OULUN AMMATTIKORKEAKOULU

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OPTIMIZATION OF SLM PARAMETERS FOR IN718 PRODUCTION

OPTIMIZATION OF SLM PARAMETERS FOR IN718 PRODUCTION

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ABSTRACT

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This thesis was made to improve the quality of objects printed from In718 -metal. Urban Alps Stealthkeys were used for the research because of their usability as samples. The keys have a small text on them, which sometimes can be difficult to read due to rough edges around them. It was also seen from previous samples that the inner structure and density of the objects were not perfect. There was room for improvements and the thesis was ordered to be made.

This thesis was made for a metal 3D printing specialized company; ProtoShape GmbH. ProtoShape is operating in Switzerland, Biel and currently it is employed by four people. An improved set of In718 -parameters were achieved for the thesis. Improvements were achieved in form of higher density of the objects and more refined outer details by altering the original parameters set for In718 production.

Keywords: Selective Laser Melting, Parameter, Inconel 718

TIIVISTELMÄ

Oulun ammattikorkeakoulu
Konetekniikka, tuotantotekniikka

Tekijä: Henri Väänänen
Opinnäytetyön nimi: SLM parametrien optimointi In718-tuotantoa varten
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Tämä opinnäytetyö tehtiin parantamaan In718 -metallista tulostettavien osien laatua. Työssä käytettiin näytteinä Urban Alps nimisen yrityksen Stealthkey tuotetta, koska kyseinen tuote on ominaisuuksiltaan sopiva testikäyttöön. Stealthkey avaimissa on ulkopinnoissa paljon pieniä yksityiskohtia, kuvioiden ja pienen tekstin muodossa. Tulostusprosessin takia kyseistä tekstiä on toisinaan vaikea lukea ja tekstissä on havaittavissa epämuodostumia. Metallografisista tutkimuksista paljastui myös, että In718 -metallista valmistetut tuotteet eivät olleet täydellisiä sisäiseltä rakenteeltaan. Tulostetuissa kappaleissa oli paljon mikroskooppisia ilmataskuja, jotka heikentävät tuotteiden kestävyyttä. Työ tilattiin, koska parantamisen varaa oli paljon.

Tämän opinnäytetyön tilasi metallin 3D-tulostukseen erikoistunut yritys ProtoShape GmbH. ProtoShape on Sveitsin Bielissä sijaitseva yritys, joka työllistää tällä hetkellä neljä henkilöä. Opinnäytetyön tuloksena yritys sai parannellut optimoidut parametrit In718 -metallin tuotantoa varten. Tuloksina saavutettiin huomattavasti parempi sisäinen rakenne, jolloin ilmataskujen määrä jäi todella vähäiseksi, sekä huomattavasti parempi pinnanlaatu, jonka tuloksena pienimmätkin yksityiskohdat avainten pinnassa ovat selvästi luettavia ja ymmärrettäviä.

Asiasanat: Selective Laser Melting, Parametrit, Inconel 718

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SISÄLLYS

1 INTRODUCTION

The main goal for this thesis is improving SLM-technology parameters for Inconel 718 metal. In the thesis there will be research of inner structures and outer quality of the In718 samples as well as theory of the main parameters used. Results are shown with pictures, graphs and data tables to make the results visually easy to see and understand. The samples used in the thesis are a product called StealthKey by company UrbanAlps. The result of the thesis will be improved parameters for metal 3D printing In718.

1.1 Background of the study

This thesis was comissioned by ProtoShape GmbH. ProtoShape is a 3D-printing specialized company located in Canton Bern in the city of Biel, Switzerland. ProtoShape produces parts for production, prototyping and one-time orders. ProtoShape prints objects from Aluminium, Titanium and Inconel 718. Additive manufacturing allows production of one time customized orders, without the need of creating molds or using traditional tools. Only limitations for production are size, some geometrical challenges and small surface details.

Additive manufacturing and especially Selective Laser Melting (SLM) requires a wide usage and knowledge of different parameters. Things such as Laser speed, -power, hatching distance, beam compensation, focus and layer thickness affects the print result crucially. Changing one parameter affects as a whole. Decreasing speed affects directly in inner structures and density but also size of the object. That's why changes need to be made in relation to other parameters.

1.2 Problems of the research

The main goal of the thesis was to improve SLM parameters for Inconel 718 production. The research was done by creating different sets of parameters that were tested with small samples resembling a production piece. In total, 5 tests were implemented with each having multiple sets of parameters researched and compared to each other. This type of research allows finding the correct parameters and direction in a logical way.

The results were researched by cutting and embedding a piece of the sample. These embedded samples were researched under a microscope to see their inner structure and density. Also the outer details were researched with a microscope to see the improvements with the text quality.

The main problem with the original Inconel 718 -parameters was the over all quality. Density of the printed parts wasn't in the level the company expected it to be. Also small details such as text wasn't as good as hoped for. All of these traits were seen in a large scale production part made at ProtoShape. StealthKey by UrbanAlps is a next level safety key produced at ProtoShape. These keys have small details printed on them such as phonenumbers and other information. The product is a good sample for parameter improvement and that's why it was chosen to be used in the thesis.

1.3 Conducting the research

The research style which was used for the thesis is a common procedure used at ProtoShape. The research methods used in the thesis are a result of the equipment available at the time. Metal saw, embedding chemicals and a microscope allows the research of inner structures in the most efficient way. Also the SLM machinery allows the use of multiple parameters inside a buildjob, making the direct comparison of 4 parameters at time more reliable and affordable.

The used research method can be described as narrowing technique, where the correct parameters were found out by creating many similar parameters with changes made for just one or two parameters at time. The methods used in the research are affected by the working environment since similar type of research has been done inside the company for smaller projects. Other official methods could have been used, such as Taguchi method, but since the companies methods had been used sucessfully to other projects, there was no need to create different procedures for the research.

2 SELECTIVE LASER MELTING

Metal 3D-printing is a field of manufacturing with a wide range of terminology. Because of being a relatively young type of manufacturing the field has many different names, often caused by small differences within machinery or region. This section of the report will have all the most important terms explained.

2.1 Additive Manufacturing

Additive manufacturing covers all forms of 3D-printing. Everything printed with plastics, metals and other materials are within the concept of additive manufacturing. GE Additive (2020), defines the term as such:

”It is yet another technological advancement made possible by the transition from analog to digital processes. In recent decades, communications, imaging, architecture and engineering have all undergone their own digital revolutions. Now, AM can bring digital flexibility and efficiency to manufacturing operations.

Additive manufacturing uses data computer-aided-design (CAD) software or 3D object scanners to direct hardware to deposit material, layer upon layer, in precise geometric shapes. As its name implies, additive manufacturing adds material to create an object. By contrast, when you create an object by traditional means, it is often necessary to remove material through milling, machining, carving, shaping or other means.

Although the terms "3D printing" and "rapid prototyping" are casually used to discuss additive manufacturing, each process is actually a subset of additive manufacturing. While additive manufacturing seems new to many, it has actually been around for several decades. In the right applications, additive manufacturing delivers a perfect trifecta of improved performance, complex geometries and simplified fabrication. As a result, opportunities abound for those who actively embrace additive manufacturing.” (1).

2.2 CAD

”Computer aided design or CAD is an important industry within the tech world. It involves utilizing computers to help with engineering and design for a wide range of projects. Common types of computer aided design include metal fabrication, carpentry, and 3D printing, as well as others that have impacted modern manufacturing and other business processes.” (2).

2.3 Inconel 718

”SLM Solutions' IN718 is a precipitation-hardenable nickel-chromium-alloy. With excellent tensile, fatigue, creep, and rupture strengths up to 700 °C, IN718 is an important alloy for production of components for aircraft engines, (gas) turbines, and other high temperature applications.” (3).

In718 –metal has high strength, good ductility, excellent mechanical properties up to 700°C and excellent oxidation resistance. The most typical application areas for In718 are aerospace-, energy-, chemical- and turbine industries. (3)

2.4 SLM

SLM stands for selective laser melting. This type of manufacturing is known with a slightly different name depending of where in the world it is used. For example, in the United States SLM is usually referenced as selective laser sintering ”SLS”. Other better known variations are ”DMLM” direct metal laser melting and ”LPBF” laser powder bed fusion. However, in Europe this manufacturing style is best known as SLM.

The way SLM works: ”Heat is generated using a focused heat source, normally a laser, sufficient to melt a thin layer of powder applied to the surface of a substrate. Material is added layer by layer by lowering the build by a small amount and spreading a thin layer of powder over the surface. To create the desired geometry, the heat source is traversed over the powder bed, locally melting small regions to form successive layers. The layers eventually build up to form the solid structure. Material addition in SLM is very stable. Unlike powder feed systems, unmelted material is not lost and can generally be reused. Furthermore, because the layer height is defined by the amount the build chamber is lowered, the layers can be very small, resulting in very fine feature resolution.” (4).

2.5 SLM 125

”The compact SLM®125 Selective Laser Melting metal 3D printer offers a build envelope of 125 x 125 x 125 mm or reduced to 50 x 50 x 50 mm with a single 400W fiber laser. Precise, economical and suitable for research and development as well as small lot production environments, the open software architecture and system parameters allow you to make modifications according to your specific manufacturing needs. Achieve the fastest build speeds in its class from the system's patented bi-directional powder recoater movement. Internal re-circulation of inert gas at laminar flow also provides for safe and cost-efficient gas consumption.

The SLM®125 is equipped with software for importing CAD / STL data or slice data to configure the processes and component-specific parameters. Achieve greater system control by customizing your own construction processes through the unique, flexible and open software architecture. The system processes most metal powders through a material saving, closed-loop powder handling unit. Changing the metal powder is quick, easy and designed to lower your production costs. Further available options also increase the versatility of the system and our Laser Power Monitoring and Melt Pool Monitoring quality assurance modules ensure process transparency." (5).

2.6 STL

"The STL file format has become the Rapid Prototyping industry's defacto standard data transmission format, and is the format required to interact with Quickparts. This format approximates the surfaces of a solid model with triangles. - - Almost all of today's CAD systems are capable of producing an STL file. For the user the process is often as simple as selecting File, Save As, and STL. Below are steps for producing high quality STL files from a number of today's leading CAD systems. In all cases, export your STL file as a Binary file. This saves on time and file size.

As a general rule, changing options such as Chord Tolerance or Angular Control will change the resolution on your STL file. The larger the STL file, the more triangles placed on the surface of the model. For simple geometry (not a lot of curves), the file may only be a couple hundred kilobytes. For complex models, files sizes in the range of 1-5MB will produce good parts. For many geometries, files larger then 5MB are unnecessary and will often just result in more time to get your quote and parts back." (6).

2.7 UrbanAlps – StealthKey

UrbanAlps is an award-winning lock company located in Zürich, Switzerland. Their product StealthKey is manufactured at ProtoShape GmbH. The idea of the StealthKey is to be the most safe and secure key in the markets. StealthKeys are traditional keys without any magnets, electronics or batteries inside them but the structure is completely different from most usual keys. All of the security features are hidden inside the key, so that they are not exposed to the outer world. This makes mechanical copying of the key impossible, making the product safe. (7).

3 MAIN PARAMETERS AND HOW THEY WORK

For the thesis, there was a series of parameters to work with. The parameters presented with green color in table 1 are the ones that affect the result most when changed. The parameters were categorized by the probability and necessity of being changed. Green (will be changed), yellow (sometimes changed), orange (almost never changed) and red (never changed).

Changing one parameter like speed is simple but it’s harder to realize why for example the object grows out of allowed parameters. It’s good to remember that everything affects as a whole while working with SLM parameters. This is why parameters are mostly changed in the relation to each other. In the tabel 1 there are seen the main parameters with their values and their categories.

TABLE 1. Original parameters V0

Original Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	100 %	100 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3.5
Border distance (mm)	-	0.12
Beam compensation (mm)	-	0.07
Layer thickness (mm)	0.03	0.03
Volume Energy density (J/mm^3)	47.619	55.556

PARAMETERS EXPLAINED

Many times, it's difficult to know the real meaning of a parameter just by looking at its name. Here are the definitions for the parameters presented in table 2.

TABLE 2. Basic parameters explained

Speed: Defines how fast the laser moves on this vector type.
Power: Defines how many watts are used for this vector type.
Hatch distance: Is the distance between "hatch" vectors".
Focus: Defines the necessary shift of the scanner for this vector type.
Border distance: Distance of the first "following border" to the first border and between consecutive following borders.
Beam compensation: This parameter compensates for the width of the melt pool. The value determines by which amount the original slice border needs to be offset to the inside to guarantee the correct build size of a part.
Layer thickness: Height of a each layer.

4 OPERATIONS

4.1 Buildjob preparation

To create a Buildjob, you need an STL file of the structure you want to manufacture. Materialise Magics is a software for creating SLM files for the SLM machines. STL file is opened in Materialise Magics, where the object is oriented and set on a default height of 4 mm. The default height is for the support structures that need to be created between the part and the buildplate. Once the object has been oriented to its correct position, the support structures are created. Once everything is set, the SLM file can be made.

Materialise Magics allows a great feature for research purposes. While configurating the buildjob, you can choose different parameters for each object or group. This allows different parameters to be tested with just one print, saving alot of time and money.

4.2 Preparing the machine and starting the build

Starting the buildjob on the machine, can take from 10–30 minutes of time, depending on the status of the machine. Clean and calibrated machine needs only the created SLM file and fresh powder. First layer of powder needs to be set manually controlling the machine but after that everything is automated. Once the SLM file is loaded the machine can be started.

4.3 Unloading the machine and collecting the samples

Once the print is done and the chamber has cooled down, it can be emptied. Right after the print, the done parts can be seen only by their upskin (the last printed layer) surrounded by metal powder. The buildplate needs to be removed from the machine in order to collect the samples. The excess powder needs to be collected and sieved for re-use. The samples can be removed easily from the buildplate but the support structures need a bit more force in order to remove them. Used buildplates are polished and sandblasted in order to keep up the good buildsurface.

4.4 Cutting, embedding and polishing the samples

The samples need to be cut for the metallographic inspection. The samples are cut by using Discotom-2 metal cutter. The samples are then cold embedded in methymethacrylate.

Once the samples are ready, the polishing can be started. The procedure is done with multiple steps using a Presi Mecapol P230 sample polishing machine. First the samples get grinded with three different levels; 70 um, 30 um to 18um. After grinding phase the samples are polished with two levels; 6um and 1um. The polishing phase is done with additional lubricant. The samples are ready for research once there are no visible srat-ches on the surface.

4.5 Microscopic research and volume evaluation

The polished samples are researched with a camera equiped Leica microscope. This allows documenting the inner structure and quality of the samples. For the reports, I took six pictures of each sample, four pictures showing the density and two showing the quality of the edge.

The volume evaluation is done by Fiji software. The software recoqnizes holes and calculates the areas of each pictures. This gives an estimation of how dense the samples are.

4.6 Reporting

The analyzed pictures are gathered into a report. These reports help with writing the thesis, since the overall data can be gathered easily from them. The reports consists of pictures and calculated densitites. The density data is collected into an excel file where a group formatting is displaying the densities around the buildplate. This gives a clear view of which parameter works the best and how the position in the plate affects the results.

5 BUILDJOB 1

5.1 Strategy

For the first buildjob it was tested if slowing down the speed and decreasing power would result in better quality. What ended up being created was two set of parameters where the speed and power were decreased and one set where they were increased. The increased parameters were made just for creating more variations and scale for the study. The research was started with relatively small changes just the see which direction to go with the parameter changes. The percentage figures in the chart are describing how much speed and power were altered.

TABLE 3. Buildjob 1 parameters

Original Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	100 %	100 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	47.619	55.556

V1 (80%) Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	80 %	80 %
Power (W)	80 %	80 %
Hatch distance (mm)	120 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,144
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	39.683	46.296

V2 (70%) Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	70 %	70 %
Power (W)	70 %	70 %
Hatch distance (mm)	130 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,156
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	36.630	42.735

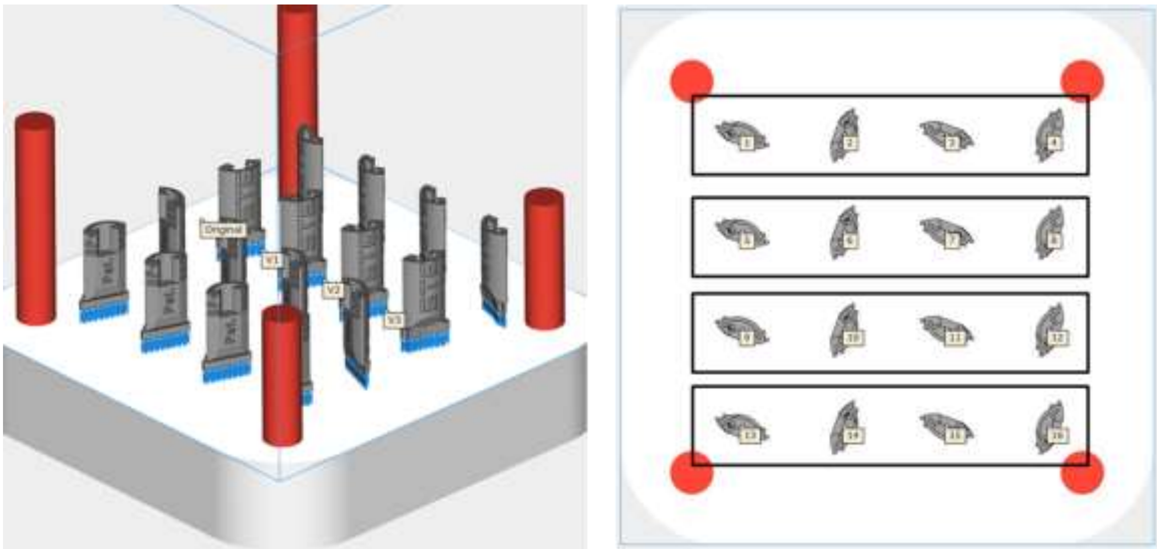
V3 (120%) Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	120 %	120 %
Power (W)	120 %	120 %
Hatch distance (mm)	80 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,096
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	59.524	69.444

From the table 3 can be seen that speed and hatching distance are being changed in relation to each other. This was done in order to keep the dimensional tolerances same as the original key. What was later found out was that these changes didn't work as planned and the tolerances were fixed by increasing the beam compensation.

5.2 Orientation of the samples

There are 16 samples made with each buildjob. Four samples for each parameters tested to give more reliable results. The samples are short versions of the actual keys to save material and time. Each sample has a text on the outer surface and enough material to make a metallographic inspection.

The orientation of the samples are important for the quality of printing. As seen on the pictures, each row is moving from left to right in relation of the buildplate. The reason for this particular orientation is the SLM 125 machine. Inside the machine there is argon gas flowing through the chamber from right to left. Small burnt particles are created during the printing process. The gas flow affects these particles and some of them land on the samp-les on the left side of the buildplate affecting their inner structure. When each row of parameters are oriented the same way, the defects caused by the machine are equal to the samples, which gives a more reliable comparison. These orientations can be seen in picture 1.

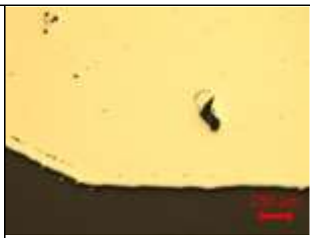
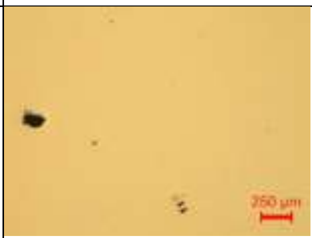
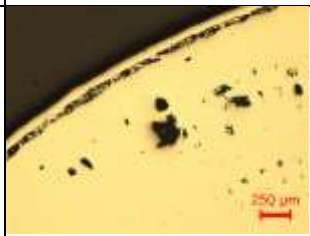
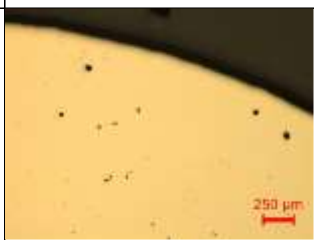


PICTURE 1. Sample orientations on the buildplate

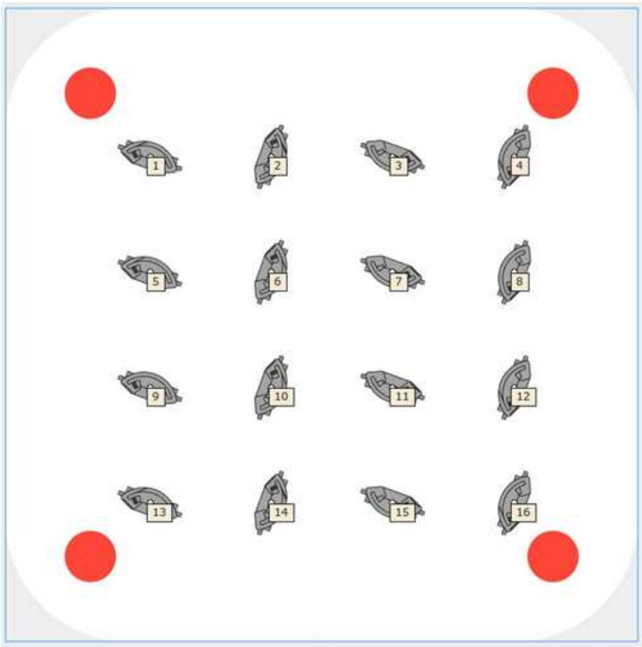
5.3 Results

The results of the first buildjob are good guidance and something that wasn’t expected. The parameters V1 and V2 were worse in density and surface quality than the original parameters. Instead the V3 parameter of increased values showed much more promising results, being the best of the group with density up to 99.99 %. While being near perfect from the inside, the outer quality seemed to have decreased. Quality of the text on the samples are more rough and clearly worse than the original. In table 4 there are pictures picked from the made report, showing the quality of structure, edge and surface.

TABLE 4. Buildjob 1 density and surface quality

V0 Origi-nal para-meters			
V1 80%			
V2 70%			
V3 120%			

As seen from the table 4, the differences between original, V1 and V2 parameters in comparison to V3 is remarkable. The inner density is much more better and consistant in relation to the other samples. There is alot of ”edge tearing” seen along the V1 and V2 parameters, but it was also seen with one sample from original parameters. The V3 parameter indicated that the quality problem was not solvable by reducing speed and power.



Original (V0)	99.82	99.76	99.91	99.87
Parameter 1 (V1)	99.81	98.46	99.46	99.97
(V2)	98.9	99.23	99.37	99.9
(V3)	99.98	99.99	99.94	99.94

PICTURE 2. Buildjob 1 densities in relation to the buildplate

The picture 2 above is to visualize the densities across the buildplate. The chart makes it easier to see the whole picture and probable affections of orientation and location. What is clearly seen is the quality difference between parameters. Within V0 to V2, there are few good samples. When looked into V3 parameter the quality and consistancy can be noticed. With these results it is clear that the parameters can be improved by increasing speed and power. Next step is to find the correct values for best result with least energy used.

6 BUILDJOB 2

The second buildjob was a turning point for the thesis. After some research done, a study was found about Volume energy density and it's affection to 3D-printing In718. Volume energy density is an indication of energy used per cubic millimeters built. Volume energy density or "VED", is calculated as shown in equation 1 [8, page 2.] The study was suggesting that a VED of 61.2 J/mm^3, was optimum for In718. The work needed was to create parameters which result close to 61.2 VED. [8]

P = Power (W) *EQUATION 1*

h = Hatch distance

s = Laser speed

t = Layer thickness

$$VED = \frac{P}{h \cdot s \cdot t}$$

PICTURE 3. VED equation

6.1 Strategy

The strategy used for buildjob 2, was to achieve VED close to 61.2 J/mm^3. There are many ways to come up with these results, so four set of parameters were made with each having a different apporach to the situation. First set V4 has a VED of 61.444 J/mm^3. It was achieved by decreasing hatch distance, making the laser do more vectors each layer. The second set V5 affects the speed. Slowing down the speed makes the laser melt each spot a bit longer than originally. V6 parameters are higher in laser power compared to others, which means more intense melting. V7 parameters was a mix of everything. The goal VED was achieved by decreasing Speed, Power and Hatch distance.

TABLE 5. Buildjob 2 parameters

V4 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	100 %	100 %
Power (W)	100 %	100 %
Hatch distance (mm)	77,50 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,109
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.444	61.162

V5 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	77,80 %	90,75 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.200	61.218

V6 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	100 %	100 %
Power (W)	128,30 %	110 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.111	61.111

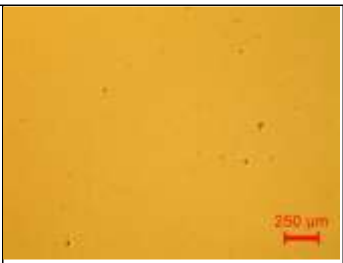
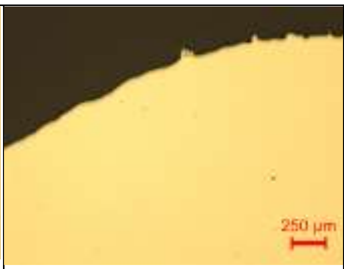
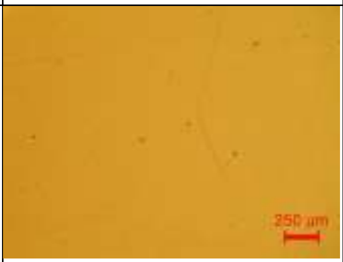
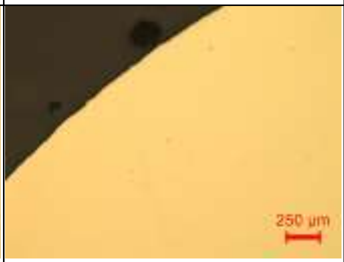
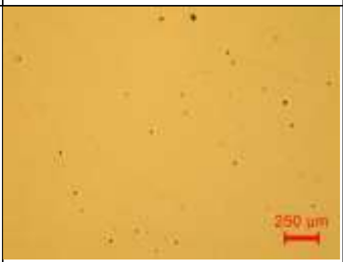
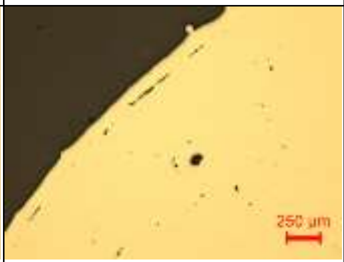
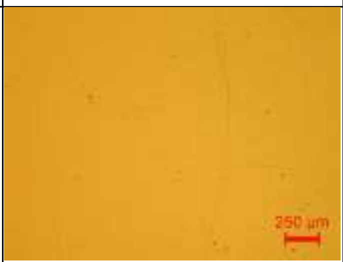
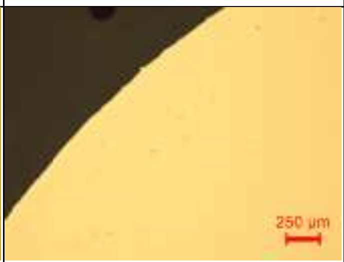
V7 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	92,86 %	92,75 %
Power (W)	94,44 %	93,75 %
Hatch distance (mm)	79,17 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,11
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.179	61.259

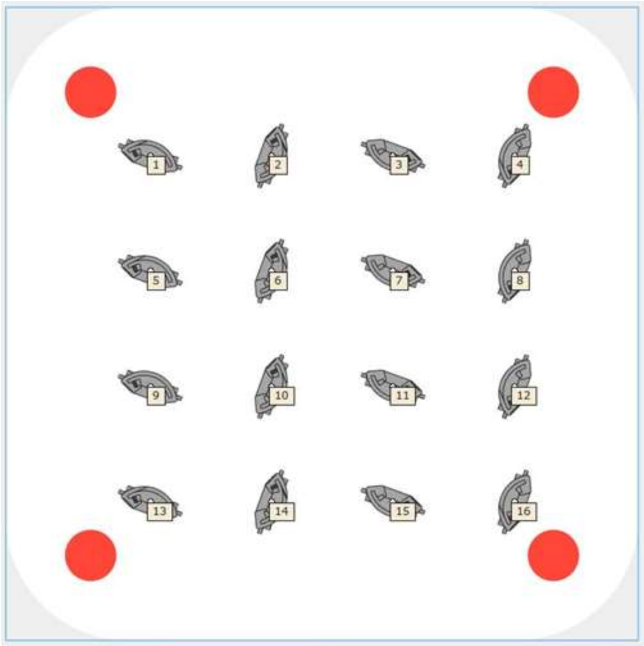
6.2 Results

As it turned out, going for the recommended VED really helps alot with the overall quality of parts. A significant change is seen with the density but also the surface quality is improved. This can be seen especially on the parameter V5, where the text is much more clear compared to others.

Worst parameter of buildjob 2 was V6. The increased power of V6 didn't get rid of porosity and edge tearing as well as other parameters. Porosity and edge tearing was seen in all of the parameters but definitely least with V5 (speed) and V6 (mix). Parameter V5 stands out with extremely smooth edges around the sample, resulting the best text quality so far.

TABLE 6. Buildjob 2 density and surface quality

V4			
V5			
V6			
V7			



(V4)	99.98	99.97	99.92	99.92
(V5)	99.93	99.98	99.98	99.97
(V6)	99.76	99.99	99.98	99.91
(V7)	99.95	99.98	99.97	99.97

PICTURE 4. Buildjob 2 densities in relation to the buildplate

6.3 Test batch and needed improvements

The newly found V5 parameters were put to test and a full batch of production ready keys were made. The quality seemed just as good as the samples but soon there was a problem found. When the keys were tested with UrbanAlps lock housing, the keys were getting stuck. Inserting and removing the keys was difficult and not acceptable for a production piece. It was soon discovered that the dimensions of the new keys were out of production tolerances.

The UrbanAlps stealthkeys with original parameters measure 11.30 ± 0.02 mm wide, and around 4,97+0.02 mm thick. With the newly found V5 parameter, the dimensions were around 11.34 ± 0.02 mm, and 5.02 ± 0.02 mm. To fix this problem with the parameters, two different tests were implemented.

7 BUILDJOB 3 & 4

Buildjobs 3 and 4, were implemented to research two different things. Dimension tolerances and structure quality. Since the Stealthkey dimensions got too large from slowing down the speed, it was suitable to see how much the keys decrease in size by increasing the speed step by step.

7.1 Strategy

Parameters V0 (original) and V5 have a difference only with laser speed. By doing a test with different lasers speeds between these two parameters, it is possible to see if the inner density is possible to reach with higher speed, which would result as faster production times and less energy used for the same result. If the similar densities can be reached with higher speeds, there is a chance that also the correct tolerances are achieved.

For buildjob 4, there were more changes done. In addition of changing speed, also beam compensation was changed from 0.07 mm to 0.09 mm to reduce the outer dimensions.

TABLE 7. Buildjob 3 & 4 parameters

V8 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	79,33 %	92,50 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	60.024	60.060

V9 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	80,67 %	94,25 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	59.032	58.945

V10 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	82,10 %	95,75 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	58.005	58.021

V11 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	83,52 %	97,50 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,07
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	57.013	56.980

V12 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	79,33 %	92,50 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	60.024	60.060

V13 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	80,67 %	94,25 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	59.032	58.945

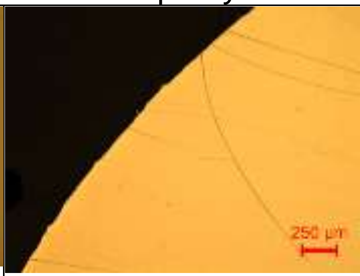
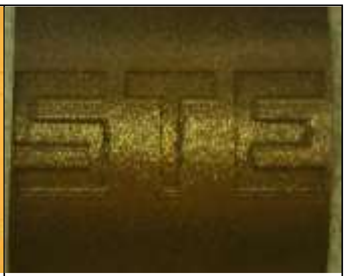
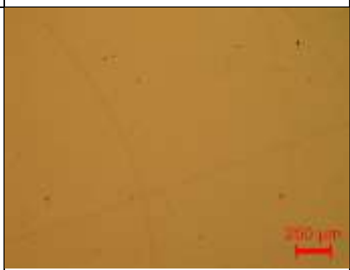
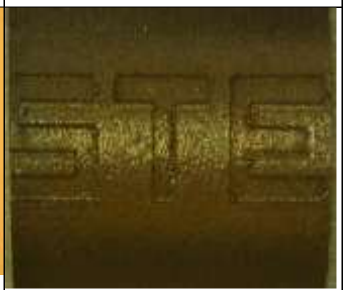
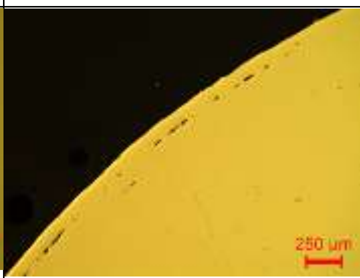
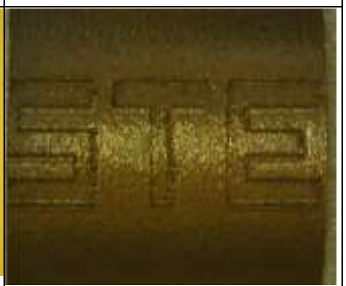
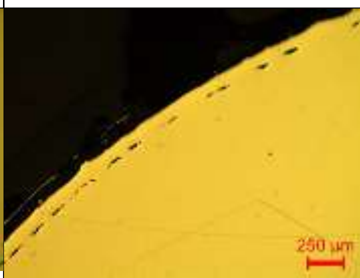
V14 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	82,10 %	95,75 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	58.005	58.021

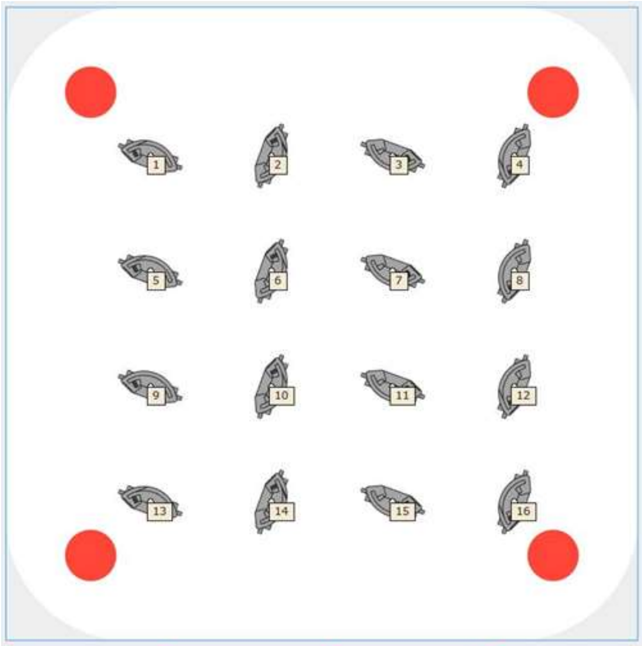
V15 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	83,52 %	97,50 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	57.013	56.980

7.2 Buildjob 3 results

When it comes to density it is clearly seen from buildjob 3 that the density gets worse with lower speeds (Parameters V10 and V11). Unfortunately with these buildjobs the samples were harder to research because of wearing on the polishing discs. The samples were scratched, which affects the density readings. Although the pictures still show clearly which parameters are suffering from pores and tearing alongside the edges. The parameter V5 is still the best parameter when it comes to density.

TABLE 8. Buildjob 3 density and surface quality

V8			
V9			
V10			
V11			



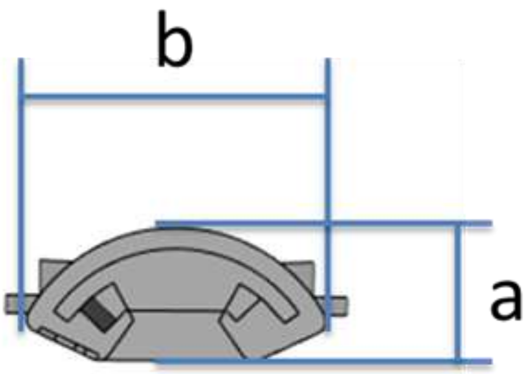
(V8)	99.90	99.75	99.76	99.83
(V9)	99.97	99.97	99.96	99.92
(V10)	99.83	99.89	99.81	99.87
(V11)	99.68	99.78	99.71	99.77

PICTURE 5. Buildjob 3 densities in relation to buildplate

The outer dimensions of buildjob 3 samples were not in tolerance, even those with faster laser speeds. The samples were measured using a calibre, which can allow some measurement errors, but with such high amount of samples showing the same measurements it’s safe to say that tolerances were not met. The effect of laser speed can be seen on the table 9. Samples 9 – 16 are starting to get slightly smaller in size.

TABLE 9. Buildjob 3 measurements

Key	a	b
1	5.02	11.33
2	5.02	11.34
3	5.03	11.35
4	5.03	11.34
5	5.04	11.34
6	5.04	11.35
7	5.03	11.33
8	5.03	11.34
9	5.02	11.34
10	5.02	11.34
11	5.02	11.34
12	5.04	11.34
13	5.02	11.34
14	5	11.32
15	5	11.33
16	5.02	11.33



PICTURE 6. Sample measurement methods

7.3 Buildjob 4 results

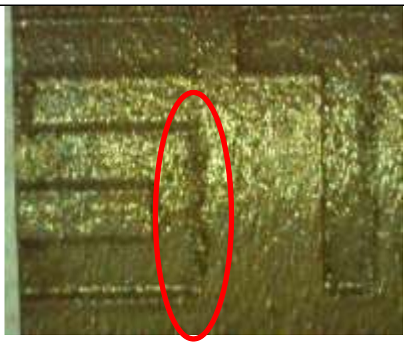
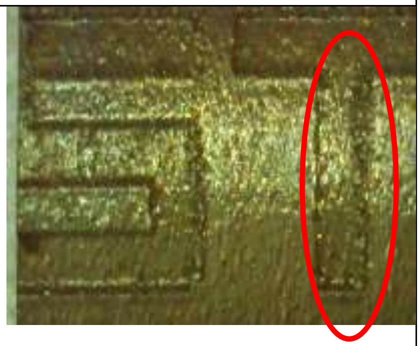
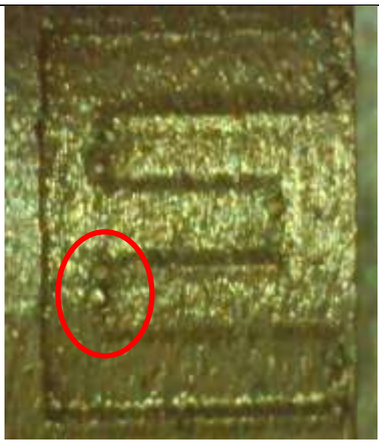
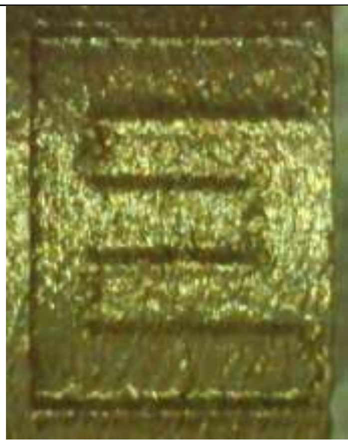
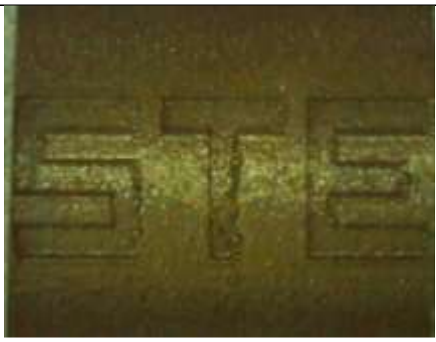
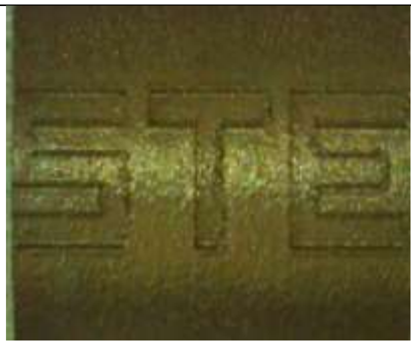
Buildjob 4 was not used for researching density, since the parameters for inner structure is identical with buildjob 3. What we can see from buildjob 4, is the difference in dimensions and surface quality compared to buildjob 3. The beam compensation was the key for achieving the right tolerances. As seen from the graph below, the dimensions are inside the orginal tolerances of 11.30 ± 0.02 mm wide, and around 4,97+0.02 mm in each parameter. Once again it can be seen that higher speeds result in smaller parts.

TABLE 10. Buildjob 4 measurements

Key	a	b
1	4.98	11.31
2	4.98	11.3
3	4.96	11.31
4	4.97	11.3
5	4.98	11.32
6	4.96	11.31
7	4.96	11.3
8	4.98	11.3
9	4.97	11.3
10	4.98	11.28
11	4.97	11.29
12	4.98	11.28
13	4.98	11.3
14	4.98	11.28
15	4.96	11.28
16	4.98	11.28

The differences on surface quality between the buildjobs was also noticable. Higher beam compensation results in slightly sharper letters. What seems to be happening with increased beam compensation is more controller meltpool for the downskin areas. Downskin is the part of object which is printed ”above nothing solid”. This can be seen as rough surfaces. When the beam compensation is increased, the laser spot is not moving as much towards the edge of the object as before. Beam compensation can’t affect the rough looking downskin itself, but for text and other visual details it keeps the meltpool closer to the structure, resulting in better quality along the edges.

TABLE 11. Buildjob 3 & 4 surface comparison

	Buildjob 3	**Buildjob 4**
Down skin effects can be seen a bit smaller on the buildjob 3.		
Buildjob 3 sample is suffering from balling effect caused by unstable meltpool. Also the lines are sharper on buildjob 4.		
Buildjob 4 looks over all more clean. This can be seen when looked at any edge of the samples.		

8 BUILDJOB 5

For buildjob 5 it was time to make a conclusion of the best parameter. For the buildjob, three parameters were implemented. The V5-B, V13 and new V16 parameter, a combination of the two mentioned. This buildjob would be that last one to be examined both inside and outside. Later tests would be of full sized keys for larger outer examination and comparing.

8.1 Strategy

The strategy for the buildjob was to see if the earlier results can be repeated and if the V16 parameter can outperform the previous V5-B and V13 parameters.

TABLE 12. Buildjob 5 parameters

V5-B Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	77,81 %	90,75 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.2	61.218

V13 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	80,67 %	94,25 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	59.032	58.945

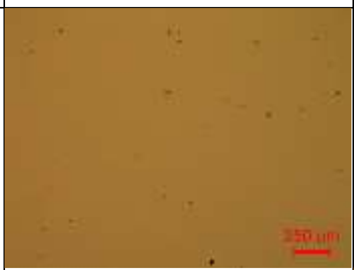
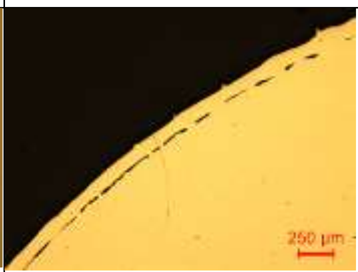
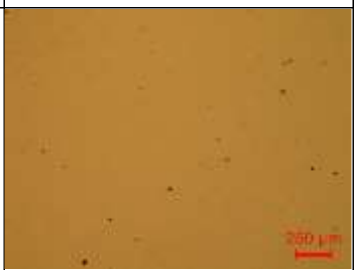
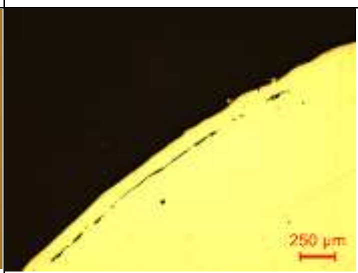
V16 Parameters	Hatching (Outer Hull)	Border
Speed (mm/s)	77,81 %	94,25 %
Power (W)	100 %	100 %
Hatch distance (mm)	100 %	-
Focus (mm)	4	3,5
Border distance (mm)	-	0,12
Beam compensation (mm)	-	0,09
Layer thickness (mm)	0,03	0,03
Volume Energy density (J/mm^3)	61.2	58.945

8.2 Results

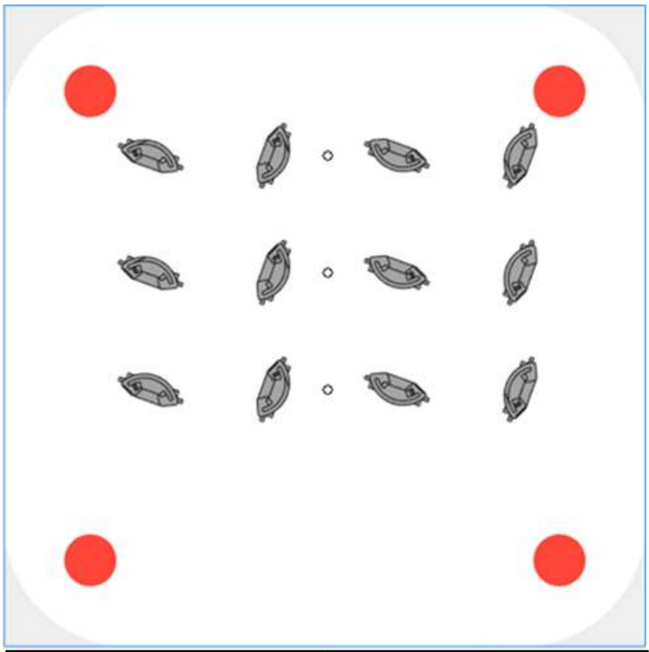
The results of buildjob 5 are somewhat contradictory. What can be seen from the latest metallographic inspection is that even the V5-B parameter is suffering from edge tearing and porosity. When earlier the density was near 100 %, now it was varying from those near perfect surfaces to samples with average density of 99.89 %. The porosity can be a result of a few different things.

The slm machines are delicate devices and require the perfect conditions to work properly. Airfilters are changed rather often to ensure good quality production. Used airfilter allows more particles into the buildchamber, which then affects badly with the melting process. The tearing of edges can be a problem related to heat but also parameters. Tearing happens because of inner stresses. This means that the border area is getting too much heat during building process, which leads to cracking while cooling down to room temperature. Parameter changes can fix this problem, but it's unclear wether this happens only with the small samples.

TABLE 13. Buildjob 5 densities and surface quality

V5B			
V13			
V16			

When looked into surface quality, no real differences can be seen. Downskin defects are seen in each sample, almost the same amount. When the parameters are looked as a whole, it is clear that the winner is parameter V5-B. The parameter is showing the best density numbers, the least amount of heat affected cracking and a good surface quality.



(V5-B)	99.9	99.89	99.95	99.94
(V13)	99.89	99.88	99.89	99.88
(V16)	99.84	99.9	99.9	99.88

PICTURE 7. Buildjob 5 densities in relation to buildplate

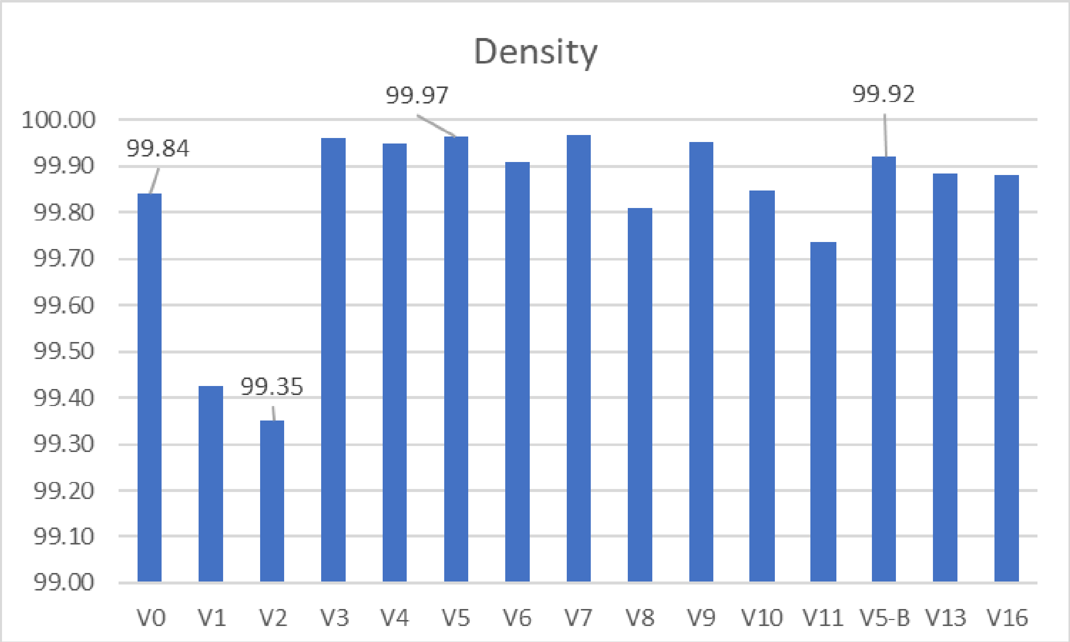
9 FINAL RESULTS

This part of the thesis is showing the final results by comparing the winning parameter V5-B to the original parameter V0. The comparison will demonstrate how much the parameters were improved physically and why it should be put to production use over the original parameters.

9.1 Density

Overall the density numbers were improved very well. When looked into just the best samples the difference was 0.11 % between the parameters. This doesn't sound much but the difference is huge when viewed visually. Even the worst sample of V5 parameter was nearly matching the best sample of original. This is a clear sign of improvement. Then there is consistancy. With V5 parameters the standard deviations between samples was 0.021 and with the slightly worse V5-B, 0.025. These numbers are over twice as low compared to original parameters. Consistancy has a huge impact to production quality and less deviations mean less chances for faulty parts.

FIGURE 1. Average densities of each parameter



The tearing effect seen on many samples can be fixed with decreasing border distance. This means stronger bond between the inner- and border structure, which even the high stresses can't break. The effect of border distance can be seen in the figure 2, where the amount of edge tearing is scored from 0 to 3 (0=no tearing, 1=minimal tearing, 2=medium tearing, 3=alot of tearing).

FIGURE 2. Effects of border distance to tearing

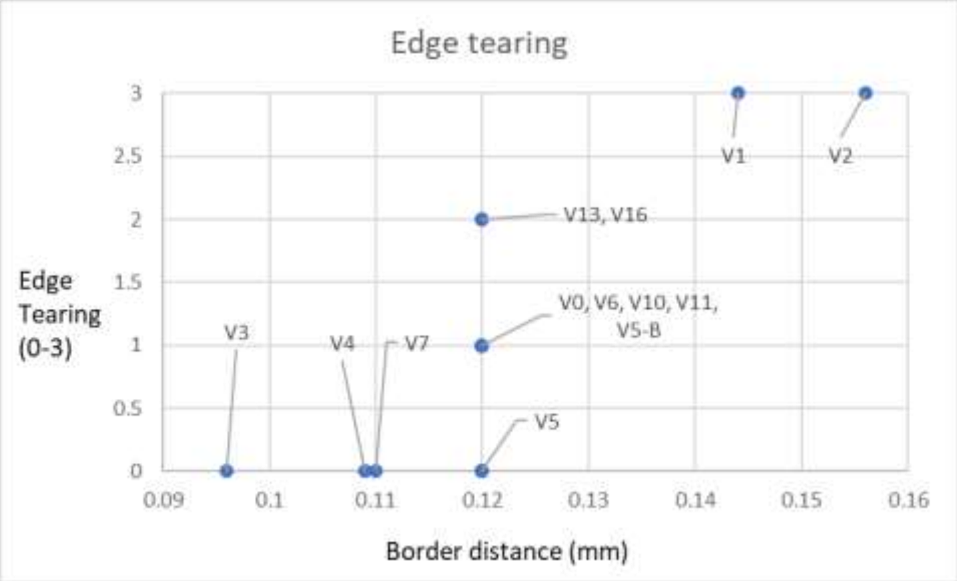
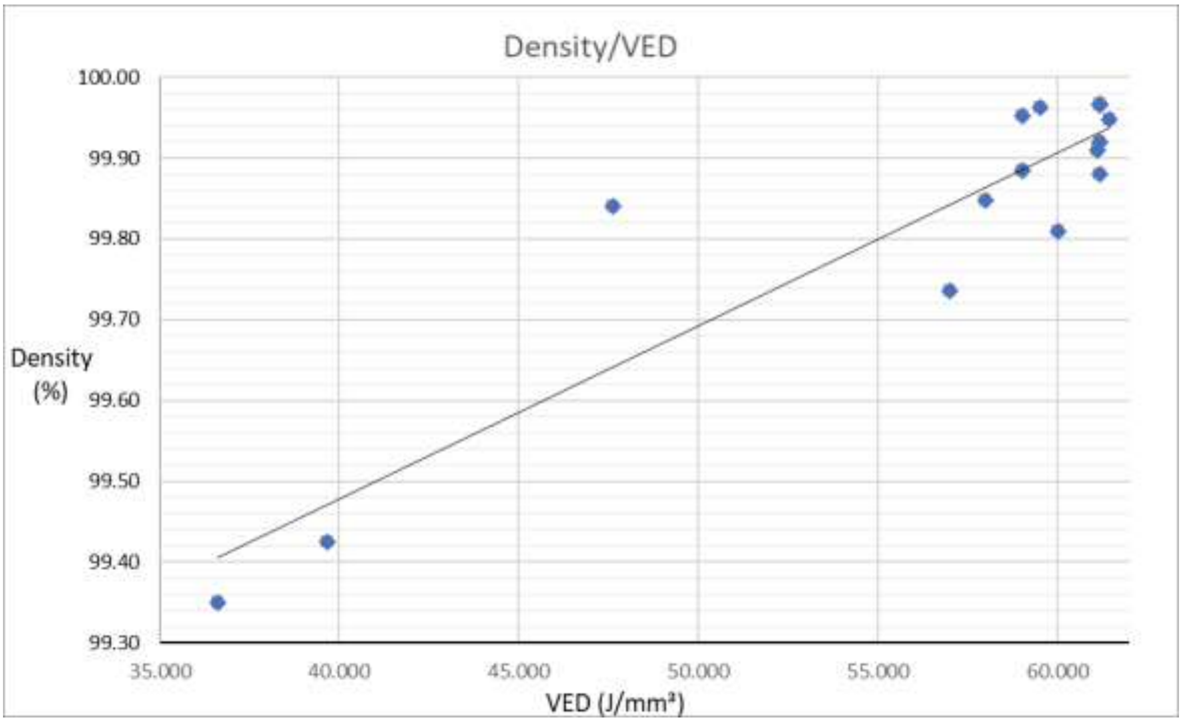


FIGURE 3. Effects of VED to density



The only downside of the improved density is energy usage. Volume energy density was increased from 47.6 J/mm³ to 61.2 J/mm³, meaning a rise of around 29 %. This ofcourse causes higher production costs. High quality parts are more expensive to make but in the end they can help with marketing and finding new customers. Also the parameters should be used to a cause. If a part doesn't simply require highest quality features, then original parameters can be used and thus, energy will be saved. The effects of VED to density can be seen in figure 3.

TABLE 14. Density- and standard deviation comparison between original and improved parameters

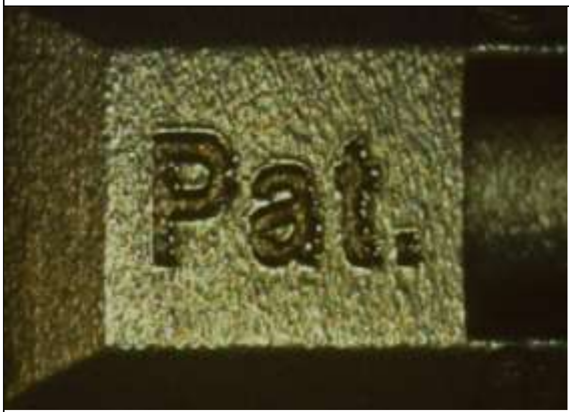
Parameter	Samples				Stand. Dev.
V0	99.82	99.76	99.91	99.87	0.056
V5	99.93	99.98	99.98	99.97	0.021
V5-B	99.9	99.89	99.95	99.94	0.025

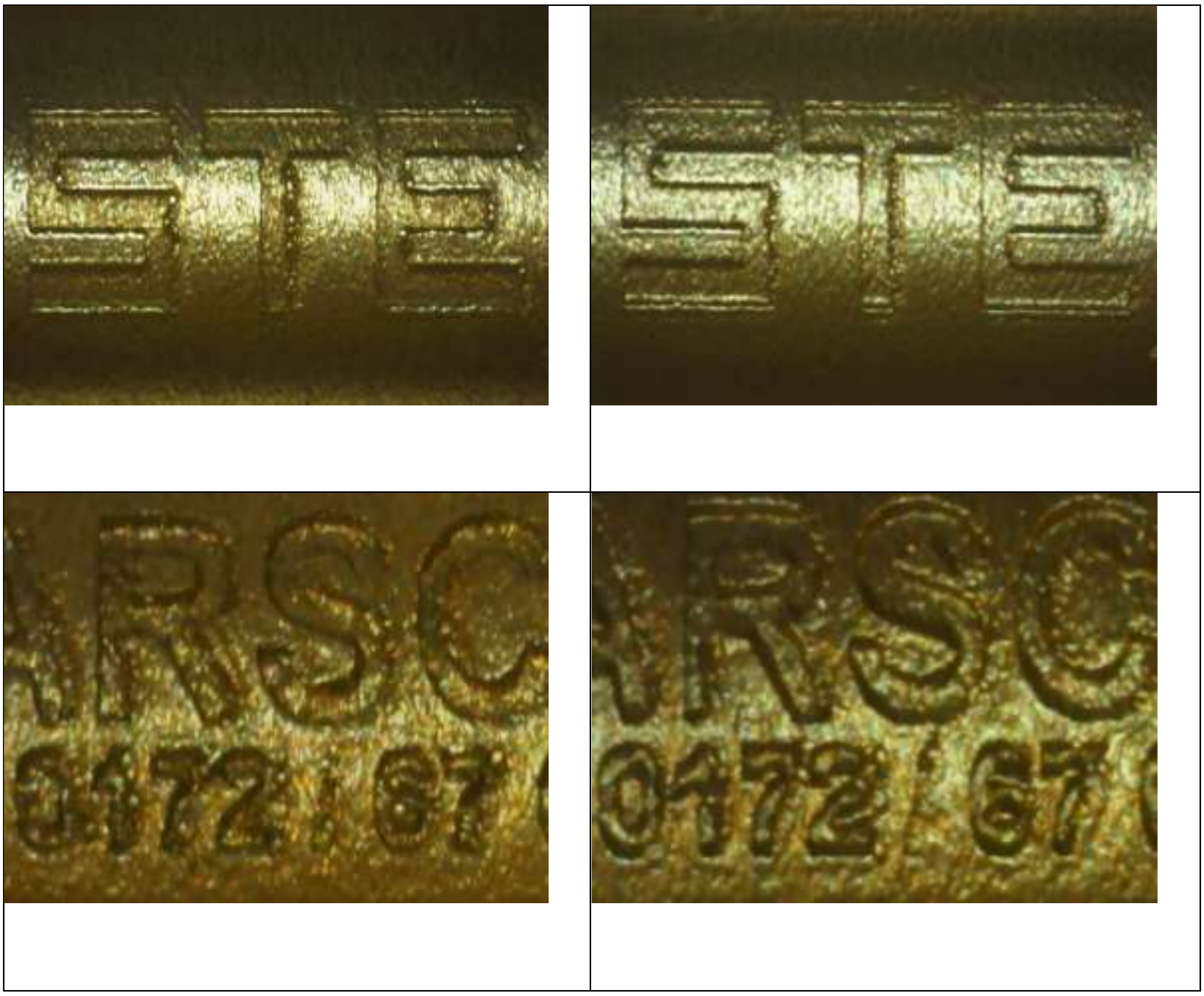
9.2 Surface quality

For the final surface quality comparison, there were full sized keys made. The keys quality difference can be seen immediately even without a microscope. The text on the keys of V5-B parameter is sharper, the lines are straight and the rough edges are noticed only when looked close upon. The V5-B parameter worked well especially for the smallest details such as phonenumbers, making a noticable difference on the readability between the keys.

When looked into table 15 pictures, also the surface looks smoother on the improved parameters. Unfortunately due to not having good equipment the surface roughness was impossible to measure reliably.

TABLE 15. Surface comparison between original and improved parameters

Old V0	**New V5-B**
	
	
	



9.3 Other benefits

It is clear that a normal household key doesn’t probably need a density of near 100 %, especially when made of super alloy like Inconel. But the parameters that were created withing this thesis can be used to print every Inconel 718 object the company will make. The new improvements guarantee higher strength and possibilites for smaller details to be made with good quality.

Good parameter knowledge is important for SLM technology companies. Small benefits over competition can affect great within market and sales. High density and possibility of smaller details acts a great deal with marketing and reputation in companies.

10 DISCUSSION

10.1 Results of the study

In this thesis, the optimization of parameters in SLM 3D-printing technology was studied using a narrowing down techniques. As a result, the company got an improved set of parameters for their In718-production. The surface quality turned out better than original parameters, giving a clear and more refined look for the product used for testing. Higher density for In718 products ensures tougher parts that can withstand more stresses, which is a very positive outcome for customers.

What was found out in the study was that the optimized volume energy density for In718 products was 61,2 J/mm^3, when using the V5-B parameters. This tells us that VED can be used as a guiding tool for the optimization work for selective laser melting. There are plenty of studies that are using VED as a measurement tool, but since the machinery and materials are so different, it is impossible to say that VED is always working when switching to a different setup. This is something that must be notified while optimizing SLM parameters.

The optimization work itself is a very straight forward work. Narrowing down technique is a good method for working, since the research data will be alot of comparisons. The results can be chosen easily by always choosing the best outcome and then moving on to the next test. With the setup used for the research, there were three main parameters that affected the results most. These paremeters were; laser speed, laser power and hatching distance. The main parameters work in relations to each other, which complicated the research at first, but again, the correct working methods of narrowing down, soon gave the idea of correct path for the study.

10.2 Analysis of the results

The thesis was succesfull and the main goals were achieved with good results meaning that the company got an improved set of parameters for their Inconel production. The biggest affection to the results was shown to come out from VED optimization. In this thesis the optimization was mostly done through changes to laser speed but this doesn’t necessarily mean that the same changes will result in same quality parameters. VED can be a good guiding tool, but since it is measured by three different parameters, it's obvious that the optimized VED of 61.2 J/mm³ can be calculated with completely unrealistic values.

The methods used for this thesis were working well through out the research. Some methods, like measuring the density of the samples could be done even more precisely by using Archimedes' principle. The software used for measuring densities works fine but can only give data of the exposed layer. By using Archimedes' principle, there wouldn't be any doubt about the density, since the value comes straight from the weight and volume measurements.

The study could have been done by using more strict type of research, such as Taguchi's method. This would have given the research perhaps a more clear template, but since the company working methods had been previously learned and used, there was no real need to change the working methods. All and all the research is using similar style of research methods as in Taguchis principles, but in a more flexible and free form, narrowing down the parameter values to create a better outcome.

10.3 Further studies

The budgeting was left out of the thesis because of running out of time. Future research in relation to this thesis could be done in many ways. The effect of border distances could be researched more and optimized, as well as a research could be made to see if similar results can be done without using as much energy. Also a research could be made where production costs and quality are optimized. There is always room for improvement, especially in a field so young as selective laser melting.

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