Crucial Parameters for Additive Manufacturing of Metals

A Study in Quality Improvement

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Abstract

Production by Additive Manufacturing creates opportunities to make customized products in small batches with less material than in traditional manufacturing. It is more sustainable and suitable for niche products, but entails new production demands to ensure quality. The goal of this study is to define the most crucial parameters when creating Additive Manufactured products in metal and suggest tools for quality improvement. This is done by analysing earlier studies and evaluating the standard production procedures for manufacturing by Selective Laser Melting.

The results from this study stated that porosity and insufficiencies in shape are the most common factors leading to deviation in quality. To avoid it, the most crucial parameters to consider are; The laser freeform fabrication-system related parameters, hatch distance, laser power, layer thickness, scanning pattern, scan speed and flowability of the powder. Concluded is also that crucial parameters within additive manufacturing are very dependent on the definition of quality for a certain product and can therefore vary. By continuous collection and analysis of data, the task of improving quality will be simplified.

Sammanfattning

Produktion genom Additiv Tillverkning möjliggör tillverkande av skräddarsydda produkter i små batcher och med mindre material än vid traditionell tillverkning. Det är ett mer hållbart tillverkningsätt och mer passande för nischprodukter, men innebär nya produktionskrav för att säkerhetsställa bra kvalitet. Målet med denna studie är att definiera de viktigaste parametrarna vid Additiv Tillverkning av produkter i metall och föreslå verktyg för att förbättra dem. Detta genom analys av tidigare studier och utvädering av klassiska produktionsrutiner för Selective Laser Melting.

Resultaten från denna studie visar att porositet och formfel är de vanligaste faktorerna som leder till bristande kvalitet. För att undvika detta är de viktigaste parametrarna att ta i beaktande; parametrar kopplade till "laser freeform fabrication"-system, distans mellan laserstrålar, kraft på lasern, lagertjocklek, skanningsmönster, fart på skanningen och flytbarhet på pulvret. Slutsatsen pekar även på att avgörande parametrar inom Additiv Tillverkning beror på definitionen av kvalitet för en speciell produkt och kan därför variera. Genom kontinuerlig insamling och analys av data kommer förbättringen av kvalitet förenklas markant.

Keywords

Additive manufacturing, Production parameters, Sandvik, Quality improvement, Selective laser melting, Powder bed fusion, Process control.
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1. Introduction

The development of Additive Manufacturing (AM) has tended to become increasingly efficient. Thereby changing from being largely characterized by research and development to become more applicable to actual product manufacturing, opening for new markets. The possibility to make customized products and small batches without it entailing extra cost is considered a huge advantage for niche products.

AM is considered more sustainable than traditional manufacturing methods because the material consumption is lower and the production can be done make-to-order [1]. Another aspect that strengthens this statement, is that AM allows optimization of design for lean production and thereby enables more environmental friendly product designs, as lean is based upon the reduction of waste [2]. Also, the products can be designed in a way that optimizes the functionality and required less energy during operation, for an example by being lighter [3].

It is of great importance to take social responsibility when it comes to sustainability work and for larger companies it is a necessity that it is taken into account. As an aid in sustainability work, United Nations (UN) has set sustainable development goals, which research institutes and companies should base their actions and future work on [4]. To achieve these goals United Nations Industrial Development Organization (UNIDO) has pinpointed technologies that have to be the base in the Industry 4.0. One of them is AM [5], [6].

Sandvik Machining Solutions (SMS) aims to adopt AM techniques within specific areas. However, the problem of applying a new manufacturing method on traditional products is that the usual customer requirements for performance are unchanged. Sandvik therefore want to investigate how a company can assure the quality of products and meet customer requirements, even when using AM.

When AM is used, other parameters affect the final result as compared to traditional manufacturing. It is therefore of high importance to locate the different parameters and define to what degree they affect. Highlighting the most important production parameters for a general products final quality would contribute to a significant reduction of time creating new products.

In addition to this, different standards set requirements of the process to ensure quality of the delivered product. These varies depending on different sectors where quality is of importance (e.g. aerospace, defence and medical industry) and have to be adopted if a company wants to enter these markets.
1.1 Aim

The aim of this study is to define the most crucial parameters when creating AM products in metal, to contribute in achieving production stability and ensure product quality. This to also shorten the time for qualifying new products and give suggestions of tools to further improve quality of Additive Manufactured products.

1.2 Parameters

The parameters in this study are production steps that affect the result. They can be software driven such as CAD-programs, as well as hardware driven, like build platform. Different parameters will affect printed products in different ways and have different degrees of importance. However, all parameters cannot be controlled and are therefore beyond the scope of this study. Thomas G Spears presented a table where key parameters within AM were categorized as Predefined or Controlled [7]. The controllable parameters are listed below and the whole table is to be found in Appendix A.

- Average Power
- Scan spacing
- Layer thickness
- Pressure
- Spot size
- Scan strategy
- Powder bed temperature
- Gas flow velocity
- Scan velocity
- Deposition system parameters
- Oxygen level
- Ambient temperature

These are not the only parameters within the scope of this study. Another way to categorize them is through a Fishbone Diagram and it will be the base of this study. This will be brought up in the next chapter.
2. Method

This study is divided into two main parts. One is theoretical, where earlier studies regarding which stages of the AM process that are most important to receive a satisfying production result. The other is a discussion part, where the different factors that affects quality are evaluated. It also relates to future trends in development and optimization of AM as well as the essential actions to take for an AM-company, in terms of quality. Through the report every main area with affecting parameters is addressed with regard to when in the process it takes place. The structure is therefore process-line oriented and will be based on the Fishbone Diagram that is introduced in the following chapter.

2.1 Fishbone Diagram

To evaluate which parameters that matters the most when producing a product with AM a Fishbone Diagram can be used. The Fishbone diagram is based on quality control and is a tool to visualize and categorize potential problems, in order to easier identifying them when shortcomings appear \[10\]. This study will evaluate parameters based on a Fishbone Diagram of functions and concern aspects that are categorized as classical in AM through Selective Laser Melting, that will be brought up later in the report. The Fishbone Diagram is to be seen in Figure 1.

Thus the purpose of this study is to define the most crucial parameters a company can consider during production to ensure quality. The scope will despite this not include the whole Fishbone Diagram. The study will instead focus on operations taking place “in-house” or routinely and are linked to the process. For example, the effects of the powder will be considered but not the powder production, since these quality issues are beyond the responsibility of the production unit. Mechanical properties will also be considered but the chemical composition will not.
Figure 1. Fishbone Diagram for Laser Freeform Fabrication
3. Requirements and methodology in quality

The following section is dedicated to describe terms that are important regarding quality. Standards are used to set specific product requirements and therefore also to define quality. Further, statistical methods such as Six Sigma are good tools in quality improvement. As is material informatics, which is becoming an increasingly important tool for the whole of AM.

3.1 Standards

Standards set requirements for both the product and production process depending on the product's intended use. Standards are used both to streamline and secure reliability of the work in production and therefore also to ensure quality. Meanwhile they also regulate industries towards sustainability. Some standards containing high demands are EN9100:2018, ISO/TS 16949:2009, IDT and ISO 13485:2016. These are to be implemented to ensure the deliverance of qualitative products for different sectors.

EN9100:2018 seeks the commitment of European organisations, that design, develop or provide goods or services for aviation, space or defence industry and whose products are to be used in these sectors [11]. Meanwhile ISO/TS 16949:2009, IDT and ISO 13485:2016 are intended for international implementation within production of vehicles and medical devices respectively [12], [13]. However, each standard varies and it is therefore difficult to precisely determine that each of them are fulfilled and does not relate to the objectives of this study. The intent of this section is instead to cause awareness of their importance in defining quality that will be further discussed later on.

3.2 Six Sigma

Six sigma is a way to make the activities and developments more effective. The streamlining is obtained by reducing the main cause of defects and variation in the production. This method is commonly used at larger companies, often in manufacturing industries. The name, Six Sigma, comes from the mathematical term where the sign sigma (σ) is used to denote standard deviation. All industries have deviations in the production and it is of great importance that the deviations do not exceed the tolerance. Six Sigma includes working with many different statistical and quality methods together with other methods to lead the optimization work [14].

3.3 Materials Informatics

Applications of informatics methods are increasing across domains within materials science. The rapid discovery of new materials and improved characterization methods have been enabled thanks to the use of data-driven methods. This also provides a path for understanding material behaviour.
Screening of databases is a common type of study that uses informatics to find existing materials that suit a new application. Another common type of informatics study is to extract design rules from large collections of materials data. Some important trends are only visible in large data sets which also allow for better understanding of materials. Furthermore, it is increasingly common to use machine learning to accelerate materials design. The emphasis in machine learning driven studies is on building a predictive substitute model and less on improving human understanding. After careful validation, these models can perform screening far faster than conventional computational tools.

Materials informatics can be used in experimental materials science. Databases are particularly prominent in crystallography, where there already exist several different databases, but databases of experimentally measured properties are also growing significantly. The Calculation of Phase Diagrams (CALPHAD) approach relies on databases that are the product of comprehensive curation of computational and experimental data. The use of both experimental data and machine learning has been important to accelerate the discovery of new materials.

There are challenges to automate physical experiments, but there is considerable progress in High-throughput Experimentation (HTE). HTE focuses on evaluating many materials in rapid succession and creating informatics ready data. The adoption of HTE is slowed down by technical limitations and limited access to HTE equipment, such as automated characterization equipment. Increased use of HTE and autonomous methods will produce richer materials data and could increase the development of informatics techniques in many fields.

The metadata for most materials data is never recorded in digital form, which is limiting the use of materials informatics. For example, experimental data is often placed in non-digital resources. Therefore, softwares such as electronic lab notebooks and laboratory information management systems that describes and shares data, has been developed to address this problem [15].
4. Production Processes

The basis of AM is that material is added layer by layer to create the final product, in contrast to traditional manufacturing where material instead is removed from the solid [8]. The build is based on Computer Aided Design (CAD) where the CAD-data is used as a blueprint to describe the design of the component. Production by AM can be done by various techniques, which can be categorized into seven main groups, that describes different ways of adding the material [9].

- Powder Bed Fusion
- Binder Jetting
- Material Jetting
- Direct Energy Deposition
- Material Extrusion
- Sheet Lamination
- Vat Photopolymerization

The groups are brought up below. But as the study will focus on a technique within Powder Bed Fusion, it will also be highlighted the most.

4.1 Powder Bed Fusion

Powder bed fusion (PBF) is the most commonly used method for AM. The method intends melting metal powder together by thin layers, applied one at a time on a building plate. Melting is done by adding energy, through either a laser or electron beam and the energy is applied on predetermined spots, to create the desired geometry of the product [16], [17].

The principles of PBF are described in Figure 2, which is a schematic overview of the Selective Laser Melting process. The basis of this process, together with the Electron Beam-based process, is having the energy source from above. Lowering the building plate followed by adding new powder layer from the sides to operate on.
The most important process parameters to take into account when using PBF are listed below [19].

- Laser-related parameters, such as power, laser spot size, pulse duration and pulse frequency.
- Scan-related parameters, referring to the speed, spacing, and scanning pattern.
- Powder-related parameters, such as particle shape, size, distribution, powder bed density, layer thickness and material properties.
- Temperature-related parameters, like powder bed temperature, powder feeder temperature and temperature uniformity.

The different methods of PBF are characterized into Selective Laser Melting (SLM), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS) and Direct Metal Laser Melting (DMLM) [8]. SLM is the only method within the scope of this study and the discussion will focus on that process.

4.1.1 Selective Laser Melting

The SLM process is often taking place in a gas filled chamber to reduce the effect of oxidation. During consolidation of the powder in AM different mechanisms can be used, depending on if it is taking place under or over the melting point of the material and the amount of mass transport. In SLM, the most commonly used mechanism is full melting.
The material that is exposed to the heat energy is melted to a depth that is exceeding the layer thickness. The idea is to re-melt some of the earlier solidified structure and thereby create well bonded structures with less porosity. Another significant advantage using full melting is the possibility of making nearly fully dense products in one step. Despite this, full melting typically brings mechanical shortcomings as shrinkage, internal stresses and part distortion.

There are some general issues in SLM manufacturing that producing companies within the AM industry have to deal with. The most common are non-connected layers, inner residual stress in the structure and porosity, which all contribute to lowering the mechanical strength of components. Non-connected layers are caused by insufficient melting in the powder bed that connects to the laser. Inner residual stress are an effect of insufficient combinations of parameters such as laser power and the thermal conductivity of the powder bed. The porosity arises due to a wide range of factors. These errors will be further explained in this report within their respective factors.

In summary, the general advantages using PBF processes is the wide range of material that can be used within the process and the excellent dimensional accuracy it has, compared to other methods. But also the fact that it enables great repeatability, which is necessary in process industry. Instead, the disadvantages include porosity and residual stresses that normally are more common when using this technique compared to other.

The most important parameters to ensure good quality are therefore precise control of the powder bed temperature, output power of the laser beam, atmosphere and particle size. Advanced techniques that are growing as tools to control these are temperature monitoring systems, thermal modelling and image processing techniques, temperature feedback control systems and real time defect detection and correction. Further, the main challenges for PBF are developing a laser output feedback control system in real time, atmosphere control and a way to relieve the material from residual stresses [20].

### 4.2 Other Methods

The methods Binder Jetting, Material Jetting, Direct Energy Deposition, Material Extrusion, Sheet Lamination and Vat Photopolymerization does not coincide with the scope of this study and will not be taken into consideration. These methods are, with today’s technology better suited for other areas with other specifications regarding quality and are not relevant for this study. Therefore, separate mappings should be made to highlight the potentials and limitations of these.
5. Powder

Due to requirements of applied standards, companies needs to have control of their powder and must be able to ensure that it follows the specifications of the standards. The effort in this study is directed into classifying important process related parameters of the powder. These are characterized by numerous of tests, that are routinely made on every new batch of powder before entering any machine. The methods are all closely related to the flowability of powder.

5.1 Properties

The demands on properties of the powder can vary depending on the material and what product it will shape. However, the most important property for powder to be used in PBF is good flowability. The significance of good powder properties can therefore be translated into good flowability [21]. The following part will discuss flowability and other important powder properties.

5.1.1 Flowability

There are many parameters that affect the building process and the quality of the parts being built. Therefore, it is important to have a correct assessment of the powder. In order to create good quality powder layers, the powder flowability should be included in such an assessment. Flowability is the result of the combination of material physical properties that affect material flow and the equipment used for handling the material.

Powder properties include many different aspects, such as particle size distribution, powder density and flowability. The optical and thermal properties of the powder are also affected by these parameters. It is important to consider that a thin powder layer has different properties than the bulk powder. Therefore, the coordination of process parameters is directly affected by the layer properties. For AM, where very thin layer thickness is required with good layer properties, there is a tendency to use as fine powders as possible to improve the scan speed, microstructure, part density and surface qualities. However, this increases the risk to processing powders with low flowability and end up with bad layer quality. Moisture, inter-particle forces and gravitational forces can also influence the behaviour of the powder.

When characterising powders, it is generally important to use methods that are as close to the manufacturing process as possible. The requirements for flowability depend on the machine concept. It is influenced by the type of coating device, whether it is a ruler or a rotating drum, and if the powder is taken from a powder reservoir next to the build plate or if it has to be transported through a funnel into the coating device [22].
5.1.2 Particle size

The size of the powder particles is strongly connected to cohesive forces between the particles with a decrease in particle size leading to an increasing cohesiveness of the powder bulk. Particle size is therefore essential for optimizing powder layer quality of the powder bed. Leading to both low, varying packing fractions and non-uniform surface profiles of the recoating layer. This due to cohesive forces outweighing the gravitational forces [23].

Forces such as gravity depends on the volume of objects. Powders with fine grain size are therefore more vulnerable to cohesive forces due to lower volume than powders of larger grain size and are less suited for usage in SLM without additional processing. Particle size is therefore an important parameter to take into account for the process of powder selection [24]. Particle size also affects powder segregation, where differences in the particle size can cause inhomogeneity in the formulated mixtures. This could result in extra costs due to customer dissatisfaction and batch failure leading to insufficient product quality [23].

5.1.3 Particle shape

The shape of powder particles plays an important role in minimizing powder segregation. High flowability has been shown to increase the particles proneness to segregate. Rounded particles are therefore more inclined to segregate due to their shape benefiting flowability. In contrast to irregularly shaped particles whereas the irregularity in shape impedes the flowability, leading to retardation of the segregation [19]. The shape of the particles tends to become more irregular depending on the number of times it is used. This is further discussed in the particle reuse section of this report.

5.2 Testing

Methods of testing different powder includes measurements of powder stability, flow rate, compressibility, aeration, permeability, consolidation and shear properties. These tests should regularly be conducted and the data stored. When the tests are performed it is important to have control over room temperature and humidity, thus it can cause differences in the results. For instance, a higher humidity affects the powder properties by lowering the flowability. Common for the tests are that they all relate in some way to the flowability and how the powder will act in the varying environments encountered in the printing process. The exact descriptions of the different methods can be seen in Appendix B.

5.3 Particle reuse

Reuse of powder particles plays a big part in making the AM process a viable and profitable process in the industry. The quality and amount of reused powder in production affects both quality and profitability of the printed product. The ability to reuse unaffected powder that has gone through the printer is an additional economic advantage leading to an overall increase in utilization of the powder [25].
The disadvantage of powder reuse is however that the powder is somewhat affected by the exposure to high temperatures in the printer. E.g. long-time exposure to high temperatures in the printer has been shown to affect the composition of surface chemistry in recycled 316L stainless steel powder. Whereas it was compared to virgin powder (i.e. powder used for the first time). The exact effect on the mechanical properties caused by this change in composition are however not fully studied, but could affect the microstructure and in turn the mechanical properties of the end product.

The exact effect on different materials is also hard to predict as different materials have been observed to react differently to the long-time exposure of high temperatures [25]. The variation in the mix of virgin- and reused powder could therefore in turn affect the mechanical properties differently for different materials that is used for printing. This has to be taken into consideration when deciding upon the amount of reused powder that is to be used.
6. Machinery

Machinery refers to all the parameters affecting the part related to the printing machine. This includes removable objects such as the building platform, but also software parameters and the actual processing.

6.1 Process Preparation

In the initial stages of the process there are several parameters that could affect the production once it starts. The right preparation is therefore important and must be considered due to the effect it could have on mechanical properties of the product. However, this study assumes that the standard human-made procedure when changing from one print to another is done correctly.

6.1.1 Build Platform

The usage of a correct build platform is essential for the quality of the product as it could affect the geometry of the build. Builds with large contact areas causes a larger heat transfer between the build and the platform. This heat can in turn cause the platform to warp which the machine does not account for in the building process. This means that the structure of the build can take damage and lead to structurally incorrect components of lower quality. To prevent this, thicker building platforms can be used when the builds consists of large contact areas.

The platform is cleaned and measured before mounting in the machine. It is also manually corrected to achieve an even first layer of powder across the platform before the printing starts. Preheating of the building platform can in some cases be preferred as preparation because it has been shown to affect the end product. Both microstructure and mechanical properties are affected by the preheating of the building platform as it acts as a form of ageing heat treatment on the material. This in turn affects the mechanical properties of the product. E.g. it was shown that ultimate tensile strength of a printed product could be increased by 17% by selecting the optimal preheating temperature for the building platform in study [26].

6.2 Laser Freeform Fabrication System

The Laser Freeform Fabrication system (LFF-system) refers to hardware- and software-parameters that are linked to the machine, but are not necessary to change or control. These are parameters such as gas supply function and how the laser beam is formed. Generally, these are factors that can cause large quality errors if something deviates from them.
6.2.1 Process control

In the AM process there are several steps that require close control to ensure satisfying results and good quality. Process control is therefore about functions handling the parameters that have a direct effect on the process result and product. According to Anders Pettersson at Sandvik Additive there are two main ways to verify this;

1. Installation of own sensors in the machines, that states that the machine data is correct and the values within likable range.
2. Have very regular machine calibration [27].

Process control mostly regards LFF-System- functions, such as oxygen level in the building chamber and flow rate of process gas. Hoejin Kim et al. suggests process control by using cameras when building. This helps identifying abnormalities and responds by quitting the ongoing process, or correcting easy controlled parameters, such as powder bed temperature, is possible [20]. In the future it will also be important to predict optimal printing parameters, mechanical properties, having real time monitoring process control and feedback interaction between design and part evaluation. Regarding future technologies, Hoejin Kim pointed out some that are crucial for the future development of AM and ensuring better quality. The most important of them are highlighted below.

**Prediction of optimal printing parameters/mechanical properties**
This is done by using softwares with simulation capability or mechanical prediction module and predict optimization of printing parameters and mechanical property.

**Real-time monitoring and process control**
In the building process, close-feedback loops control and defect correction during building can be made. This data can then be used to monitor the process parameters in real time. It requires integration of machine vision, data collection, image processing and closed-feedback loops. For some AM techniques, real-time monitoring systems have been used to monitor temperature, layer thickness, image processing and closed-feedback loop control.

**Feedback interaction between design and part evaluation during printing**
It is possible to correct design and printing factors in real-time by having a software that enables feedback on aspects such as inner defects, dimensional inaccuracy and surface cracks. Defects can thereby be prevented by using the feedback of generated data to adjust printing parameters.

**Agile part evaluation**
Doing non-destructive evaluation through technique imbedded in the machine in real time would enable internal quality evaluation during printing process, without using a separate step, doing destructive testing.
Other
High speed fabrication and cyber quality control are two aspects in AM that also are highly discussed. The limitation of printing speed, that equates to higher building speed with poorer quality is now a huge problem and a challenge for AM. Increasing this speed with an increase in quality will be a goal to aim for within the technology. Cyber quality control instead refers to comparing different companies’ product quality digitally and thereby massive and customized AM productions would be feasible in less time and cheaper cost of production in the near future [20].

6.2.2 Process gas supply
The processing chamber is operated under pressure using argon gas. The atmosphere is circulated to remove by-products such as vaporized powder from the chamber that could arise during the manufacturing process. Which could affect the laser properties if left in the chamber. This as the generated condensate could absorb energy from the laser, leading to insufficient energy delivery to the powder bed.

The method of how the gas is delivered to the chamber has been seen to affect the outcome of the process. E.g. the consistency of the gas flow has been observed to affect porosity and in turn mechanical properties of products using titanium. Ferrar et al. showed that the design of the gas delivery rail could decrease the effect of porosity on mechanical compressibility widely, as shown in Figure 3. Where the different colored boxes represent different designs of the gas delivery rail, causing a more uniform gas delivery [28].

![Figure 3. Effect of porosity on compressibility caused by gas delivery rail design [28].](image)

The process gas flow also affects the positional variation of products within a build. This as the placement of the gas delivery rail in the chamber causes variations in velocity due to frictional forces encountered by the gas. Leading to less uniformity of the gas flow across the building platform [28]. The effect of the process gas supply is however machine-dependent and the positive effects of re-design varies depending on the current design.
6.2.3 Mechanical components

The mechanical components of the machine can affect the process and the most important to highlight is the blade that builds the layers of the powder bed. Rubber or steel blades is most often used, which both have advantages. The rubber blade is flexible and therefore causes less harm if unevenness occurs during the build, while the steel blade is hard and less sensitive to scratches. The blades are however chosen depending on the process. It is hard to question mechanical components and potential improvements within this field as it is something that requires substantial testing and analysis. Therefore, this report does not further discuss this.

6.2.4 Beam forming

Beam forming seek parameters affecting the formation of stable scanning tracks in the powder bed. This is largely dependent on the uniformity and continuity of the laser beam, which is affected by scanning speed and laser power. Where instabilities can occur due to unbenevolent combinations of both parameters. Deviations and defects occurs more in tracks formed with to slow scanning speed. This is due to repeated re-melting and overheating of the track causing extension and deepening of the melt pool with additional material loss due to evaporation. High scanning speeds on the other hand, causes more of the effect called balling. This as the insufficient melting causes the track to fragment, leading to the possibility of breaking the continuous merging of melt pools in the track [29].

The effects are further affected by the thermal conductivity of the material used. High thermal conductivity narrows the gap of acceptable scanning speeds for lasers of high power. This in turn also causes the effects to be dependent on factors which affects thermal conductivity such as particle size and shape of the powder [29].

6.2.5 Beam delivery

Beam delivery regards to the parameters of the beam deliverance to the surface of the powder bed. One of these parameters to precise is the laser delay, when the laser jumps from melting one object to another. If the laser delay is too short or too long, it will cause a chain reaction that affects the end result significantly. A too short delay means that the laser is switched on too early and thereby risks melting powder which is adjacent to the starting point of the scanning direction, alternatively, result in burn-effects around them. Instead, if the delay is too long, the laser is switched on after the scanner has moved. The first part of the scanning path will therefore not be marked, which may lead to porosity. Notably is that the opposite situation is liable to arise after the laser finishing printing on one object, before jumping to another [30].
6.3 Process

Parameters linked to the machining process refer to all the actions within the machine that create the product and consistently affecting parameters such as melt pool, hatch distance and scanning speed. The most important outcome of this is having a low fraction of pores and achieving the desired shape, thus it is the characteristics that most often have high effect on functionality. According to Filip Johansson, R&D technician at Sandvik, the most important parameters in this stage are the powder bed layer thickness, scanning speed, laser power and hatch distance. Their quantities will determine the resulting microstructure [31]. These parameters will, among others, be considered in following section.

6.3.1 Powder bed

Powder bed density is a strong influence on the quality of printed objects. The density of the powder bed is mainly affected by powder distribution, shape, size and spreading mechanisms. Generally, a higher density means higher thermal conductivity in the bed and thereby better mechanical properties on the produced object. The most common density in powder bed is in the range of 50-60 % [19].

In Kim Hoejin et. al. study it was pointed out that the largest issues regarding quality was a heterogeneous distribution of temperature in the powder bed and non-homogeneous power output from the laser. However, the preferred way of solving it is by using thermal modelling techniques to predict the thermal properties and use of analysing IR cameras during process [20].

6.3.2 Process response

Process response is the direct effects of actions in the process, controlled by parameters. For example, shape of the melt pool and powder splattering as an effect of laser power. Process response will always be present when processing something and is hard to control in detail. However, the most important thing is ensuring that the response is within acceptable range and working towards preventing major errors. This is now mostly done by comparisons of earlier printings with similar powder, or otherwise by doing a print with test cubes with variation of parameters. By analysing the test cubes, the most suitable process response as well as process result can be found.

Powder splattering effects often initiate pores and can be prevented by starting the printing of each layer furthest from the gas outlet and working towards it [31]. The response may also vary depending on where at the platform the products are built. The powder splattering would then have a direct effect on quality distribution on products.

6.3.2 Process parameters

The factors that interact the most during processing and are easy to vary, is in this study referred to as process parameters. According to earlier studies, the most important parameters to consider within this topic are scan speed, hatch distance, scanning pattern, layer thickness and laser beam power [32]. They are illustrated in Figure 4 and will be discussed in the following sections.
**Scanning speed**

Scanning speed is the parameter that is controlling the average building speed the most. Therefore, a high scanning speed is desirable to gain a higher effectivity. However, the limitation is that the laser must have time to melt enough of the layers to connect with the solid part. When passing a crucial point in speed and going too fast, the effect will be that the porosity increases, thus more particles may be unmelted [34]. A higher scan speed can partly be replaced with a shorter hatch distance and therefore, variation of scanning speed and hatch distance is an important interplay to have control of. Instead, when having too low scan speed a risk of exposing the material for too much energy occurs. It is also often a transition to keyhole welding, which may cause negative effects on the printed product [35]. Figure 5 shows characteristic formations of pores as a consequence of too high and too low scanning speed.

![Figure 5. Showing pore formation as a consequence of wrong scanning speed. The left shows too high speed and the right too low [35].](image)
**Hatch distance**
A layer printed through SLM consists of several hatches with a specific hatch distance, or hatch spacing, as described in Figure 4. To gain a solid sample with good quality, an overlap between two hatches is necessary. In SLM processes an overlap of 20% is recommended to ensure better quality [32]. Lack of overlap instead initiates defects; thus pores will grow along the hatch lines [36].

If the distance is too small the build rate will decrease, but also, the material will be exposed to too much energy. This causes an inadequate surface and microstructure, leading to inhomogeneity [35]. Figure 6 shows the negative outcome of having lack of overlap and large overlap.

![Figure 6. Significant outcome of faults in hatch overlap. To the left there is lack of overlap and the right there is too large [35].](image)

**Scanning pattern**
Scanning pattern is defined as the orientation of patterns within, or between each layer. The scanning pattern can be varied in different ways, which will lead to various properties as an outcome. Different SLM- parts can have specific requirements regarding scanning pattern. The pattern will be repeated every layer, but possibly with a rotation for every new layer, to gain better boundary between them [32]. Figure 7 shows examples of three common scanning patterns. Dividing the pattern into stripes or islands will create a more homogenous distribution of residual stresses and is therefore more suitable for larger products, and will increase the building time significantly [37].

![Figure 7. Meander hatching pattern, Stripe hatching pattern and Chessboard hatching pattern [37].](image)
Layer thickness
When using SLM, each and every new layer have to make a strong fusion bond to the underlying solidified layer. It is therefore an essential requirement that the layer thickness is small enough to re-melt the previous layer, thus the degree of re-melting will largely depend on transmitted energy through the new layer. The general rule is according to Kusuma Chandrakanth that smaller layer thickness will increase the bond between layers, resulting in higher density components [32]. Despite this there is a line where the thickness gets too small, resulting in troubled outcomes such as increased part resolution, exposure of too much energy and wear from the coating device [35].

Laser beam power
One parameter that is of great importance regarding the laser, is using the right power. The challenge is mainly to melt the current layer with a number of the previous ones. If too many layers are melted, there is a risk of deteriorated properties. Materials having a higher melting point and lower powder bed temperature need a higher power, but according to Ian Gibson et. al., the required power of the laser also depends largely on other sub-parameters [19]. One important factor to take into account is the absorptivity characteristics of the powder bed, which is influenced by packing density, powder shape, powder size and the material type. Therefore, selection of laser power largely determines the choice of other process parameters. Laser power can directly be linked to the size of the focused laser spot and optimization of the energy density will be very important in order of quality and properties of printed parts [32].

6.3.3 Duration
Process parameters interact in a very high degree and it is an important aspect to reflect upon when determining which parameters should be regulated and not. Childs et al. created a process map regarding combinations of scan speed and power for a M2 steel powder, which is a base to start from when setting parameters for standard steel powders. The different combinations made different tracks in the scanning pattern [38]. By analysing the result, the process map could be divided into six areas depending on the parameters, which is shown in Figure 8 a). The different areas translated to tracks is shown in Figure 8 b) and in the F- area no melting occurred, because of too low scan speed in order of the power.

Figure 8 a). Process map for scanning tracks made in *150/75 μm M2 steel powder in an argon atmosphere with a CO2 laser beam of 1.1 mm spot size. Figure 8 a). Five examples of scanning tracks in the corresponding conditions as is a) [19].

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7. Material properties

Properties of AM materials differ from traditionally manufactured materials. How they differ depends on many different parameters, which makes it difficult to form principles of exactly how SLM differs from traditional methods. This chapter highlights some of the differences in properties between traditionally and additively manufactured materials.

7.1 Metallurgical properties

Generally, laser built parts are different from parts made of the same material but manufactured in a different way. A survey made of Pavel Hanzl et al. shows that AM made parts of metal often have much finer grains than cast or molded structures, due to the rapid heat conduction from the melt to the surrounding material [39]. This rapid cooling may also result in metastable crystal phases. In SLM, the part is built layer-by-layer and every individual line is gradually melted and resolidified. Therefore, it could be expected that all AM made metal parts will have small grains but in an investigation of laser built Ti6Al4V component, it was shown that these components had no such fine-grained structure. It had crystals with at least the height of the thickness of one layer. This is shown in Figure 9.

This is explained by the fact that the effect of the laser was so large that it remelted the bottom layer of the manufactured part which enabled crystal growth through several layers due to repeated solidification. According to these facts, the structure and properties of the material depend on the selected parameters of the production. However, the large temperature gradients and complex heat transfer that form in a molten pool can cause heterogeneous structures [40].
Figure 9. Microstructures of different materials fabricated with SLM. (a) Ti-6Al-4V, (b) Fe/SiC [40].

7.1.1 Defects

The main defects for SLM manufactured parts includes pores, cracks and residual stress. Cracks are often caused by both internal and external reasons. Micro-defects are the internal reason and residual stress is the external. Residual stress is caused by two main mechanisms. The first mechanism is the non-uniform deformation that is formed during following cooling procedure, due to the distribution of laser energy along the horizontal direction and the high temperature gradient that occurs in the laser affected area. The second mechanism is the poor heat transfer between two layers in height direction which forms compressive stress in the bottom section and tensile stress in the upper section.
Due to the rapid solidification, brittle phases and pores can easily be generated in the SLM process. Stress concentration is formed in the effect of residual stress and thereby leading to cracks. However, residual stress can be improved with preheating the build plate, and the distribution of residual stress can be controlled by optimizing the scanning path [40]. The properties and performance of additively manufactured components have been shown to have a significant correlation with the size and fraction of porosity in the material. This due to pores reducing effect of part density and as they act as stress risers. Increased porosity could arise as an effect of several factors [41]. Different contributors could be:

- Gas pores, which are inherited from gas-atomized powder or caused by moisture on the powder particle surface.
- Keyhole pores, formed due to the collapse of a steep and deep melt pool.
- Elongated pores, caused by insufficient melting. I.e. has higher laser scan speeds been observed to lead to formation of these pores between neighbouring layers due to the lack of melting [42].
- Irregular pores caused by unstable melt pools due to low laser scanning speeds.
- Intra-layer porosity which is generated due to lack of overlap caused by the laser delay.

The formation of these types of pores are however related to the type of material used. I.e. gas pores have been shown to have a significant formation in aluminium alloys but next to no effect in Ti6Al4V. It is instead important to note that their formation typically leads to a decrease in mechanical properties [41].

7.2 Mechanical properties

In a study from Bo Song et. al where SLM built parts were compared with traditional casted or wrought parts it was shown that there is a difference in mechanical behaviour between these different methods [40]. The SLM parts yielded high tensile strength, low ductility and high anisotropy related with building direction. In general, SLM parts showed higher yield strength, ultimate tensile strength and hardness than the wrought parts. The improvement of the parameters is attributed to the grain refinement in the SLM parts. The wrought parts showed higher ductility and the SLM parts showed strong anisotropy in different kinds of alloys. Some researchers think that the anisotropy is caused by residual stress in the parts, while some think that the unique microstructure is the reason. However, it has been proven that heat treatments reduced anisotropy significantly.

7.3 Other properties

There are other properties that differs SLM parts and traditional manufactured parts. It is known that SLM fabricated parts shows higher surface oxidation and roughness. Capillary forces in the molten pool allows the un-melted particles to be absorbed on the surface during the cooling process, which leads to high surface roughness. By decreasing the scan spacing and speed, the molten pool morphology can be stabilised, which can reduce the surface roughness. It is known that SLM can fabricate parts with complex geometry and therefore it is important to obtain dimensional accuracy. Powder, processing parameters and equipment affects the dimensional accuracy [40].
8. Discussion

As brought up earlier, the concept of quality varies heavily. It is very dependent on the requirements of the intended application set by the customers. It could therefore be argued that good quality is when the performance of the product is sufficient for its intended use. Customer satisfaction is in turn the key to ensure that products are regarded as qualitative. For this reason, companies should be able to secure the fulfilment of customer needs and be able to adapt accordingly. This can easily be done through standards.

Even though this is carried out successfully today, the method of how it should be carried out could be improved further. The study showed that AM production highly is carried out through the trial and error approach. That could be adjusted to enhance the ability of quality improvement. The improvement of quality is benefited by the usage of methods such as Six Sigma and that allows for tracking of deviations in quality. To adopt these types of methods there is a need to record and track values of process parameters. This would allow for companies to better note relations between different parameters and use this data for quality improvement. Statistical analysis would then facilitate the whole process of quality improvement. One of the many examples of future work could be to track mechanical properties depending on the amount of defects in the product. The exact propositions of what is important to track and what is not will however be further discussed later in their respective section of this discussion.

The relevance of process parameter tracking becomes more essential as new standards for regulation of the industry will set in place which can cause limitations for companies within the market. Standards that regulate industries such as aviation require significant work with quality and will be easier to utilize with the discussed methods intended for improvement of quality. This would also imply that the process becomes more standardized and regulated. I.e. standardization of the testing methods which are used to track the process parameters would become more significant as it would strengthen the quality further.

Generally, eventual actions which can be adopted to further improve quality would require the implementation of internal guidelines for companies of what could be seen as qualitative. Today this is not the case since there seems to be different opinions on how good quality is defined. Perhaps product-specific guidelines could be a suitable choice for future standardised products, but since the business still is in development this would be in the distant future.

By systematically analysis of data, companies could also create and tighten tolerances for different parameters or properties. For an example, data from the powder testing that is stored in different excel-files is not an optimal way to store data from manual testing. This way of storing data makes it hard to track the product properties back to the powder and analyse the relations between different properties.
During process, the printing machines are often able to store a lot of data linked to the building process. The problem is therefore most often not the lack of process-data, but new techniques helping analysing it. This can be techniques such as HTE equipment, that can help them to analyse big amounts of data. This will be important for the future where there will be higher demands on the processes and the products. The optimal scenario would be if all companies involved in AM could share data (i.e. process and powder data) to contribute to more successful research. Investigating microstructures of AM builds to greater extent could also benefit companies in future research.

8.1 Powder

To get a good build with AM, it is of great importance that the powder is of good quality. Before even testing the powder properties, it is essential to make sure that it is of the desired composition. This due to that the properties of the material vary with different compositions. Therefore, it would be optimal to analyse the powder composition in-house where the production is located. This would reduce one factor that could affect the quality of the powder negatively.

There are many powder properties to take into consideration but studies about powder properties indicate that many of them partially affect the flowability. The flowability is crucial to get good properties of additively manufactured products. Therefore, it is important to be able to track powder properties when analysing the properties of the product to be able to examine if there are any connections between them. For example, to what extent the flowability determine the density of pores. Since flowability is such an important powder property, it would only be reasonable to study this parameter more closely and find a tolerance to ensure good quality of the end product. The tolerance for what is good flowability can differ depending on the powder and product requirements and should therefore be studied together with resulting product properties.

Another important aspect to take into consideration is the number of times the powder runs through the printer. This affects the powder properties and therefore it is essential to make sure that the powders do not exceed the tolerance for advantageous properties. In some cases, it is good to use the same powder more than once, because this reduces the number of fines in the powder [25].

However, the properties will deteriorate when using the powders too many times and therefore it is important to keep track of how many times the powder is used. Some machines have automatic sieving which makes it almost impossible to know exactly how many times the powder is used. Companies should therefore focus on finding an optimal number of runs and a method to keep track on how many times the powder runs through the printer.
8.2 Before processing

In regard to the start of the production, factors such as the computational design of products causes the most effect on the end result. The quality of the CAD is very dependent on the designer. Their understanding of the process is today the key to minimize the errors connected to the CAD-file in regard to factors such as build geometry and supports. In addition to this, tests of shape accuracy causes an important tool to discover errors related to these files. This could be seen as a possibility to further ensure quality of products. Continuous testing could be most advantageous for the types of products intended for usage within aerospace and aviation regulated by tight standards. Companies would then be able to ensure the accuracy of products delivered and imply the possibility to faster react to insufficiencies observed by customers regarding the shape of the products.

In terms of preparation of the process, it is important to enable the process to be carried out correctly. This is done by securing the functionality related to the process. Which could be achieved through frequent calibration of the machine combined with measurements of different factors such as gas levels and laser power. There is however a question of how frequent this actually should be conducted. The knowledge of this today is somewhat insufficient and it could therefore be investigated further to ensure that it does not cause problems in the future. Because it could be seen as advantageous to realize any disadvantages now while the business still focuses on development and not later when there is extensive production towards customers.

One important part of the process preparation especially worth mentioning is the preparation of the build platform. This stands as a good example of how important preparation of the process can be as it can cause devastating effects if not adjusted to suit the build which is to be printed. Insufficient measurements or curvature of the platform can cause the building process to collapse and force the process to be restarted. This is the type of effect that insufficient calibration can cause and that should be avoided.

8.3 LFF-system

One of the factors that would benefit from frequent calibrations is the LFF-system. The importance of being able to secure the functionality by conducting recurrent calibrations with respect to the different factors of the system is essential to be able to ensure that no deviations affects the process.

One of the most interesting parameters that could deviate is arguably the process gas supply. This parameter stands as a typical example of how easily the LFF-system could affect the process. The uniformity of the gas flow affects the porosity which as previously mentioned has great impact on the mechanical properties of the material. The gas flow also contributes to the variation that can be seen between different areas of the platform in builds. It could therefore be seen as beneficial if the gas flow could be continuously checked during the process to ensure the uniformity of the flow and minimize this variation. Control of the gas flow could in addition also decrease the build-to-build variation.
8.4 Process

In terms of processing, the most important aspect to consider is the interaction between different standard parameters. This study states that interaction between layer thickness, laser power, laser speed and hatch distance is the most essential parameters to define a suitable combination of [29]. What is sought is a sweet spot gaining an optimized performance of the product, when combining them. To receive an optimal process result, continuous mapping of these parameters and analysis of how different combinations lead to different qualities have to be made. Also, different materials and powder types will require different combinations of parameters. However, these parameters can be combined in different ways and still generate the same performance and quality. Theoretically, a print with high laser power, high layer thickness and wide hatch distance can be just as solid as a print having a faster printing speed but smaller hatch distance or thinner layers. When being highly commercial in AM this is an aspect that is important to master for optimization of productivity. When reaching a level of almost equal quality when using different parameter setups, the aspect of time can instead be considered.

Efforts to secure quality regarding processing, should be put in continuous optimization of process parameters. Constantly trying to minimize the accepted process window, by analysing big amounts of data. The process window is in this study the accepted range of output properties and quality, as a consequence of a specific set of parameters. Desired output is generally a product having the right shape and accepted mechanical properties [27].

Some parameters cause reactions linked to other parameters. It can be a reaction such as powder spattering, as a consequence of high laser power, that can affect the printing badly. Many of them are avoidable by regulating other parameters. For instance, both lowering of laser power and a higher gas flow over the powder bed leads to less powder spattering. When having two parameters that are possible to regulate, it is of big importance to realise which one of them that is easier to compromise with. In the current example, having the right laser power to gain a suitable melt pool is the most crucial. Therefore, it is better to change the gas flow to get rid of powder spattering, instead of changing laser power.

Debatable is also how the response can vary depending on the location at the platform where the products are built. It could have a direct effect on the quality distribution on products, but no facts or relevant studies is to be found within the area. However, it is an area easy to investigate by continuous mapping of properties and errors.

8.5 Material properties

There exist some general differences in properties between traditional manufactured and additively manufactured parts, but can it be guaranteed that all parts made with the same machine and the same type of powder have the same properties? Today, the answer would be no. Because of this, there is a need for optimization in the process so that companies could guarantee specific properties for their customers.

In general, the microstructure of an additive manufactured part is much finer than a traditional manufactured part, and it also has more anisotropic properties, as can be seen in
figure 9. This is important to take in consideration when making a new product. By heat treatment, the anisotropic effect can be reduced. It is also known that all alloys do not behave the same way and therefore it is important to investigate all powders separately.

When producing additively manufactured parts, it is also of high importance to study the most crucial defects that may occur. Pores are one of the most critical defects and are quite hard to get rid of. The fraction of pores is depending on many parameters (i.e. oxygen, flowability and laser effect). The oxygen parameter has the narrowest tolerance and it is therefore crucial that the oxygen meter shows correct values [7].

The laser has a big impact on the pore fraction. The high laser effect can cause keyhole pores, the laser delay can cause intra-layer porosity and the laser scan speed can cause elongated pores and irregular pores. Therefore, parameters such as laser effect, scan speed and laser delay are important to optimise to reduce the pore fraction [29].

If relation is found between the mechanical properties and the pore fraction for different materials, companies could more easily know what limit they should set for a specific product. All products do not have the same requirements. Some parts need to have better mechanical properties than other and therefore it is not necessary that all products have the same limit for the pore fraction.

Another common defect is residual stress. This can though be counteracted by preheating and optimising the scanning path. Components made with AM often have higher surface roughness than components made with traditional methods. Therefore, more after treatment of the surface is often required. It is important to know which products that actually need more surface treatment since this is both time consuming and expensive. It is also important that any surface treatments are taken in consideration when constructing the CAD-file.

8.6 Sustainability aspect

It is easy to understand why UNIDO has pinpointed AM as a means to achieve the sustainability development goals set by the UN. This as it in many ways contribute to the development of sustainability in industry. The method allows production of complex products that, if produced in a more traditional matter, would demand more work and use of more resources. The possibility to produce more complex products also contributes to make other industries more efficient, where a certain product could make a difference in how technology is designed. E.g., the new complexity in a certain part could allow for reduction in power consumption and in turn emissions. Which would be most favourable in regard to the sustainability aspect of the industry.

Being able to ensure quality of AM products may benefit the development of today’s infrastructure. There will be more demands on the climate footprint of each product and to be able to keep living the way we do today it is important to reduce the environmental footprint already. Product quality is also important in an ethical aspect. Companies wants to produce additive manufactured products for both aerospace and the medical industry. If they cannot ensure the quality of the products, they may be risking human lifes which is ethically unacceptable.
8.7 Future Efforts/Investments

AM is a process that still is being developed rapidly. Better hardwares and softwares that makes the process more efficient and precise are often released. Thus the manufacturing method is in a grow phase, it is crucial for companies that will use it commercially to not fall behind. Adopting the right future technologies is therefore of great importance as well as being a company leading the development. Currently, there are relatively few standards that apply to AM, but it will increase as the technology becomes more commercial. However, upcoming standards will most likely be based on how leading companies acts.

It is therefore a huge competitive advantage for companies to be a quality leading from start, having the knowledge of what it takes to obtain different performances. As mentioned earlier the first step to get there is by creating procedures for continuous data collection and mechanical testing, followed by a higher grade of analysis.

AM techniques seems to be focusing on having better process control. As mentioned earlier, it will be one of the most important aspects to be able to make the quality and efficiency better. A lot of new techniques are upcoming and it has to be highly prioritized for companies to follow the development and invest in the right things.

As earlier mentioned, the technology faces some major challenges before it can be fully commercialized and efficient. The way of becoming the leading player regarding knowledge of the production and quality control is by continuously putting more effort in analysing the processes and results, but also being early adopters to upcoming software-applications facilitating manufacturing.
9. Conclusions

In conclusion it be said that the most crucial parameters within AM are very dependent on the definition of quality for a certain product. The relevance of different parameters vary heavily depending on this definition. This in turn reveals the importance of working more actively with quality assessment and investing in new technologies.

Currently the most deviations in quality are closely related to porosity within components. In addition to this, the quality is widely affected by insufficiencies in shape of components relating to different parameters during the process. This highlights the significance of process control, which can be further improved through the implementation of surveying softwares alongside the process.

Generally, there are some parameters that are crucial to consider during SLM:

- LFF-system related parameters are non-controllable and the importance lays instead in securing their functionality.
- Process parameters are highly dependent upon each other but the most important ones to correlate are hatch distance, laser power, layer thickness, scanning pattern and scan speed.
- Powder parameters are mostly about securing sufficient flowability, which has the greatest effect on the printing.

From this follows suggestions regarding quality improvement. These include dedicating a separate taskforce for work with quality and generally making procedures for collecting and analysing process data.
10. Future work

The following is by this study recommended work, directed to companies in general, to further improve quality of their AM products:

- Connect fractions of porosity to mechanical properties for the different materials used in production.
- Investigate possibilities of using data of microstructures to derive different parameters.
- Investigate possible tools for handling of data to improve analysis.
- Introduce general guidelines on storage of data to improve awareness of how this is done.
- Map consequences of the methodology in powder handling and perhaps investigate the possibility to better control the amount of laps a powder takes in the machine.
- Investigate possibility in implementation of systems regarding process control and real-time monitoring.
- In depth studies in optimization and correlation of process parameters, such as hatch distance and laser power.
- Introduce general guidelines for defining quality to cause awareness of this within the workforce.
11. Acknowledgement

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12. References


# Appendix A: Controllable/predefined parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Controlled or predefined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser and scanning parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average power</td>
<td>Measure of total energy output of a laser</td>
<td>Controlled</td>
</tr>
<tr>
<td>Mode</td>
<td>Continuous wave or pulsed</td>
<td>Predefined</td>
</tr>
<tr>
<td>Peak power</td>
<td>Maximum power in a laser pulse</td>
<td>Predefined</td>
</tr>
<tr>
<td>Pulse width</td>
<td>Length of a laser pulse when operating in pulsed mode</td>
<td>Predefined</td>
</tr>
<tr>
<td>Frequency</td>
<td>Pulses per unit time</td>
<td>Predefined</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Distance between crests in laser electromagnetic waves</td>
<td>Predefined</td>
</tr>
<tr>
<td>Polarization</td>
<td>Orientation of electromagnetic waves in laser beam</td>
<td>Predefined</td>
</tr>
<tr>
<td>Beam quality</td>
<td>Related to intensity profile and used to predict how well beam can be focused and determine minimum theoretical spot size</td>
<td>Predefined</td>
</tr>
<tr>
<td>Intensity profile</td>
<td>Determines how much energy added at a specific location</td>
<td>Predefined</td>
</tr>
<tr>
<td>Spot size</td>
<td>Length and width of elliptical spot (equal for circular spots)</td>
<td>Controlled</td>
</tr>
<tr>
<td>Scan velocity</td>
<td>Velocity at which laser moves across build surface</td>
<td>Controlled</td>
</tr>
<tr>
<td>Scan spacing</td>
<td>Distance between neighboring laser passes</td>
<td>Controlled</td>
</tr>
<tr>
<td>Scan strategy</td>
<td>Pattern in which the laser is scanned across the build surface and associated parameters</td>
<td>Controlled</td>
</tr>
<tr>
<td><strong>Powder material properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td>Material density, limits maximum density of final component</td>
<td>Predefined</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Measure of material’s ability to conduct heat</td>
<td>Predefined</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>Measure of energy required to raise the temperature of the material</td>
<td>Predefined</td>
</tr>
<tr>
<td>Latent heat of fusion</td>
<td>Energy required for solid-liquid and liquid-solid phase change</td>
<td>Predefined</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>Temperature at which material melts; for alloys the difference between the liquidus and solidus temperature is typically of greater interest</td>
<td>Predefined</td>
</tr>
<tr>
<td>Boiling temperature</td>
<td>Temperature at which material vaporizes; may only be important in certain process conditions</td>
<td>Predefined</td>
</tr>
<tr>
<td>Property</td>
<td>Description</td>
<td>Control</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Melt pool viscosity</td>
<td>Measure of resistance of melt to flow</td>
<td>Predefined</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>Measure of volume change of material on heating or cooling</td>
<td>Predefined</td>
</tr>
<tr>
<td>Surface free energy</td>
<td>Free energy required to form new unit area of solid-liquid interfacial surface</td>
<td>Predefined</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>Measure of the tendency of material to vaporize</td>
<td>Predefined</td>
</tr>
<tr>
<td>Heat (enthalpy) of reaction</td>
<td>Energy associated with a chemical reaction of the material (e.g., oxide formation), not always relevant</td>
<td>Predefined</td>
</tr>
<tr>
<td>Material absorptivity</td>
<td>Measure of laser energy absorbed by the material, as opposed to that which is transmitted or reflected</td>
<td>Predefined</td>
</tr>
<tr>
<td>Diffusivity</td>
<td>Important for solid state sintering, not as critical for melting</td>
<td>Predefined</td>
</tr>
<tr>
<td>Solubility</td>
<td>Solubility of solid material in liquid melt, unlikely to be significant</td>
<td>Predefined</td>
</tr>
<tr>
<td>Particle morphology</td>
<td>Measures of shape of individual particles and their distributions</td>
<td>Predefined</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>Arithmetic mean of the surface profile</td>
<td>Predefined</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>Distribution of particle sizes, usually diameter, is a powder sample</td>
<td>Predefined</td>
</tr>
<tr>
<td>Pollution</td>
<td>Ill-defined factor describing change in properties of powder due to reuse as dust and other particles added to powder</td>
<td>Predefined</td>
</tr>
<tr>
<td><strong>Powder bed properties and recoat parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Measure of packing density of powder particles, influence heat balance</td>
<td>Predefined</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Measure of powder bed’s ability to conduct heat</td>
<td>Predefined</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>Measure of energy required to raise the temperature of the powder bed</td>
<td>Predefined</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>Measure of laser energy absorbed, dependent on Ab and state of powder bed</td>
<td>Predefined</td>
</tr>
<tr>
<td>Emissivity</td>
<td>Ratio of energy radiated to that of black body</td>
<td>Predefined</td>
</tr>
<tr>
<td>Deposition system parameters</td>
<td>Recoater velocity, pressure, recoater type, dosing</td>
<td>Controlled</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>Height of a single powder layer, limiting resolution and impacting process speed</td>
<td>Controlled</td>
</tr>
<tr>
<td>Powder bed temperature</td>
<td>Bulk temperature of the powder bed</td>
<td>Controlled</td>
</tr>
<tr>
<td><strong>Build environment parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Control</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Shield Gas</td>
<td>Usually Ar or N2, but may also be He, or something else</td>
<td>Predefined</td>
</tr>
<tr>
<td>Oxygen level</td>
<td>Probably most important environmental parameter; oxygen can lead to oxide formation in metal, change wettability, energy required for welding</td>
<td>Controlled</td>
</tr>
<tr>
<td>Shield gas molecular weight</td>
<td>Influences heat balance, diffusivity into and out of part</td>
<td>Predefined</td>
</tr>
<tr>
<td>Shield gas viscosity</td>
<td>May influence free surface activity of melt pool, convective heat balance</td>
<td>Predefined</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Term in heat balance</td>
<td>Predefined</td>
</tr>
<tr>
<td>Heat capacity of gas</td>
<td>Term in heat balance</td>
<td>Predefined</td>
</tr>
<tr>
<td>Pressure</td>
<td>Influence vaporization of metal as well as oxygen content</td>
<td>Controlled</td>
</tr>
<tr>
<td>Gas flow velocity</td>
<td>Influences convective cooling, removal of condensate</td>
<td>Controlled</td>
</tr>
<tr>
<td>Convective heat transfer coefficient</td>
<td>Convective cooling of just melted part by gas flowing over the surface</td>
<td>Predefined</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>Appears in heat balance, may impact powder preheat and residual stress</td>
<td>Controlled</td>
</tr>
<tr>
<td>Surface free energy</td>
<td>Between liquid and surround gas influence melt pool shape</td>
<td>Predefined</td>
</tr>
</tbody>
</table>
Appendix B: Testing of powder

Stability Method

Before starting measurements on powder, it is important to test its stability. The stability refers to how well the powder will avoid being changed as a result of tests and therefore stability tests is made by running the powder through a series of identical measurements. Instability in a powder will instead degrade its properties during the tests. For instance, a powder tending to be compressible may be agglomerated during flow testing and as a consequence of this have its flow properties changed.

Stable powder is significantly robust and have a relatively flat graph, with minimal deviation between first and last test cycle. A typical graph for a stable powder is to see in Figure 1. Graphs for unstable powder can instead look in two different ways, which is shown in Figure 2 and Figure 3. The first case does most often depends on de-aeration, agglomeration, segregation, moisture uptake or electrostatic charge. When the other depends on aspects such as attrition, de-agglomeration or over blending of an additive, if used.

![Graph](image.png)

Figure 1
Variable flow rate

The rate which powders are moved through the process will vary from point to point. Even the most simple transfer system will require the powder to flow at high rate in some places and low rate in others. Variable flow rate of a powder is an important parameter when describing its flow properties. Cohesive powders are often more sensitive to changes in flow rate than non-cohesive, mainly as a result of the high air content in cohesive materials.

Some factors that can affect the flow rate sensibility is:
- At high flow rates, more air is entrained, which acts as a lubricant and reduces the interparticle contact and allows the material to be more compressible. This will reduce the energy required to produce flow.
• At low flow rates, it is likely to get interlocking of particles where the adjacent particles nestle together. This is not as likely at high flow rates because the relative particle velocities are greater.

Compressibility
Compressibility is a measure of how density changes as a function of applied normal stress. This bulk property is influenced by many factors, such as particle size distribution, cohesivity, stiffness, shape and surface texture. It is not a measurement of flowability, yet relates to many process environments, such as storage or behavior during roller compaction. Generally, cohesive powders are the most compressible while granular powders being less compressible.

Aeration
Aeration seeks how air affects the flow properties. Air affects all powders in some way when present in the space between particles. This because it influences how the particles interact with each other which causes a change in flow properties. Powders with low cohesive forces between particles often leads to a more fluidized behavior of the powder and therefore also enhances the flowability. Aeration is measured by quantifying how introduced air in the base of the powder changes the flowability by measuring the reduction in flow energy.

Shear cell
To understand how easy, a previously at rest, consolidated powder will begin to flow it is important to have knowledge the shear properties of the powder. The powders till be subjected to consolidation stresses that causes changes in density and mechanical interparticulate forces in every process and storage environment. It is necessary that the yield point of the powder is exceeded for the powder to flow.

The yield point is greatly influenced by physical properties such as size, shape, and surface characteristics of the particles, but also variables such as humidity and level of flow additive. In any kind of transportation, powders will be subjected to some level of consolidation stress during their handling. Measuring the shear properties will provide important information as to whether the powder will flow or whether bridging and blockages are probable.

Permeability
Permeability is a measurement of how easy a fluid can be transmitted through the bulk of a material. The permeability is of interest to understand how different process environments will affect the powder. Powder with different permeabilities will behave differently in environments such as vacuum transfer and during powder flow in the machine due to the effects of permeability which in turn can cause negative effects on the flowability of the powder.

So called “fines”, very small particles, can cause the powder to pack tightly by filling the spaces between the larger particles which in turn makes the bulk less permeable. Permeability is also affected by factors such as consolidation whereas the consolidation stress causes a difficulty for fluids to pass through the bulk.
Tapped Consolidation

It is of importance to understand changing in the flow energy of a powder, when consolidated by vibration. Powders are often exposed for uncontrolled vibration from machines or transportation and therefore, securing its properties not are changing over time are desirable. It is measured by controlled tapping, which is a process that provides simulated vibrations repeatedly.

Likely, the bulk density will increase some, while the flow energy often increases significant as a consequence of a higher particle-particle interaction. Because of this the tapping will make the powder reduce in volume. This will also preferably be followed by a recovery test, providing information if the consolidation of the powder causes maintaining impacts on the flow behavior, even after re-condition.