder from the gaps Measure the tolerances.	(Caliper/ 3D-scanner) Visual analysis
3 	Walls	Straightness of the walls	(3D-scanner) Visual analysis
4 	Text font	Resolution	Visual analysis
4 	Threaded holes	How the roundness is affected by the holes in both the X-, Y-direction and the Z-direction.	Test and see if it is possible to screw in a screw in the hole.
4 	Radius/fillet	Evaluate the roundness and how the "staircase effect" is affected at different radii.	(3D-scanner) Visual analysis
5 	Stress	Do any stresses occur when wall thicknesses are different?	(3D-scanner) Visual analysis
6 	Extensibility	When do you need to add support structure? The straightness of the protrusion.	(3D-scanner) Visual analysis

Note. Describes how the various artifacts are intended to be analyzed and by what method.

7.2 The Manufacturing Process

It's difficult to identify where in the manufacturing route various defects are arising as Digital Metal AB were providing full support during printing. The parts arrived after a few weeks and were at arrival decided to be evaluated manually using a caliper (dimensions) and visually. However, to get a better insight with respect to the dimensional accuracy, it was also decided to include 3D-scanning of a cube with similar features as the artifacts. The scan system used was ATOS III Rev. 0.2 with the measuring point distance: 11.58 – 95.46 µm. How the scan is done is described in 7.2.1 below.

7.2.1 3D-Scanning

A 3D-scanner is used to collect information from a physical object and transfer the data into a computer software. The scanner uses the surface as reference on the object and with help of the scanner, puts the different views into a 3D-model. In this project the 3D-scanning is used to define the accuracy of the artifacts and to analyze how reliable the process is.

1. Make sure everything is calibrated.

The first step is to calibrate the equipment, such as setting up the cameras and make sure everything works properly.

2. Prepare the object for scanning.

The object needs to be prepared for scanning which may be done in different ways. One way is to use reference points markers on the object which reassure high accuracy. Before scanning the markers are put into places on the object, often three reference points are needed on each side of the object. When scanning the reference points markers are detected and helps the software program to detect the object. Another way is to use titan-oxygen spray which reduces the reflections that may occur during the scanning and makes the surface of the object matte. However, this adds an additional layer, usually between 2-40 µ, otherwise the titan-oxygen might oxidize and be useless, the spray usually last for 30 minutes.

3. Scan the object.

Various software's may be used to be able to 3D-scan the object into a digital environment. In this work a program called GOM Inspector is used for collecting and evaluating the data. When starting up the GOM Inspector program select new in the start field and then go to the symbol that look like this (paste in a figure here). Then select the measurement temperature and select OK. Thereafter, the object can be scanned and if a worktable with reference points is used this can be removed from the scan. Then setting for how many scans in each view is set up, this might take a while.

4. Analyze the 3D-scanned object.

The scanned object and the CAD-model are transferred to a 3D-scanning program, in this case GOM Inspect. Now it's possible to measure the wanted factors with help of GOM Inspect. For instance, it's possible to measure distance of different objects, roundness, cylindricity etc. When all the measurements are created the program transfer the data to a excel document.

7.2.2 GOM Inspect

GOM Inspect is a software in which a 3D-scanned part can be compared with the original CAD-file. An opportunity to evaluate an already finished scanned component was presented. A cube with similar features as those in the artifacts from 7.1 was studied to get a better insight with respect to the dimensional accuracy, see figure 14. The steps to find out how much the CAD-model differs from the printed model are described below.

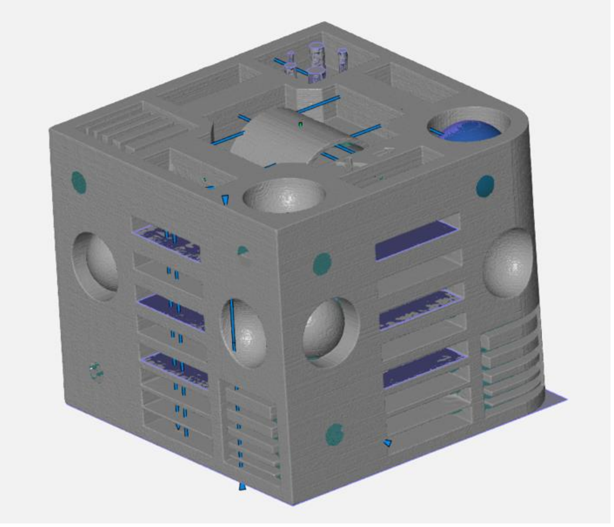


Figure 14. Shows the compared component in GOM Inspect. Andersson, L (Private).

Diameter check:
This artifact evaluated cylinders, holes, and distance accuracy. The artifact was scanned and compared to the CAD-model with help of the GOM Inspect program. The cylinders were analyzed with help of a cylindricity and perpendicularity check. First, it's necessary to setup the required information for the cylinders. To do this click on "CONSTRUCT", "Cylinder" and "Fitting cylinder", now a popup window is shown. Then press the control button and the left mouse button on the cylinders. Sometimes not all the surfaces are selected so this might be done manually. When the surface is completely red and green the diameters can be inspected. Now go to the "GD&T quick creation" tab and select "Dimension independency principle" and make sure the cylinder is selected as well. Beside the box "Against fixed value" write the nominal value of the cylinder. Tolerances is set to zero in this case. Now a dialog is created above the cylinder and the maximum and minimum cylinder is shown.

Cylindricity check:
Next the cylindricity may be checked, go to the "GD&T quick creation" tab again and chose "Cylindricity" and select the cylinder. The tolerance is set to zero and the cylinder is given a name.

Perpendicularity check:
A datum plane is required to create a parallelism check. Go to "CONSTRUCT" and pick "Fitting plane" and select the wanted plane. To make the plane defined as a datum plane, go to "CONSTRUCT" and "Local coordinate system" and "create datum system". Give the datum plane a name, in the box "datum 1" select the datum plane and then create. Now it's possible to make a perpendicularity check. Go to "GD&T quick creation" and pick "Perpendicularity", make sure the cylinder is selected. Define the datum system and the tolerances (in this case zero). When this is done, the cylindricity, diameter and perpendicularity is checked. In the figure 15 below the dimensions for diameter, cylindricality and perpendicularity are exposed.

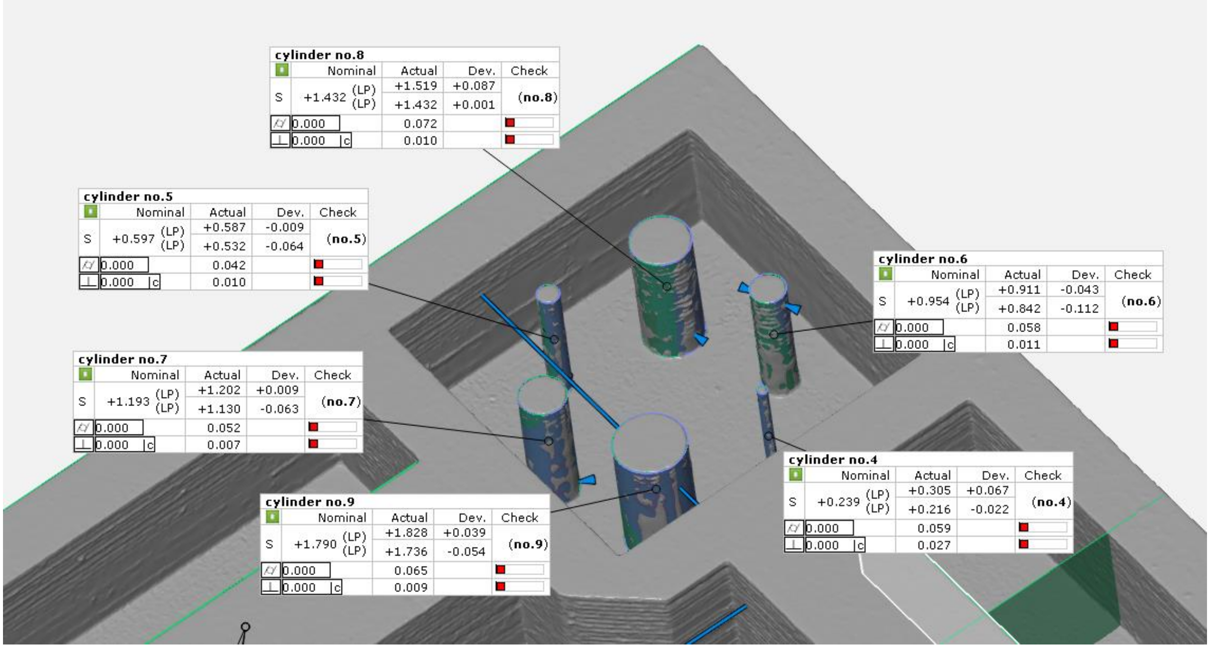


Figure 15. Shows dimensions for diameter, cylindricality and perpendicularity. Andersson, L (Private).

Position check:
A cylindric hole and a datum plane is required position check. To do this click on "CONSTRUCT", "Cylinder" and "Fitting cylinder", as before. Make sure the whole hole is selected or do it manually. Give it a name and click "create and close". Now go to "CONSTRUCT", "Plane", and "Fitting plane", select the surface of one of the sides surrounding the hole and click "create". Now do the same thing on both the other side and the top surface. When the three planes are created it's time to create a datum system. When the popup window of the datum system is shown, select each plane and click "create". After this a location inspection can be made. Click on the "GD&T quick creation" tab, pick "Position" and select the hole. Chose the datum system and tolerances.

Angularity check:
To create an angularity check, a datum plane and a plane are needed. Click on "CONSTRUCT", "Plane" and "Fitting plane". Make sure the surface is fully selected, if not this needs to be fixed manually as in "GOM Artifact 1". Give it a name and close the popup window. Construct the datum plane using the same steps as in "GOM Artifact 1". After this the angularity check can be made by using the "GD&T quick creation" tab, select "Angularity" and pick the datum system and define the tolerance.

7.3 Results/Analysis of Artifacts

In this chapter the result of the printed artifacts will be presented along with the analysis of each artifact. As mentioned in 7.2 it was decided to make conclusions by inspecting the artifacts by hand. All artifacts were printed four times which provides some insight with respect to the reproducibility of the technology.

7.3.1 Manufacturing

After powder removal:
The artifacts are lined up for the de-binding stage. Artifacts with broken or damaged parts have received their damage during the powder removal process. Notice that the some of the protrusions in artifact no.6 are broken, this is displayed in figure 16. It's mainly the thinnest and longest protrusion that has failed, but one of the artifact no.6 has lost four protrusions. This is probably because the components are very thin and fragile.

Figure 16. Artifacts after the powder removal step ready for de-binding. Pfern, M (Private, permission to publish).

After de-binding:
The artifacts after de-binding ready to be sintered, see figure 17. Notice that artifact no.2 is completely broken in all four cases. This clearly shows the severity of the being able to design the parts not only for the printing or sintering but also for the de-binding process. For example, should the part be re-oriented during the de-binding process, or additional support structure should be included, etc.

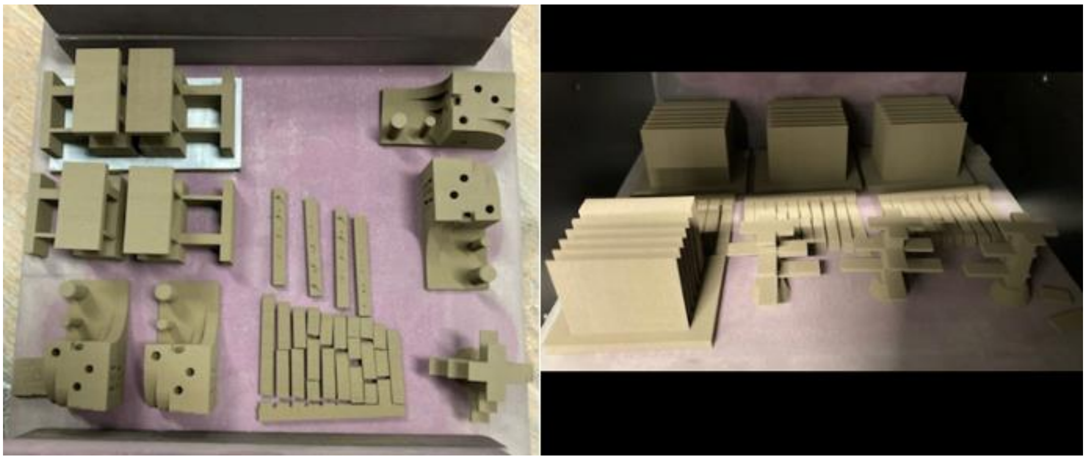


Figure 17. Artifacts after the de-binding and ready to be sintered. Pfern, M (Private, permission to publish).

7.3.2 Finished artifacts

Artifact 1:
This artifact consisted of five cylinders with different diameters and height. Five throughout holes with different diameters in both x- and z-direction and some shaped holes. The five cylinders displays the buildability and how it affects the artifact. In most cases the two of the smallest cylinders have broken off or were very injured and in one case all the cylinders are gone, as shown in figure 18. By checking the artifacts closely it's possible to see that some cylinders are tilted.

To check that the holes are continuous, light is used to see if the light penetrates on the other side. The holes showed very different results from each artifact. The artifact that has no remaining cylinders had no continuous holes at all. In the remaining three, the largest hole of Ø 0,5 mm worked and light could shine through. In one case even the hole of Ø 0,4 mm worked. The shaped holes that were printed horizontal all came out successfully. All other holes deformed.

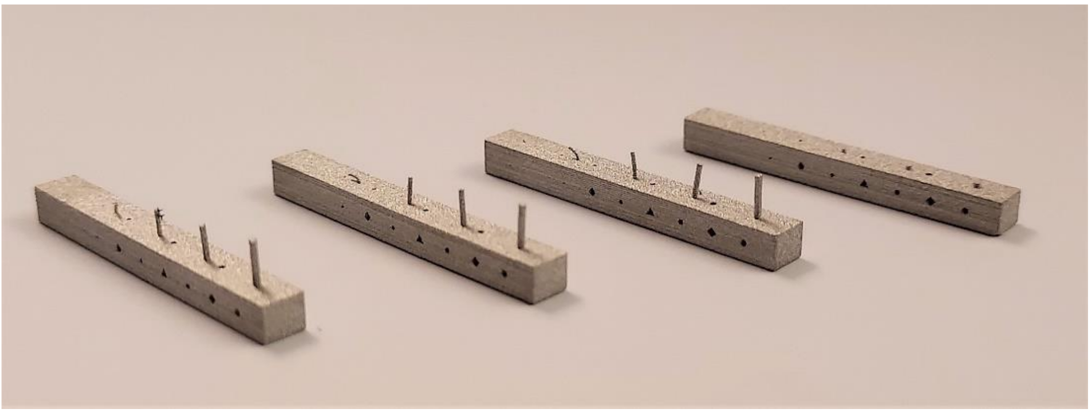


Figure 18. The four components of artifact 1. Hall, E (Private).

Artifact 2:
As mentioned in 7.4.1, already in the de-binding stage this particular artifact failed, see figure 19. This part was positioned un-supported before entering the de-binding stage, which reveals on the importance of having support to prevent the part from total collapse. Also, as highlighted before, the orientation of the part can be of importance, or in some cases a combination of adding support and potentially reorient the part.

Figure 19. One of the broken components of artifact 2. Hall, E (Private).

Artifact 3:
The third artifact is a series of walls with the same height and length but with alternating thickness, see figure 10, for exact measurements. As seen in figure 20, the artifact was printed in four examples that all showed a very similar outcome. The underlying mechanics causing the severe deformation and collapse of the thin-walled sections are not further investigated in this report. However, given the thickness and size of the wall and the high temperatures, it might be so that the strength of the material at the high temperature was not enough, causing the collapse of the thinnest wall. This is also connected to the gravity, as the temperature goes up and the strength of the material at the elevated temperature is reduced, at some point the structure can no longer carry the weight and the part will collapse.

The deformation seems to be less as the wall get thicker, however, since the walls are tilted inwards, that means towards the thicker one, it is difficult to estimate how thin single walls that can be manufactured before they collapse or deforms. Ideally, one should manufacture each wall separately to see how and when they would collapse. The thickest wall of 5mm seems to have small to almost no deformation.

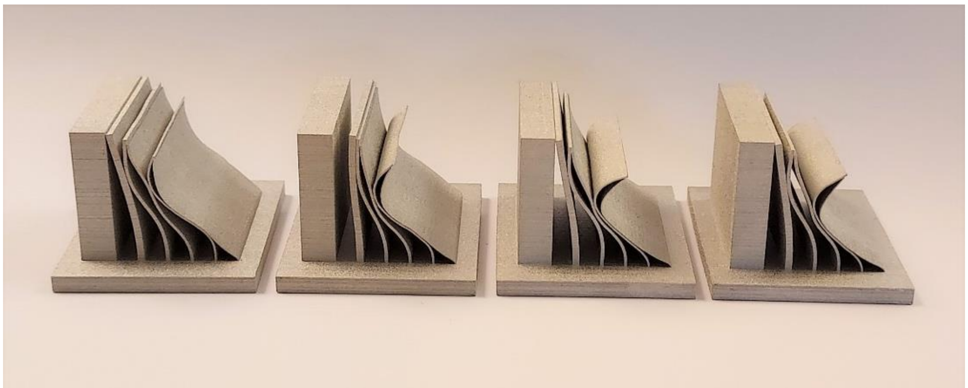


Figure 20. The four components of artifact 3. Hall, E (Private).

Artifact 4:
The fourth artifact was also printed in four examples and turned-out with visually good-looking results. The font of the text looked clean and with fine surfaces. The internal channels were checked with help of light the same way as with artifact 1. Both the channels of all four components were completely fine and successfully made, see figure 21. Two screw-nuts, M2.5 and M4, were used to test the threads. The smallest cylinder was successfully manufactured but the bigger one didn't fit the M4 nut. The three threaded holes were 2 mm and therefor tested with M2 screws. The screws were a bit too small to hook up with the thread.

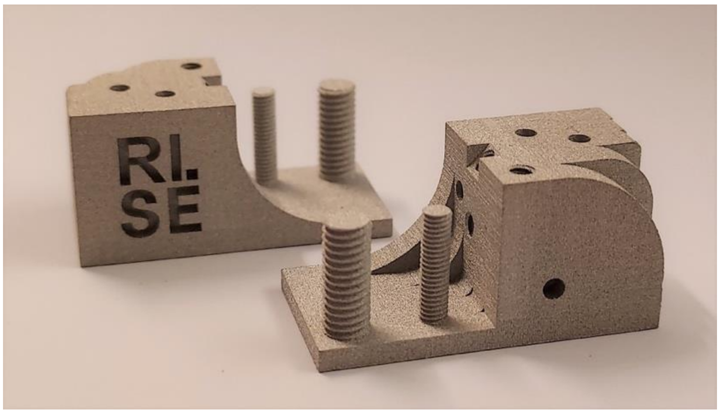


Figure 21. Two of the four components of artifact 4. Hall, E (Private).

Artifact 5:
As shown in figure 22 in 7.4.1 two of the four components of artifact no.5 was placed on a bottom plate made out of the same material as the printed artifacts. When comparing the parts sintered using ceramic or metallic substrate, it appears that the parts printed on the substrate made with the same materials had the least deformation in the sintering step. This required much more investigation, although it was an interesting observation that the substrate material played a significant role in the level of deformation.

Figure 22. Two of the four components of artifact 5. Hall, E (Private).

Artifact 6:
As mentioned earlier in 7.4.1, the broken protrusion happened during the power removal step. The result after sintering of artifact 6 can be seen in figure 23. As can be shown in the figure, the longest protrusion broke off in all but one case. On one of the artifacts the second level of protrusions also broke off. These protrusions had different thickness, and one observation that was made was that the thinner the beams are, the less protrusion it's possible to have.

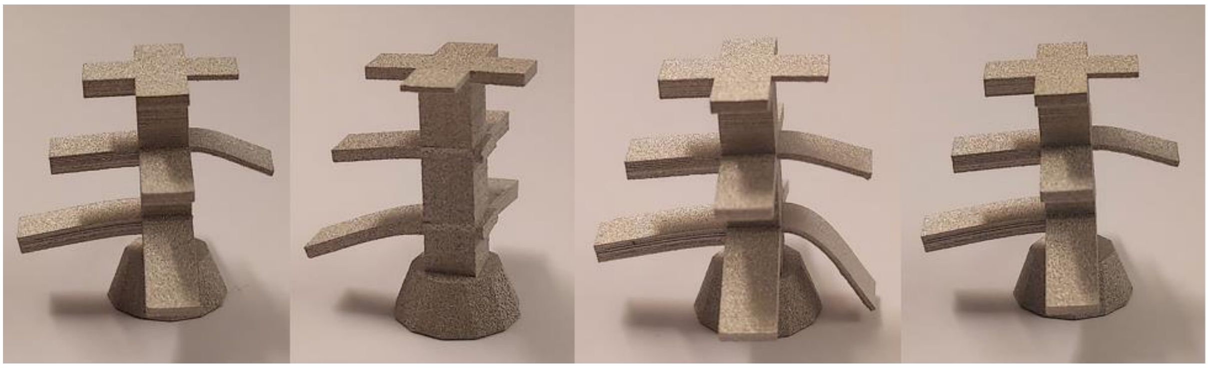
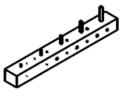
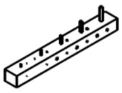
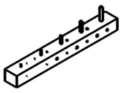
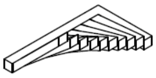
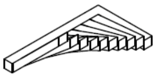
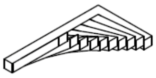
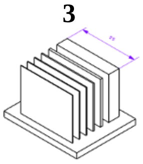
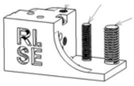
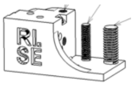
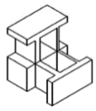
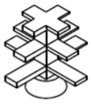


Figure 23. The four components of artifact 6. Hall, E (Private).

The results from the six artifacts are summarized in table 4. All the geometrical features in each artifact are listed, the table shows which geometrical feature was a "success" or a "failure" with a describing text of why the feature was considered a success or a failure.

Table 4
List of artifacts and summary of successful or failed features.

Artifact	Geometries	What should be evaluated?	Success	Failure
1 	Holes	How the roundness is affected by the holes in both the X-, Y-direction and the Z-direction and accuracy	X	The smallest cylinders were broken, it was therefor decided to skip the 3D-scanning
1 	Diameters	Buildability, roundness, diameter, perpendicularity	X	This was considered a failure since some of the cylinders were broken or deformed
1 	Shaped holes	The complexity (resolution)	This was a success since all the shaped holes were continuous	X
2 	Overhang	How much overhang can you have before it breaks? Want to see when it collapses and when it lasts to know when support structure may be needed.	X	The overhanging features of this component made the whole artifact to collapse
2 	Angles	Straightness of the plane at different overhanging angles, surface finish on the surface at different overhanging angles. Angularity	X	This haven't been evaluated since the component failed in the de-binding step
2 	Gaps	Show how small gaps you can have so that there is no corruption and if it is possible to remove the powder from the gaps Measure the tolerances.	X	This haven't been evaluated since the component failed in the de-binding step
3 	Walls	Straightness of the walls	X	The thickest wall was considered straight but the other once failed in the sintering stage
4 	Text font	Resolution	Really good resolution with high detail	X
4 	Internal threaded holes	How the roundness is affected by the holes in both the X-, Y-direction and the Z-direction.	All the internal threaded holes	X
4 	External threaded cylinder	How the roundness is affected by the cylinder in both the X-, Y-direction and the Z-direction.	X	The thickest external threaded cylinder didn't work, and the thinner cylinder was a bit to big

4 	Radius/fillet	Evaluate the roundness and how the "staircase effect" is affected at different radii.	The manual inspection showed that the radiuses were fine	X
5 	Stress	Do any stresses occur when wall thicknesses are different?	Only the thinnest wall had minor deformations due to stress in the material	X
6 	Extensibility	When do you need to add support structure? The straightness of the protrusion.	X	The longest and thinnest protrusion broke during the de-powdering except in one of the components

Note. Describes the printed features and what was successfully printed or not. The text under “success” and “failure” explains what worked or not.

8. Discussion

In this chapter the used methods, analyses, approach, and the results are discussed.

8.1 Literature

The literature was mostly retrieved from Chalmers Library's, (Chalmers University of Technology database) and Diva, (KTH royal institute of technology's database). The main sources used were from 2016 and newer, since MBJ is such a novel technology. However, a disadvantage of having such an emerging technology was that it is not sufficiently proven and therefore there is limited literature about the process. When it comes to AM it's important to have literature that is up to date, because the process may have changed a lot in just a few years.

The difficulty of finding good information is also limited since companies don't want other companies to know their process ways because of competition ("know-how"), this is also the reason why it was hard to find useful design rule. However, since the literature is mostly fresh it doesn't lead to outdated information.

8.2 Survey

When sending out the survey it was mainly focused on five companies. However, only five people answered the survey and in retrospect, it might have been profitable to send out a reminder of the survey or send it to more people. Even though, those who responded to the survey still had a good view of the process.

8.3 Virtual visit, Digital Metal AB

The virtual visit took place in the middle of the thesis work as expected. At first it was discussed to have a visit on site at Digital Metal AB but due to the pandemic this was not possible. As many companies do not want to share specific information about MBJ due to competition, it was not possible to predict how carefully the process steps would be gone through.

8.4 Artifacts

The components gave split and somewhat unexpected results as seen previously in table 4. For example, artifact, 2, 3 and 6 broke or deformed during different process stages. Artifact 2 broke during the de-binding stage, probably due to gravity and stress in the material. Artifact 3 deformed during the sintering stage and artifact 6 broke during powder removal. It might have been possible to prevent these outcomes by using support structure or by changing the orientation of the artifacts. Hence, depending on the part design, each process step needs to be optimized and tuned to minimize the part failure.

8.5 The Work In General

The questions from chapter 1.3 are discussed separately below:

- For whom is the guideline most useful? What should a useful guideline contain, and how can one measure the level of usefulness of the guideline?

The first two sub-questions are answered by the "survey" chapter 3. To measure the level of usefulness of the guideline, it needs to be used practically and repeatedly to see if the guideline presents similar results each time.

- What are the opportunities and limitations of the MBJ-technology in terms of geometrical features?

The opportunities and limitations of the MBJ-technology was evaluated with the help of the 6 artifacts from chapter 7. To be able to pinpoint the exact limits with the technology a higher number of artifacts that has been printed in this thesis should be printed. As learned from the “virtual visit” chapter 4 the opportunity to print an object with MBJ is almost limitless, it is the post-processing steps that limits the object.

- What is the dimensional precision of parts produced via the MBJ-technology?

This was supposed to be analyzed with help of some of the artifacts but as mentioned in “Artifacts” chapter 7 some of the artifacts were broken or deformed which made it difficult to scan the objects and therefore only a visual analysis was made on the parts. However, some dimensional accuracy was checked with the scanned cube from 7.2.2 that was analyzed in GOM Inspect.

- How can deformations in the component's geometry be controlled?

Deformations in the component can be controlled by making sure that the tips and recommendations from chapter 6 are followed as well as “trial & error” printing where the span for what is actually possible to produce with MBJ is determined. An important factor to remember is the shrinking of the part, if shrinking is overlooked the part will most likely fail. Not obvious deformations can be detected with a 3D-scan and evaluated with GOM Inspect.

- In what way can a reference part be used to test the capacity of the MBJ process?

This was also tested with help of the artifacts mentioned in chapter 7. It’s possible to see which parts that were broken or deformed, and thereby understand where in the process parts can break or deform.

To sum up the work in general it is clear that to make a “waterproof” guideline a good way to go is to print a large quantity of artifacts (“trial & error” printing) and narrow down the “safe zones” of the MBJ-technology.

9. Conclusion & Future work

This chapter includes conclusions and recommendations for future work.

9.1 Conclusion

Metal Binder Jetting is a fairly new technology, which means that the technology is not fully tested, and many companies keep information about this technology to themselves due to market competition. The technology has high potential to scale up the production at larger volumes when it comes to manufacturing of small components.

The goal of this bachelor thesis work was to set the starting point for some of the opportunities and challenges with respect to the Metal Binder Jetting technology considering the design aspects ranging including the printing and the post-processing steps.

The main conclusion of the artifacts was that it's possible to print simple as well as complex parts, but the problems that appears in the post-processes such as de-powdering, de-binding and sintering stages needs to be considered in the design phase. For example, it's important to add support structure either integrated in the part design or as additional support material to reduce the sacking or complete failure of the parts during the post-operations. Moreover, the part orientation was also identified to be an important variable, not only during the printing, but also during the de-binding and sintering operations.

9.2 Future Work

This thesis includes the general steps of MBJ and present some output data from the literature found and the analysis of artifacts. With help of this information, a foundation of basic knowledge about the theology was set.

To get more precise design rules, it is necessary to continue with more iterations of "trial & error" printing of the artifacts to refine them until the "correct" design rules are set. These design rules can then be implemented in a final guideline.

The analysis and evaluation of the artifacts would benefit from combining the visual data from the finished parts with simulation data of what happens in the key steps of the MBJ-process. For example, if the third artifact with varying wall sections had been filmed during the final sintering stage it could have shown why and where the distortions first began. This combination of methods could be interesting when evaluating the outcome and hence create a material model that enable prediction of such distortions.

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Appendix

Appendix A – Survey questions

The survey contained of ten questions with the purpose of investigating the current state of knowledge and the demand of a design guideline for MBJ. The survey was sent out to a selection of companies with a connection to the additive manufacturing community. Since the survey was anonymous all answers for each question will be listed. The ten questions are listed below.

- What do you think is the biggest challenge of creating a guideline for MBJ? And why do you think that this is a challenge?
- Have you ever been in contact with a guideline for an AM-process before and if yes, which one?
- In what way do you see a practical use for a MBJ guideline?
- How much can time can a MBJ guideline save for the designer/company?
- In what way do you think the practicality of the guideline could be tested?
- In what part of the MBJ-process do you think the most design related challenges can occur? E.g. at the printing stage or in post-processing. And why there?
- What do you think is the most challenging when printing the component with MBJ to achieve the desired dimensions? E.g. build size, support structure or wall thickness.
- What is the most challenging when sintering the component?
- In what way do you think a test component can increase the knowledge of the MBJ-process and its limits?
- Do you have any tips or suggestions of designs that possibly could be included in a potential guideline for MBJ? Leave your email and we will contact you.

Appendix B – Questions and answers

- Vad tror du är den största utmaningen med att skapa en guideline för MBJ? Varför tror du att detta är en utmaning?

    - Några utmaningar med att skapa en guideline för MBJ kan vara olika:
      Olika utrustningar har olika förutsättningar och kan därför vara svåra att kvalificera på samma sätt. En annan utmaning är att välja vilka responser (t.ex. ytfinhet, geometrisk avvikelse osv) som en guideline ska utvärderas på? Sedan är det svårt att skapa en generell guideline på ett område som är både nytt och nishat.

    - Skillnader mellan maskiner och att utvecklingen går framåt. Också att hitta bra "generella" exempel

    - Sintringssteget, är en av flaskhalsarna i tekniken. problemen där ligger i begränsningar från krymp och gravitation.

    - Att skapa en guideline som är tillräckligt specifik att den är applicerbar på den utrustning som användaren/läsaren har

    - Den största utmaningen tror jag är att kunna koka ner allt som händer i processen till enkla förhållningsregler för en konstruktör.

- Har du tidigare kommit i kontakt med en guideline inom någon AM-process och i så fall vilken?

    - L-PBF(Metall) och FDM(plast)

    - PBF-LB för plast och metall

    - Ja och nej. Jag har själv letat upp eller skapat (delvis) guidlines som gäller för den printer jag förfogar över. Dock inte fått utbildning eller anpassad guideline

    - Ja. design guide av Olaf Diegel, diverse publikationer, m.m. men allt har varit för L-PBF

- På vilket sätt ser du att en guideline för MBJ kan användas i praktiken?

    - Det kan hjälpa konstruktörer och maskinoperatörer att kunna undvika "trial and error" arbete. Minska antalet itterationer som behövs för att bygge en komponent. Det skulle också kunna fungera att använda guideline och eventuell kvalificeringsgeometri som ett kvalificeringsverktyg för nya maskiner och användare.

    - Bra hjälpmedel för konstruktören för att veta vilka begränsningar/möjligheter man har med tekniken.

    - Minimera process steg och få en mer robust process.
    - För att ge konstruktörer och användare kunskap om vilka möjligheter och begränsningar MBJ har i allmänhet och för just användarens specifika maskin eller process

    - Ett hjälpmedel för en konstruktör att effektivt ta bra beslut men även assistera under hela produktutvecklingsprocessen för att ge förståelse för hur processen fungerar.

- Hur mycket tid kan en guideline för MBJ spara för konstruktören/företaget?

    - En utförlig guideline som täcker upp för flertalet aspekter av en process kan spara många månaders jobb av så kallad "trial and error" vid experimentell processbarhet.

    - Mycket, av tidigare erfarenhet har jag sett att med hjälp av en guideline så får konstruktören snabbt ett "självförtroende" att göra en design. Om man kan undvika en omkonstruktion blir det en relativt stor vinst.

    - Beror väldig mycket på hur geometrin ser ut, men det kan handla om allt från någon timma till flera dagar.

    - Svårt att kvantifiera, men en hel del tid. Dels genom att man inte behöver experimentera sig fram och dels för att man slipper göra om konstruktioner som fallerade

    - Mycket

- Hur tror du att man kan testa att guidelinen är tillräcklig för att användas i praktiken?

    - Detta bör givetvis ske i samråd med, och via en dialog med företag intresserade av AM. Både maskintillverkare och producerande företag. Det är viktigt att få en helhetsbild för att lyckas täcka så många viktiga aspekter som möjligt i en guideline. Det är svårt att testa om den är tillräcklig för att användas i praktiken, men gedigna förstudier och datasamling för att sedan kompilera i teori och kanske testartifakt bör anses fullgott för att testa i praktiken. Efter utvärdering och säkerligen itterering av artefakt i några steg så kan en guideline med stor sannolikhet anses användbar.

    - Genom att titta på exempelprodukter från olika företag. Svarar guidelinen på alla frågor som kan komma upp.

    - Trial and error, skapa en geometri med flera utmaningar, mät sen upp den och jämför med teoretiska antaganden, eventuellt justera och gör om guidelinen tills dess att man ser att den fungerar.

    - Att låta en utvald grupp (nybörjare och erfarna) testa

    - Ge den till någon som inte kan MBJ och låt den försöka tillverka något med MBJ.

- I vilken del av processen tror du de flesta designutmaningar kan uppstå? Tex vid printning eller efterbehandling. Och varför just där?

    - Med den lilla förkunskap jag besitter in MBJ så skulle jag säga att designproblem är relaterade till sintring och krymp. Sedan är det alltid en relevant fråga inom AM och man har en robust process. Får vi samma resultat när vi printar på olika ställen i byggkammare, i olika vinklar osv. Alltså positionering/orienteringsproblematik. Och slutligen att identifiera processens faktiska begränsningar. Hur små detaljer/hål/kanaler kan vi printa? Vad kan vi förvänta oss? Hur stort kan vi printa utan att komponenter bygger upp termiska spänningar och spricker? Osv.

    - För MBJ sintringsprocessen. "säckar" detaljen ihop eller håller den formen? Stora utmaningar finns säkert också i ytjämnhet och form/läge toleranser

    - Sintringssteget, på grund av geometrisk komplexitet, och borttagandet av löst pulver, också beroende på geometrisk komplexitet.

    - Båda och även konstruktionsfasen. Hur skall jag konstruera för att bäst utnyttja processen och vad skall jag undvika för att inte tillverkningsmetoden skall skapa fel på produkten. Hur skall jag orientera detaljen under tillverkning för att maximera ytfinish och hållfasthet samtidigt som efterbehandlingen inte blir onödigt omständlig

    - Sintringen: Det finns mycket utmaningar när material krymper

- Vad tror du är den största utmaningen vid printning av komponenten för att få rätt dimensioner för MBJ? Tex byggtjocklek, stödstruktur och väggtjocklek.

    - Detta vågar jag inte svara på. Men hoppas att det kan täckas upp och besvaras av en guideline.

    - Känns som om det bör vara variationer av väggtjocklekar.

    - Förståelse för hur detaljen krymper i sintringssteget. Processen bukar inte ha någon stödstruktur, det skulle dock behövas i sintringssteget beroende på hur geometrin ser ut gällande tjocklek på gods, tunnväggighet etc..

    - Kompensering för dimensionsförändring under tillverkningsprocessen. Kommer en lång detalj krympa? Skall jag öka ett håls diameter för att processen bygger materialtjocklek inåt? Kommer konstruktionen göra att detaljer slår sig när den är klar

    - Oregelbundna väggtjocklekar

- Vad tror du är den största utmaningen när komponenten ska sintras?

    - Att få rätt slutlig geometri och egenskaper.

    - Att den inte ska säcka ihop och att den ska ändra storlek jämt.
    - Krymp och gravitation

    - Kommer detaljen ha samma hållf. i alla riktningar? Kommer den vara tät eller måste man täta under efterbearbetningen? Hur mycket skiljer sig detaljens totala hållf. jämfört med om detaljen gjutits eller maskinbearbetats fram?

    - krymp som ger sprickor

- På vilket sätt tror du att en testkomponent kan hjälpa till att öka förståelsen för MBJ-processens begränsningar?

    - En testkomponent är något man kan applicera på ett flertal maskiner, material, parametrar och förhållanden men ändå mäta och utvärdera på samma sätt. Ett sådant koncept är ett bra arbetssätt när man dels vill bygga förståelse men också bygga en databas för egenskaper och kunna analysera data på ett konsekvent sätt.

  - Tydligt sätt att visa vad som är möjligt och inte. Samt vad man kan förvänta sig från processen.

  - Den kan ge en del svar som kan implementeras i en guideline

  - Man kan tillverka en testkomponent med olika metoder och jämföra hållf., ytfinish, dimensionstoleranser mm

  - Man ser vad som fungerar eller ej, därefter är det lättare att utrede varför resultatet blir som det blir.

- Har du tips/förslag på olika konstruktioner sim eventuellt skulle kunna ingå i en potentiell guideline för MBJ? Skriv med din mejladress så kontaktar vi dig.

  - Det beror helt på vilken maskin som guiden är tänkt för. Vilka egenskaper kapaciteter maskinen har (små detaljer med hög detaljnoggrannhet, detaljer med hög hållf etc)

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