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CHARACTERIZATION OF DESIGN OF A PRODUCT FOR ADDITIVE MANUFACTURING

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TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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AM-tekniikalla valmistettavan tuotteen suunnittelun karakterisointi

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Tarkastajat: Professori Antti Salminen
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Työn tarkoituksena on kerätä yhteen tietoa lisäävästä valmistuksesta ja erityisesti tuotteiden suunnittelemisesta lisäävää valmistusta varten sekä suunnitella tuote valmistettavaksi lisäävää valmistusta käyttäen. Tässä työssä lisäävän valmistuksen menetelmänä käytetään metallien jauhepetifuusiota ja puhuttaessa lisäävästä valmistuksesta tässä työssä, viitataan juuri tähän valmistustekniikkaan.

Tämän työn kirjallisuuskatsaus käsittelee jauhepetifuusion toimintaperiaatetta, lisäävän valmistuksen eri vaiheita sekä lisäävän valmistuksen suunnittelusääntöjä. Kirjallisessa osassa myös käsitellään millä perustein tuotteita valitaan suunniteltavaksi lisäävää valmistusta käyttäen sekä esitellään menestyksekkäästi lisäävää valmistusta hyödyntäviä tuotteita. Kirjallisuuskatsaus toimii lukijalle pohjana kokeellisen osan ymmärtämistä varten.

Työn kokeellinen osa on jaettu kahteen osaan. Osassa A keskitytään kehittämään toimiva muoto itseään tukevien reikien ja kanavien tekemistä varten sekä löytämään sopivat parametrit niiden tukirakenteille. Osassa B keskitytään suunnittelemaan tuote lisäävää valmistusta käyttäen.

Osan A tuloksena esitellään itseään tukeva putken muoto ja tulokset sen analysoinnista visuaalisesti sekä 3D-skannausta hyödyntäen. Osan B tuloksena esitellään suunniteltu tuote sekä verrataan sen ominaisuuksia alkuperäiseen tuotteeseen.

ABSTRACT

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Characterization of Design of a Product for Additive Manufacturing

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91 pages, 77 figures, 3 tables and 2 appendices

Examiners: Professor Antti Salminen
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Keywords: additive manufacturing, design for additive manufacturing, powder bed fusion, 3D printing

The purpose of conducting this thesis is to gather around information about additive manufacturing and to design a product to be additively manufactured. The specific manufacturing method dealt with in this thesis, is powder bed fusion of metals. Therefore when mentioning additive manufacturing in this thesis, it is referred to powder bed fusion of metals.

The literature review focuses on the principle of powder bed fusion, the general process chain in additive manufacturing, design rules for additive manufacturing. Examples of success stories in additive manufacturing and reasons for selecting parts to be manufactured with additive manufacturing are also explained in literature review. This knowledge is demanded to understand the experimental part of the thesis.

The experimental part of the thesis is divided into two parts. Part A concentrates on finding proper geometry for building self-supporting pipes and proper parameters for support structures of them. Part B of the experimental part concentrates on a case study of designing a product for additive manufacturing.

As a result of experimental part A, the design process of self-supporting pipes, results of visual analysis and results of 3D scanning are presented. As a result of experimental part B the design process of the product is presented and compared to the original model.

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LIST OF ABREVIATIONS

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AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Assisted Design
CFD	Computational Fluid Dynamics
DFAM	Design for Additive Manufacturing
FEM	Finite Element Method
PBF	Powder Bed Fusion
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SSS	Solid State Sintering
SLI	Slice Layer Interface
STL	Stereo Lithography

1 INTRODUCTION

Additive manufacturing of metals has been studied extensively in recent years. The layer wise functional principle and development of additive manufacturing has enabled the use of additive manufacturing in designs, which would be impossible to manufacture with traditional manufacturing methods. Design for additive manufacturing (DFAM) has been studied and used by largest aircraft manufacturers of the world such as Boeing and Airbus for producing light weight parts and advanced turbine components for aircraft (Klocke et al. 2014).

The relationship between structures of nature and effective design has been recognized (Emmelmann et al., 2011A). Recently, there has been wide interest applying additive manufacturing to hydraulics. DFAM has been applied for designing of hydraulic manifolds leading to weight reduction and increase in the performance of the hydraulic systems (Saunders 2015).

Even though DFAM has been studied recently, the research is usually done inside companies and therefore it is not completely published and publicly available. Thus the published case studies of applying DFAM are giving the reader only limited information about applying DFAM to product design. Hence additional publicly available publications of applying DFAM in practice are needed. The purpose of this thesis is to give the reader a wide range of information about DFAM. This is done by gathering information about design rules for AM (Additive Manufacturing), presenting AM success stories and by introducing a design of hydraulic manifold for additive manufacturing.

2 AIM AND PURPOSE OF LITERATURE REVIEW

The aim and purpose of the literature review of this thesis is to give the reader the information necessary to understand the experimental part. This is done by introducing the functional principle of additive manufacturing and selective laser melting, introducing and explaining the design rules for SLM (Selective Laser Melting) and their relationship between building defects, explaining what kind of parts and products should be chosen for additive manufacturing and by introducing DFAM success stories.

3 ADDITIVE MANUFACTURING

The terminology referring to additive manufacturing is complex and often used improperly. To ease the reader to understand the topic, this chapter defines what additive manufacturing is and presents the most important terminology when discussing about additive manufacturing.

According to the ASTM (American Society for Testing and Materials) international committee standard F2792-12a, additive manufacturing is a process of making objects from 3D-model data, usually layer upon layer as conversely to conventional manufacturing methods (ASTM F2792-12a).

The first term for AM processes was rapid prototyping (shortened as RP). The term RP was used for presenting technologies manufacturing objects directly from 3D-model data such as visual models and prototypes. The second phase of AM technology was rapid tooling (RT) and it was used for purposes such as manufacturing of tools for injection molding and die casting- The third phase of AM is rapid manufacturing (RM) and it is used in automotive, aerospace and in many other industries. Rapid manufacturing is used to manufacture consumer goods such as hearing aids, art and jewelry and gifts and for medical applications such as orthopedic implants and dental products as well. The use of term rapid prototyping is not recommended anymore since the current technologies are capable of manufacturing ready products, not only prototypes. Use of the popular term 3D-printing is as well not recommended as it refers to inkjet printing based technology even though the term has started to gain ground referring to additive manufacturing. (Gibson, Rosen & Stucker, 2010, p. 1–8.)

Additive manufacturing enables manufacturing of complicated structures, which would not be possible to manufacture with any subtractive manufacturing methods, such as drilling or machining (Moylan et al., 2012, p. 1). The development of RP processes has enabled manufacturing of functional metallic parts with additive manufacturing (Ponche et al., 2014, p. 389).

4 POWDER BED FUSION

According to the ASTM standard F2792-12a, powder bed fusion is “an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”. The source of thermal energy needed for the process is produced by either laser beam or electron beam. (ASTM F2792-12a). Powder bed fusion process is based on layer wise scanning of powder formed material with a focused heat source to produce 3D-shaped objects. (Islam et al., 2013, p. 835.)

First PBF (powder bed fusion) process for plastic materials commercialized was selective laser sintering (shortened as SLS) process, which was invented in the University of Austin, Texas. In 1980´s the SLS process was used to produce plastic prototypes but the process is nowadays used also to manufacture end use products. The range of materials, which can be utilized is wide and it contains metals, polymers, ceramics and composites but SLS (i.e. the sintering process) is usually used for plastics and very seldom for metals. Powder bed fusion processes have become widely used around the world and the material properties of the end product are competing with material properties made with conventional manufacturing processes. All the powder bed fusion based processes share the same principles as the SLS process, which are presented in the next chapter. (Gibson et al., 2010, p. 107.) In this thesis powder bed fusion is presented by introducing the selective laser melting (SLM) process.

4.1 Selective laser melting

Selective laser melting is a powder bed fusion based laser process and is carried out in nitrogen atmosphere in a closed chamber. The recoater (leveling system) spreads thin layer of powder to the building platform. (Gibson et al., 2010, p. 107–109.) This can be seen from the Figure 1.

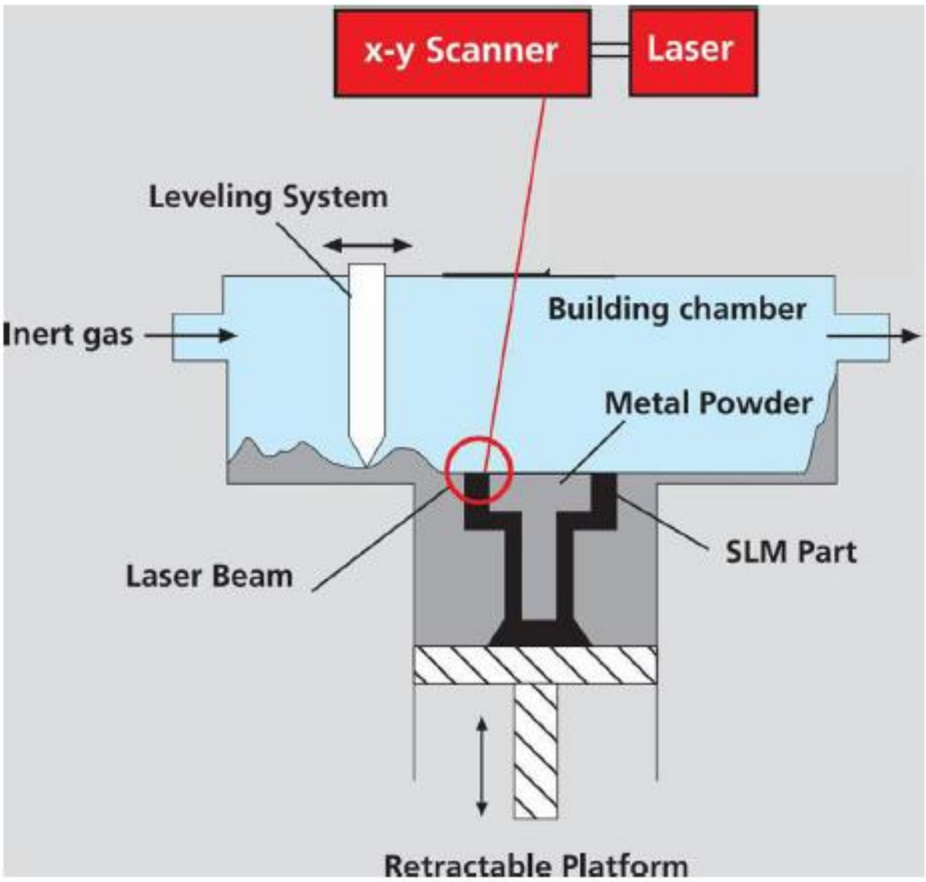


Figure 1. SLM machine layout (Zhang, Dembinski & Coddet, 2013, p. 22).

Figure 1 illustrates a typical SLM machine layout. Powder spread on the building platform is kept close to the melting temperature of the metallic powder material. Preheating of the powder by heating the building platform is done to minimize the laser energy needed for the fusion and to prevent warping of the part being build (warping means bending of the workpiece caused by heat fluctuation, warping and other build deformations will be explained in detail in chapter 6). (Gibson et al., 2010, p. 107–109.)

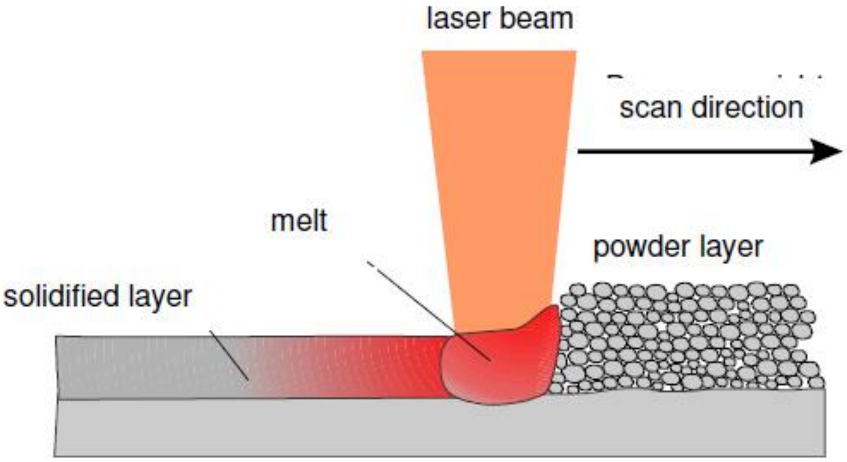


Figure 2. Principle of SLM process (Meiners 2011, p. 10).

As Figure 2 illustrates, the laser beam scans the desired regions of the powder bed using x- and y-mirrors to fuse the desired cross section. The powder, which is not fused remains in the building platform as it was before the scanning and serves support for the next layers of powder to be spread. (Gibson et al., 2010, p. 107–109).

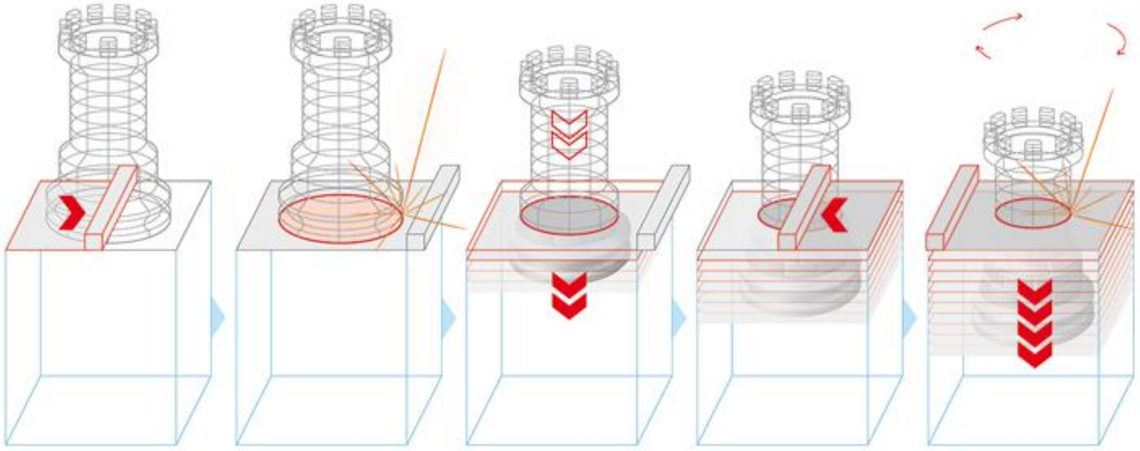


Figure 3. Functional principle of selective laser melting process (modified from: EOS 2016).

As Figure 3 presents, after this cycle is performed, the building platform is lowered distance of one layer thickness and the recoater spreads a new layer of powder from the feed container to the building platform and the new layer is fused by the laser beam. These steps are repeated until the part being built is finished. The part is now let to cool down before it can be exposed to the normal atmosphere and temperature and handled safely. Exposure to normal room temperature and atmosphere too early could cause warping of the part because it would cool unevenly. The final part of the process is removing the excess powder and removing of the supporting structures from the part. (Gibson et al., 2010, p. 107–109.)

SLM process is complicated because it involves several different physical phenomena and the melt pool is dynamic. Every layer must be successfully formed for the next layers to be built without defects. (Bauereiβ, Scharowsky & Körner, 2014, p. 2523.)

SLM process includes several steps from slicing the 3D-model CAD-data (computer assisted design) to designing support structures (Thomas, 2009, p. 17). These steps will be elaborated later in this thesis.

4.2 Binding mechanisms in powder bed fusion

The terminology dealing with powder bed fusion is confusing and different manufacturers use different names from their technologies according how the fusion occurs in the process (Gibson et al., 2010, p. 105).

Laser based powder bed fusion processes are divided into four different categories by the binding mechanism according to Kruth et al. (2005):

1. Solid state sintering (SSS)
2. Chemically induced binding
3. Partial melting (liquid phase sintering)
4. Full melting

Only full melting is elaborated in this thesis because it is the mechanism utilized in selective laser melting of metallic materials.

Full melting i.e. SLM was introduced for the need to manufacture materials that are dense, and have material properties close to those of the materials manufactured with conventional processes. Products made with full melting process have also no need for time consuming post processing such as products made with other binding mechanisms. In full melting the whole area of material subjected to thermal energy is melted to depth surpassing the depth of layer thickness. Full melting is commonly used for powder bed fusion processing of metal alloy powders. (Kruth et al., 2005 p.31; Gibson et al., 2010, p. 112.)

5 GENERAL PROCESS CHAIN IN ADDITIVE MANUFACTURING

PBF process as well as other AM processes can be divided to a sequence of operations carried out in an order. This process chain is a simplified example and some machines and processes may require up more operations to be carried out. (Gibson et al., 2010, p. 43.) The object of this chapter is to familiarize the reader with the most important steps in additive manufacturing.

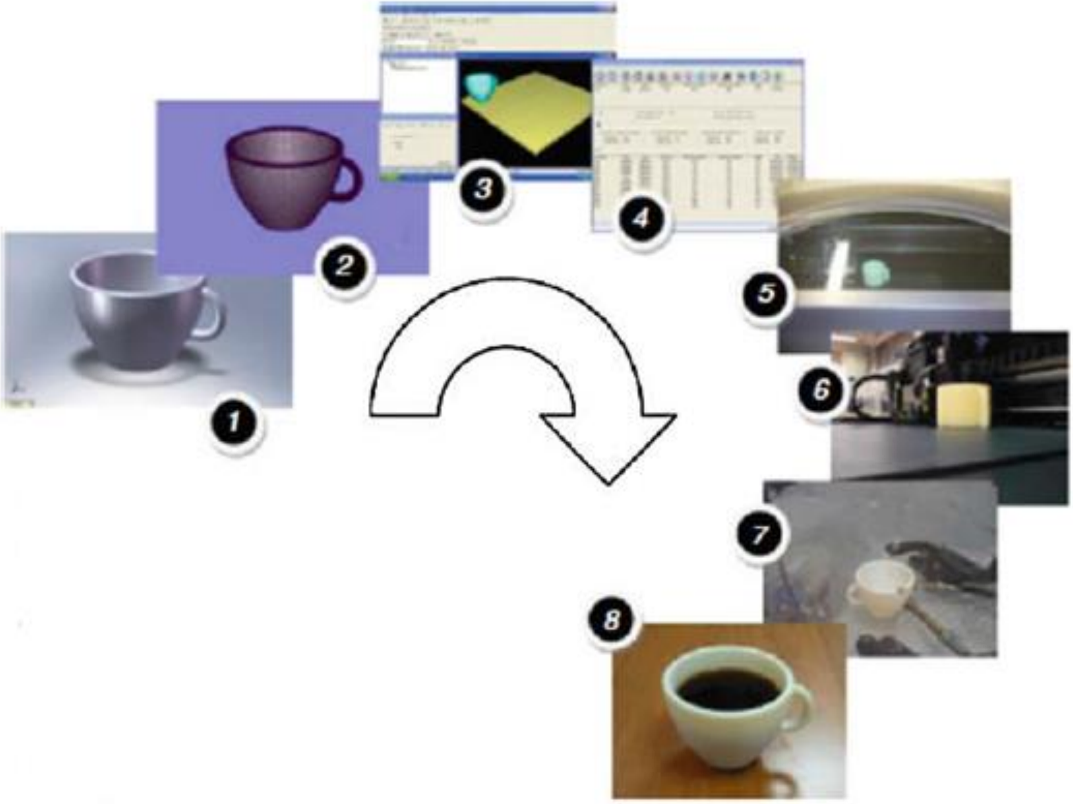


Figure 4. 8 phases in additive manufacturing (modified from: Gibson et al., 2010, p. 45).

As it can be seen from Figure 4, additive manufacturing can be divided to eight phases:

1. Conceptualization and CAD
2. Conversion to STL
3. Transfer to AM machine and STL file manipulation
4. AM-machine set-up
5. Building process

6. Removal and clean-up
7. Post-processing
8. Application

5.1 Conceptualization and CAD

Design of an AM-manufactured product begins with generating an idea for a function of the product. After the function is generated the appearance of the part is visualized. Next step is to transform the concept in to a 3D model. This can be done with CAD software (such as SolidWorks) or with 3D scanning an object or part. The 3D model created needs to be watertight, meaning that it must not have gaps in it. Gaps in the model can result in poor build quality or interruption of the building process. (Gibson et al., 2010, p. 43–45.)

5.2 Conversion to STL

Before transferring the 3D-model to the AM machine, the file must be converted to STL format (comes from the word STereoLithography). An STL file is an approximation from the original solid models surface and it consists of triangular facets. The number and size of triangles partly define the final surface quality of the product to be made. These parameters can be adjusted when saving an STL file but the minimum resolution of the machine has to be the defining factor. Incorrectly defined parameters could lead to an end result where obvious triangles could be seen in the surface of the product. STL file conversion process is an automated process but there can be flaws in it. This has led to development of software to identify and fix these flaws. (Gibson et al., 2010, p. 45–46.)

5.3 Transfer to AM machine and STL file manipulation

After transferring an STL file to the AM machine, several operations are usually to be made before the part can be manufactured. Part can be modified, manipulated and adjusted in several ways after ensuring that the part is the proper one. The part has to be positioned to the building platform and the size of the part can be scaled if necessary. It is also possible to manufacture multiple copies at the same time or add completely other parts to the same building process. Software for STL file manipulation enable adding marks to the parts to identify them and specific software are able to split the part to several parts (this can be useful if the part is too large to be manufactured in one piece). (Gibson et al., 2010, p. 47.)

5.4 AM-machine set-up

The amount of set-up required is machine and process dependent. AM machines, which are developed to use only few different construction materials and to use only few layer thicknesses, allow only small amount of changes to be made to the set-up whereas AM machines, which are designed to use multiple construction materials and layer thicknesses allow multiple set-up changes. These kind of machines and processes require more to optimize the process. AM machines usually allow the operator to save the parameters, which reduces the time needed to set-up the machine if manufacturing similar parts in the future. It is possible to manufacture a part with unsuitable parameters but it usually leads to unacceptable quality of the part. Machine set-up does not consist of parameter set-up only. There are often physical preparations to be made also. These operations can be automated in some machines but they are usually made manually by the operator. The machines using powder need to be filled with a proper amount of powder and the machines using a build plate, the plate must be leveled in x-, -y and z- directions. (Gibson et al., 2010, p. 47–48.)

5.5 Building process

Even though AM processes are automated processes, the first phases need to be either manually controlled or at least monitored by the machine operator. After these phases the computer controlled automated layer based manufacturing takes place. The AM machine repeats these building phases until the part is complete. (Gibson et al., 2010, p. 48.)

5.6 Removal and clean-up

Removal and clean-up is necessary after every AM process at certain level and in many cases this stage is challenging and time consuming. The removal and clean-up is easier in the processes in which support materials are not used than in the processes in which the part is supported with support material. Support materials can be easily removed or removal of supports may require significant amount of manual labor depending on the process and materials used in it. Metal supports require the most amount of manual labor. First the part has to be removed from the building plate and then the metallic supports need to be removed without damaging the part itself. This can be challenging and requires skills and experience from the operator. (Gibson et al., 2010, p. 48–49.)

5.7 Post-processing

Post processing stage is for preparing the part for its final use. The work is often done manually and it can involve several types of finishing like abrasive methods or coating. The amount of post processing required is specified by the application and it varies from very little amount to large amount. Machining may be required if the surface quality of the part that is limited by the machine properties does not meet the requirements for final use of the part. Specific AM processes produce fragile parts that require infiltration in an oven or surface coatings to improve the strength of the part. (Gibson et al., 2010, p. 49.)

5.8 Application

The final stage in the AM-process chain is the use of the part. As a result of AM processes differing from traditional manufacturing processes, it must be considered that the parts manufactured with AM differ from the ones manufactured with traditional processes (such as casting and molding). Parts manufactured with AM processes may have flaws caused by insufficient bonding, which may weaken the parts ability to withstand mechanical stress. AM processes lead often to anisotropic properties of the part. These features of the parts manufactured with AM might be a good thing or a bad thing depending on the application. The most important thing is that the designer has to take these possible features into account. (Gibson et al., 2010, p. 49.)

6 DESIGN DETAILS FOR ADDITIVE MANUFACTURING

This chapter gathers together design rules and important things to consider when designing a product for PBF of metals. Before going to actual design rules, background information from support structures, part orientation and building deformations is presented. New design strategies such as biomimicry and part consolidation are introduced for the reader to be able to design products that are designed especially for additive manufacturing.

6.1 Background knowledge of support structures

Support structures are required in metallic PBF for attaching the workpiece firmly to the building plate and for conducting the heat away. Support structures are also used to support overhang structures and to avoid deformation of them. (Järvinen et al., 2014, p. 73.) Figure 5 illustrates a part without supports structures (Figure 5a) and a part with supports structures (Figure 5b). The green material in the figure is the support material.

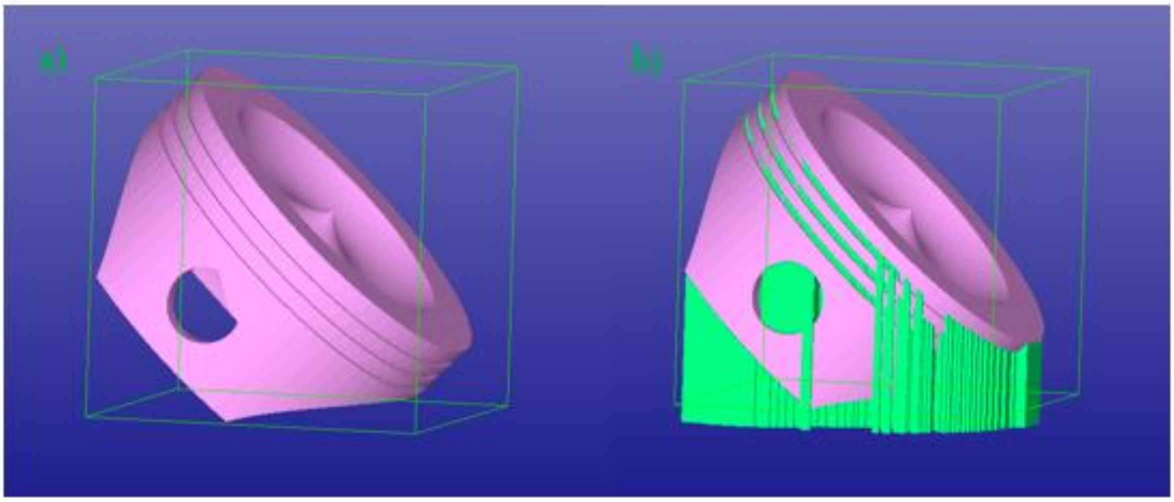


Figure 5. Workpiece a) without and b) with support structures (made with DeskArtes 3Data Expert).

Overhang structures are supported only by the powder bed under it so they are more vulnerable to building defects caused by gravity and insufficient ability to conduct the heat away. Layer wise processes as metallic PBF require formation of solid and stable layers for the following layers to be formed without defects or deformation. The influence of support structures in metallic PBF is significant for manufacturability and quality of the part.

(Järvinen et al., 2014, p. 73.) The amount of support structures can be reduced by designing the geometry to be self-supporting (Thomas, 2009, p. 159).

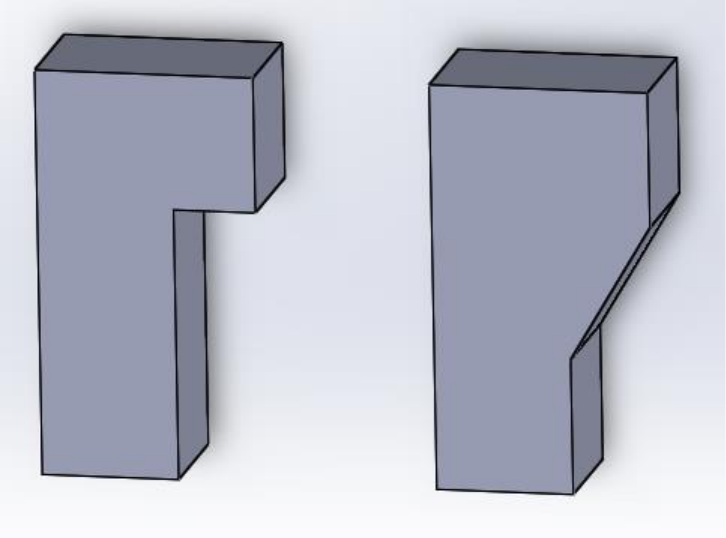


Figure 6. Geometry redesigned to be self-supporting (made with SolidWorks).

Figure 6 presents a geometry that requires supports (left part with the overhanging ledge) and a geometry that does not (right part with no overhang). This will be elaborated later in this thesis.

Even though the support structures are inevitable, the use of supports increases the building time (and costs at the same time) and complicates the cleaning and post processing stage. The support structures can be divided into two segments. The main support structure and the teeth that connect the main support structure to the part. (Calignano, 2014, p. 203.)

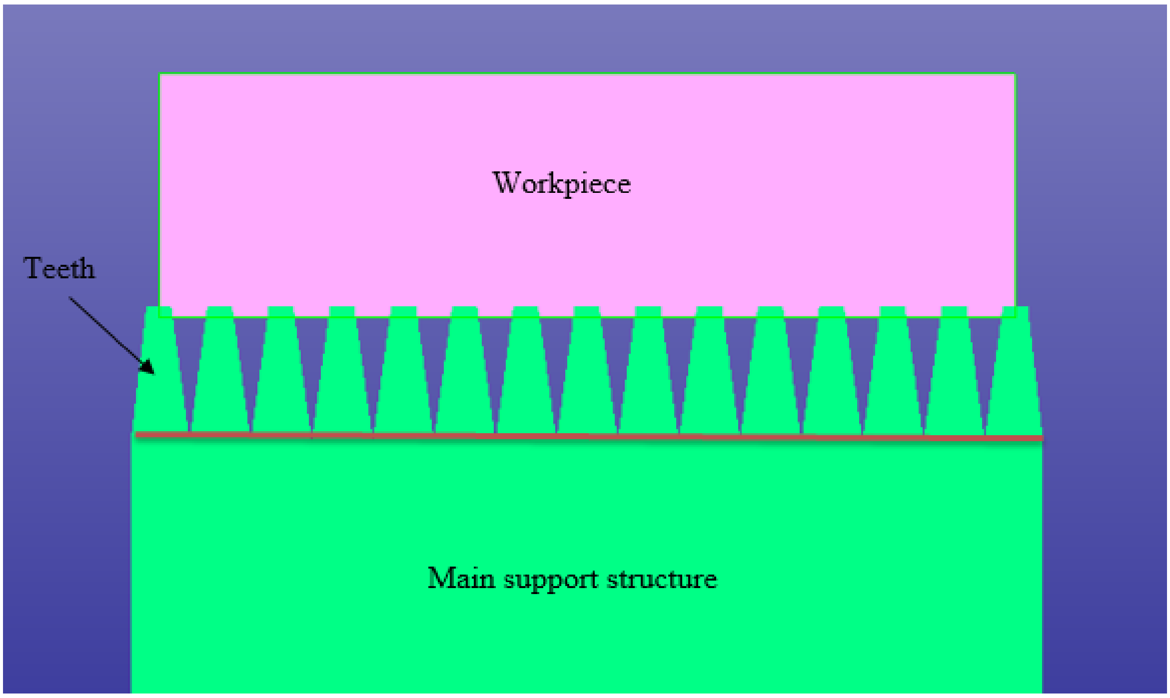


Figure 7. Support structure with connecting teeth (made with DeskArtes 3Data Expert).

As Figure 7 illustrates, the main support structure is connected to the workpiece with the connecting teeth (Calignano, 2014, p. 203).

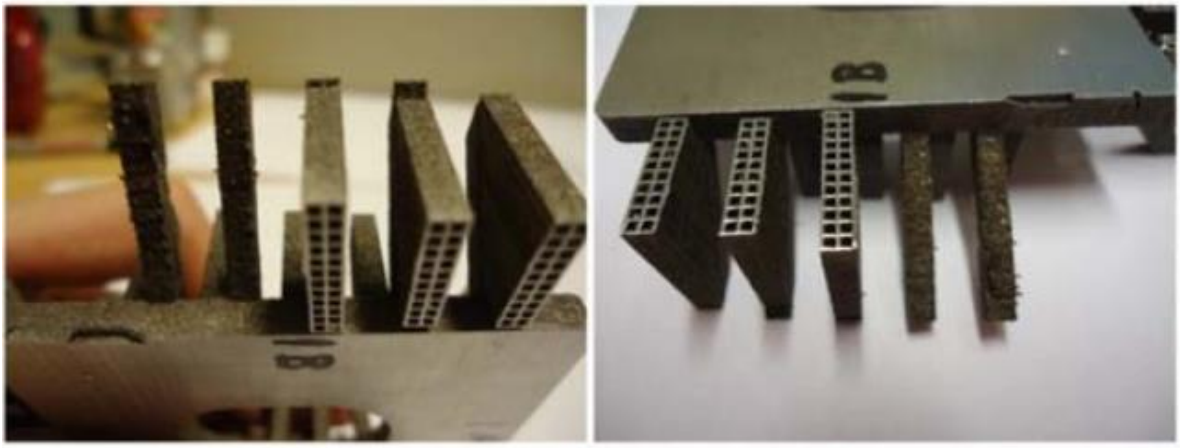


Figure 8. Support structures after the part is removed from the platform (modified from: Järvinen et al., 2014, p. 78).

As Figure 8 illustrates, the surface quality of the surface between the part and support structures depends how well the teeth and supports are designed. In this case the connection between the teeth and the bars was not sufficient and the supports have been removed easily.

This leads to bad surface quality of the bars as it can be seen from the Figure 8. (Järvinen et al., 2014, p. 78.)

The use of teeth eases the removal of the support from the part and enhances the surface quality. The teeth must be optimized in such way that supports can be removed without damaging the part itself. Teeth connected to workpiece too steadily must be removed by sawing or grinding, which can also damage the workpiece. (Calignano, 2014, p. 203.)

6.2 Background knowledge of part orientation

Part orientation affects the amount of support structures needed. When comparing two building orientations, the better one is usually the one with less support structures. The orientation of the part affects the building speed and quality of the part as seen from the Figure 9. (Thomas, 2009, p. 158–159.)

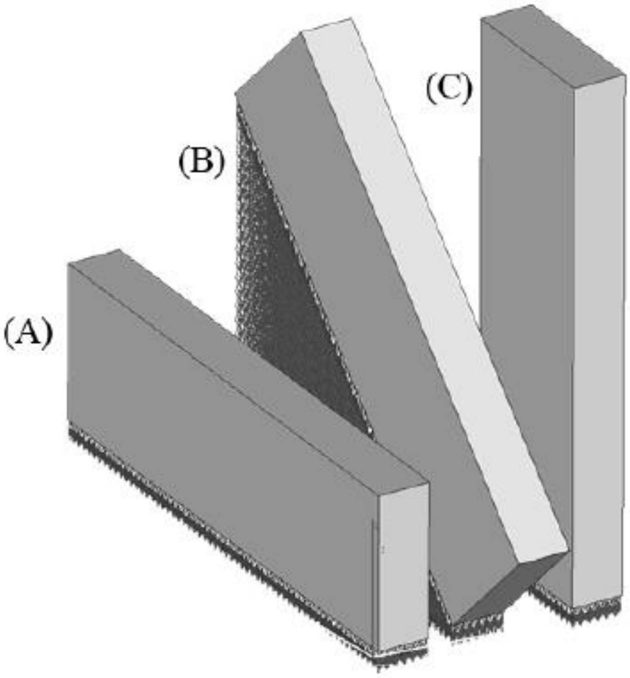


Figure 9. Effect of part orientation (Thomas, 2009, p. 159).

As it can be seen from Figure 9, orientation C gives the best surface quality for the part being the slowest orientation to build at the same time. Orientation A is the fastest orientation to build but results in worse quality of the part and excess amount of support structures required. Orientation B might be considered if the surface quality of the part is not crucial and the building time and costs are not limited. (Thomas, 2009, p. 159.) The correct orientation for each individual part depends from what is the most desired factor: the surface quality or the build speed (Gibson et al., 2010, p. 56).

6.3 Background knowledge from build deformations

Building deformations can take place during the building process due to process limitations. Sagging is a typical deformation occurring in overhanging surfaces such as ledges and top of holes and channels. (Thomas, 2009, p. 156–157.)

Figure 10 illustrates sagging in top of a round hole, manufactured perpendicular to building direction. Sagging occurs when laser radiation heats also part of the loose powder under the recently recoated layer of powder, as opposed to the optimum situation in which the newly recoated layer of powder is bonded to a solidified layer or layers. This results in deformed and oversized mass of powder. Support structures cannot prevent sagging completely. (Thomas, 2009, p. 156–157.)

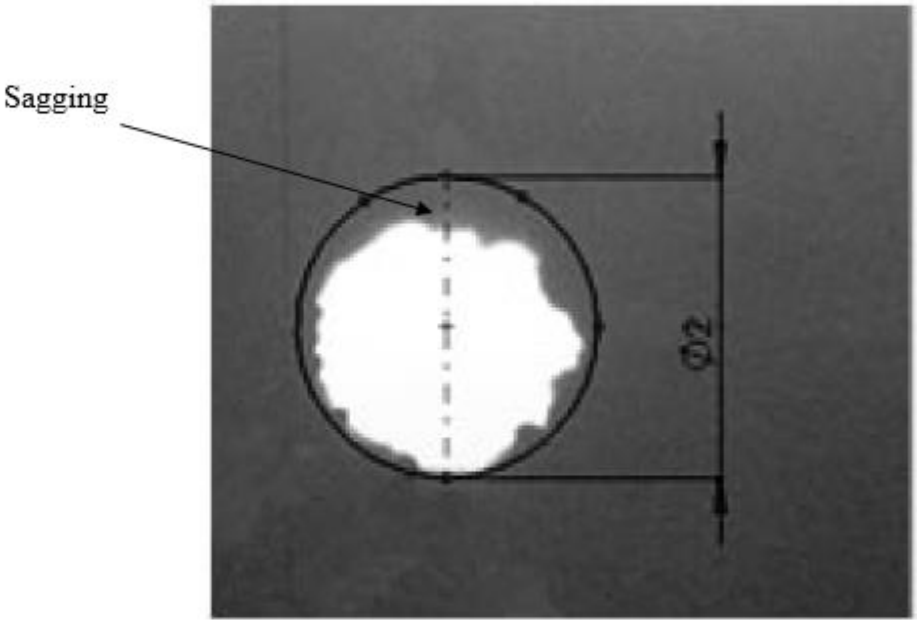


Figure 10. Demonstration of sagging (modified from: Thomas, 2009, p. 112).

Another typical build deformation is curling. Curling occurs when unsupported areas in a powder bed are affected by the laser and rapid heating and cooling takes place curling the material away from the surface of the powder bed. (Thomas, 2009, p. 157.)

As Figure 11 illustrates, the surface of the overhanging ledge starts to curl away as the length of the unsupported overhanging ledge increases (Thomas, 2009, p. 93).

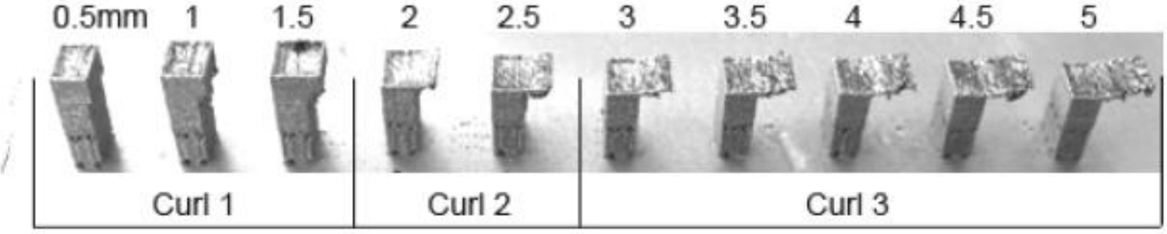


Figure 11. Curling effect (Thomas, 2009, p. 93).

Figure 12 presents curling occurring during SLM process caused by unsupported overhang. Curling can be prevented by using support structures to conduct the heat away from local areas more efficiently. (Thomas, 2009, p. 93, 157.)

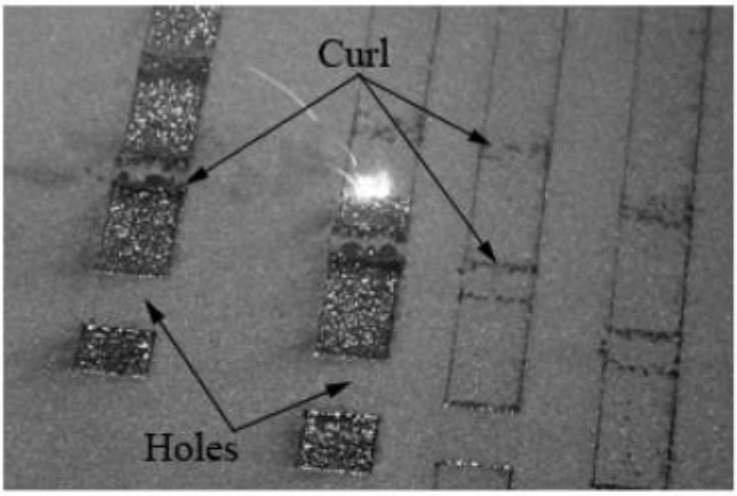


Figure 12. Curling effect during SLM process (Thomas, 2009, p. 67).

As it can be seen from Figure 13, uncontrollable curling caused by lack of support structures can lead to destruction of the geometry and part. The radius of the unsupported hole-geometry that was tested in Figure 13 is 10 mm. (Guido & Zimmer, 2015, p. 666.)

Figure 13. Result of uncontrollable curling (modified from: Guido et al., 2015, p. 667).

Figure 14 illustrates a lattice support structure created to conduct the excessive heat away and to support the overhanging area enabling the build of the cantilever part without curling or sagging (Thomas, 2009, p. 157).

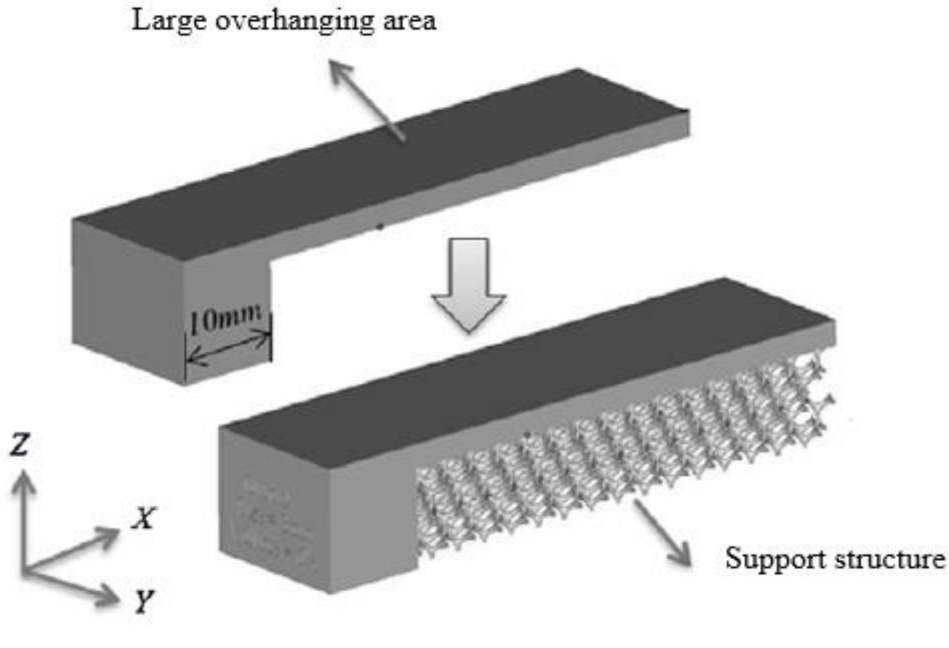


Figure 14. Support structure to avoid curling and sagging (modified from: Hussein et al., 2013, p. 1021).

Sections close to where sagging or curling occurs also small amount of shrinkage can take place (Thomas, 2009, p. 122, 156–157). This is presented in Figure 15.

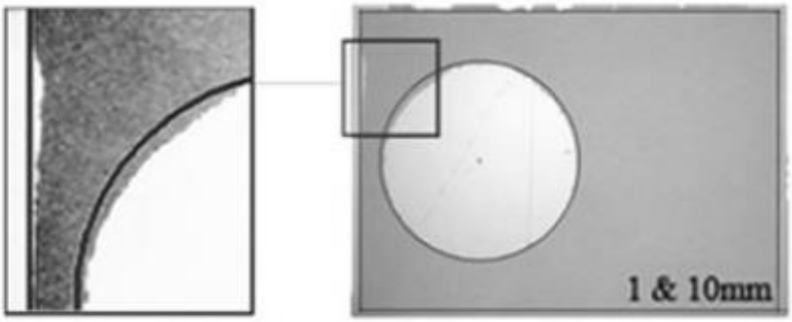


Figure 15. Shrinkage related to curling and sagging (modified from: Thomas, 2009, p. 122).

As Figure 15 illustrates, shrinkage occurs close to the area where curling has taken place. This distortion is caused by building a geometry that curls or sags close to a thin wall section (10 mm diameter hole 1 mm away from 1mm thick wall). Shrinkage (and also sagging and curling) can be avoided by designing the geometry of the part to be self-supporting. (Thomas, 2009, p. 122, 156–157.)

Delamination is a binding defect that occurs when the laser power is insufficient or the scanning speed too high to fuse the subsequent layers of powder together. Cooling of the melted material causes it to shrink and to rise up from the surface if the material has not melted sufficiently to the previous layer. (Thomas, 2009, p. 78.)

As it can be noticed from Figure 16, the cooling caused by the inert gas flow has led to insufficient bonding of the layers to each other and this can be seen as delamination in the parts. Delamination is marked with the red arrows. (Dadbakhsh, Hao & Sewell, 2012, p. 244.)

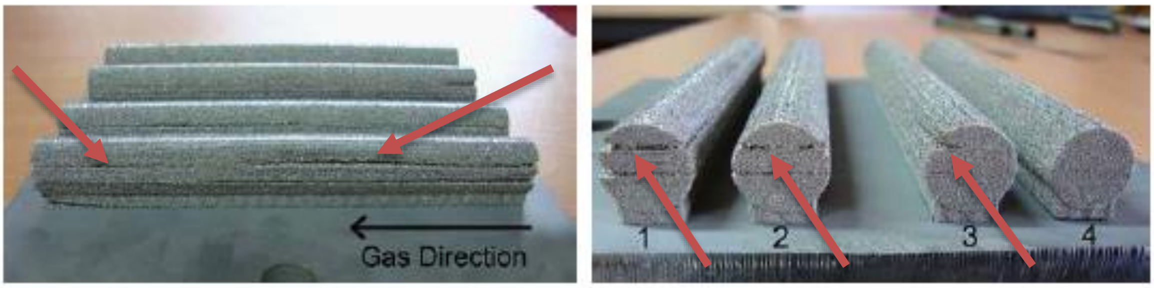


Figure 16. Delamination marked with red arrows (modified from: Dadbakhsh et al., 2012, p. 244).

6.4 Surface roughness and part orientation

The effect of part building orientation to surface quality is illustrated in Figure 17.

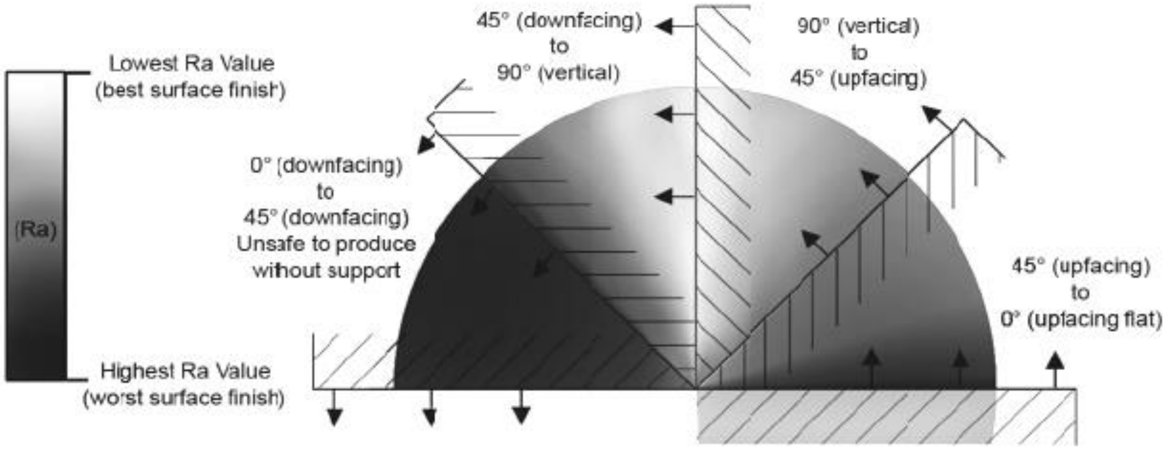


Figure 17. Influence of part orientation to surface roughness (Thomas, 2009, p. 160).

As from the Figure 17 can be noticed, to achieve the best possible surface quality the orientation of the part needs to be perpendicular to the building plate plane (i.e. 90 degrees). The surfaces, which are orientated between 90 degrees (horizontal) and 45 degrees are safe to build without supports and the surface quality decreases when moving from 90 degrees to 45 degrees as seen from the figure. (Thomas, 2009, p. 160.)

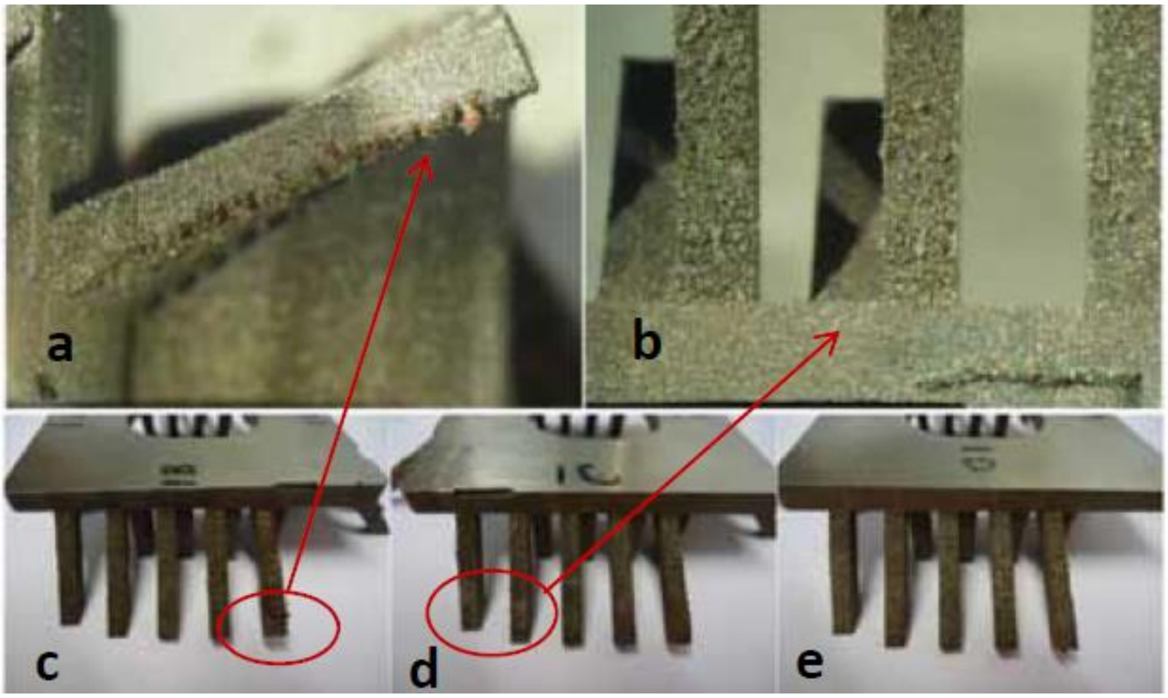


Figure 18. Surface quality of down-facing surface under 45 degrees (Li, 2014, p. 63).

As it can be seen from Figure 18, down-facing surfaces orientated under 45 degrees are not safe to build without support structures. The surface quality of them is poor and the supports do not increase it. When going from 45 degrees towards 0 degrees in up facing surfaces, the surface quality decreases until it enhances just before 0 degrees. (Thomas, 2009, p. 160–161.)

6.5 Geometrical material compensation

The surface quality directly after the build is often not suitable for an end use product. Thus extra material has to be added to the part for machining to achieve the suitable surface finish. (Thomas, 2009, p. 161.) The up-facing, side-facing and down-facing surfaces are illustrated in Figure 19.

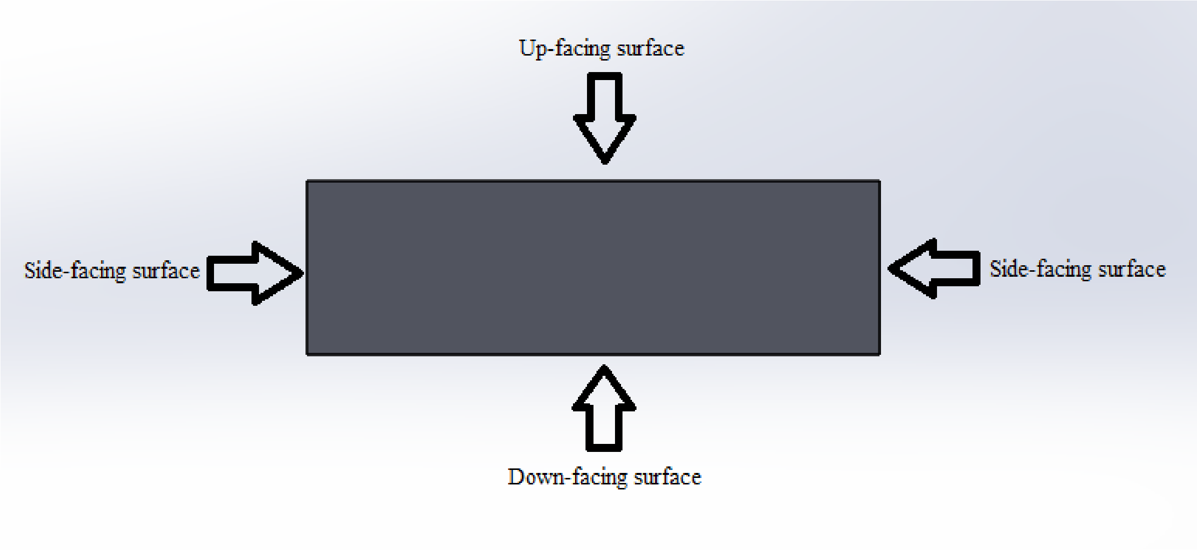


Figure 19. Explanation of surfaces.

As from figure 19 can be seen, the up-facing surface is located on the top, side-facing surfaces on the sides and the down-facing surface in the bottom of the part.

Up-facing surfaces

The surface quality of up-facing surfaces is good but to achieve a completely flat surface by machining, an extra 0.3 mm of material needs to be added to the up-facing surface. By adding 0.7 mm to a completely dense surface can be achieved by machining. (Thomas, 2009, p. 162.)

Side-facing surfaces

Side-facing surfaces do not need extra material to be added for a flat surface and are accurate within ±0.05 mm tolerance. For a completely dense surface 0.12 mm need to be added for machining. (Thomas, 2009, p. 162–163.)

Down-facing surfaces

Down-facing surfaces need be built over size and the use of support structures do not solve the problem. Down-facing surfaces have also a tendency to deform to convex shaped surface due to the stresses from the process. A value of 0.8 mm should be added in every case to the down-facing surfaces and as the surface size increases, even more material should be added as the Table 1 illustrates. The values in the Table 1 contain the 0.8 mm plus the extra material depending on the size of the part. (Thomas, 2009, p. 163–164.)

Table 1. Material compensation for down-facing surface (Thomas, 2009, p. 164).

Surface dimensions	30x30 mm	20x20 mm	10x10 mm
Removal until flat surface	1.1 mm	1 mm	0.8 mm
Removal until dense surface	1.6 mm	1 mm	0.8 mm

The values added for post processing the surface are minimal values and the removal technique should be considered when doing the material compensation (Thomas, 2009, p. 164).

6.6 Minimum gap between surfaces

A minimum distance between surfaces (holes, channels, gaps etc.) must be defined to prevent surfaces fusing together (Thomas, 2009, p. 164–165). The minimum gap is illustrated in Figure 20.

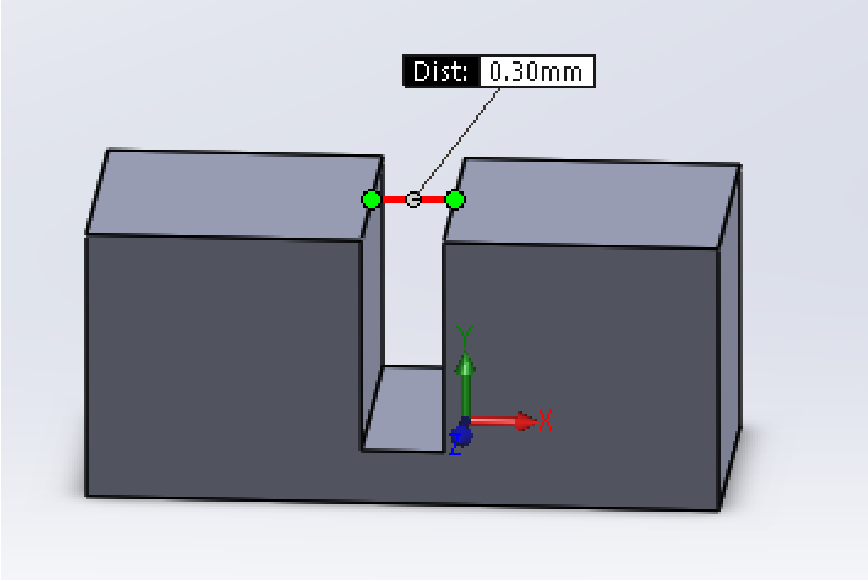


Figure 20. Minimum gap between surfaces.

As it can be seen from Figure 20, the minimum distance between surfaces is 0.3 mm for metallic powder bed fusion. In case the orientation of the feature is less than 45 degrees (90 degrees being vertical orientation), the minimum gap has to be over 3 mm or then support structures must be used. (Thomas, 2009, p. 164–165.)

6.7 Minimum wall thickness

The minimum wall thickness in SLM of metals is limited by the machine features (Thomas 2009, p. 165). The minimum wall thickness is presented in the Figure 21.

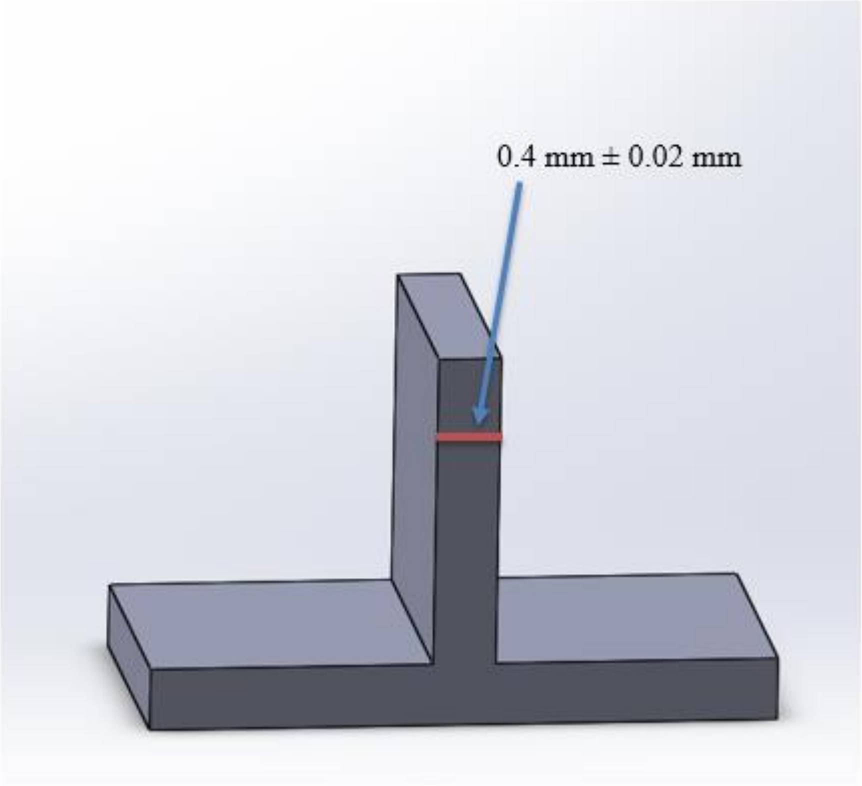


Figure 21. Minimum wall thickness.

As the Figure 21 illustrates, the minimum wall thickness for vertical walls is 0.4 mm with a tolerance of ± 0.02 mm. Walls thinner than 0.4 mm will not build successfully. (Thomas, 2009, p. 165.)

6.8 Avoiding overhangs

Building ledges perpendicular to the building direction is not possible without using support structures. The use of support structures enables the build but the surface quality will be unacceptable because of deformations. The use of support structures can be avoided by using self-supporting geometries (chamfers, concave and convex radiuses) in the design. The self-supporting geometries are illustrated in Figure 22. (Thomas, 2009, p. 166–167.)

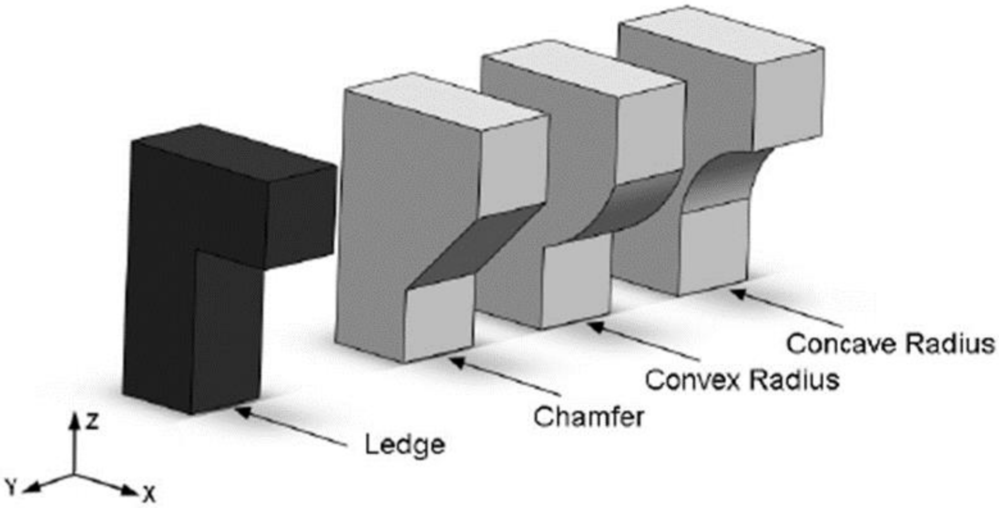


Figure 22. Self-supporting geometries (Thomas, 2009, p. 166).

As it can be seen from Figure 22, the down-facing surface of a ledge can be made self-supporting by using chamfer or radius. First geometry on the left represents a normal ledge with a sharp edge, second on the left is a chamfer and, third a convex radius and the fourth a concave radius. The use of self-supporting geometries in down facing surfaces improves also surface quality and down facing ledges with sharp corners should be replaced with self-supporting structures if the use of sharp edge is critical for the function of the part. (Thomas, 2009, p. 166–167.) The proper use of these geometries is explained below.

Chamfers

A chamfer and the building orientation is illustrated in the Figure 23.

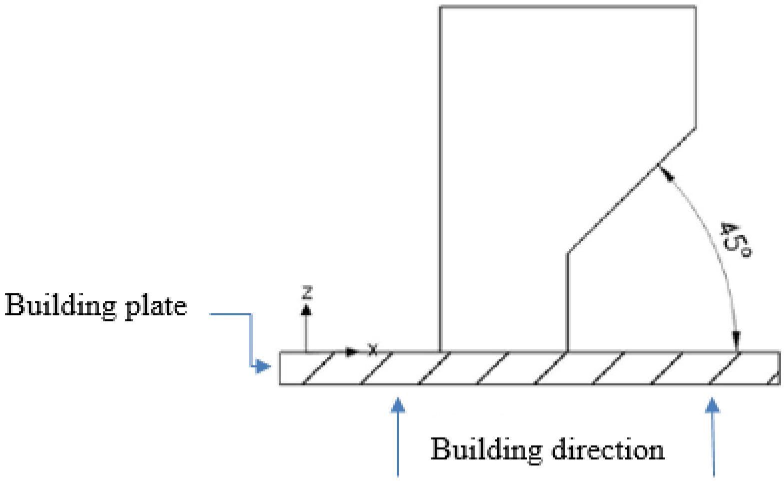


Figure 23. Illustration of chamfer (modified from: Thomas, 2009, p. 168).

As it can be seen from the Figure 23, the chamfers that are 45 degrees or more related to the building plate are self-supporting and do not need supports. The surface quality of the feature increases as the angle increases (see Figure 17 on chapter 6.4). A 45 degree chamfer produces the shortest possible height in case the part has to be short as possible and self-supporting (convex and concave radiuses require more space in z-direction). (Thomas, 2009, p. 167–168.)

Concave radius fillet

A tangential concave fillet radius is presented in Figure 24.

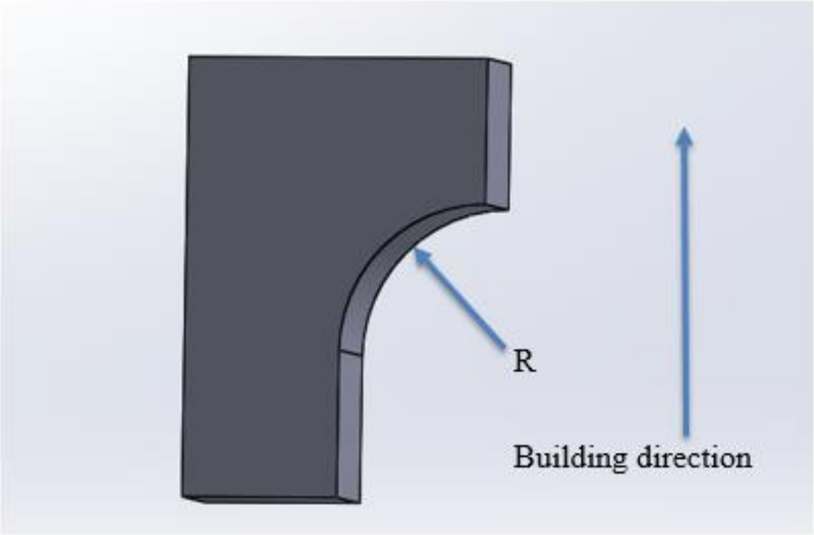


Figure 24. Tangential concave radius.

As the Figure 24 illustrates, the larger the radii is the larger the down-facing unsupported area in vertical direction becomes. Tangential radiuses up to R3 (3 mm radius) can be built in the building direction shown in the figure and the surface quality of these features will be poor. Parts with larger radiuses need to be built in a different orientation. Otherwise support structures need to be used to prevent the deformation (curling) from happening but they will not enhance the surface quality of the feature. To build fillet radiuses larger than R3 and fillet radiuses smaller than R3 with better surface quality, the geometry of the feature has to be altered as illustrated with help of Figure 25. (Thomas, 2009, p. 168–169.)

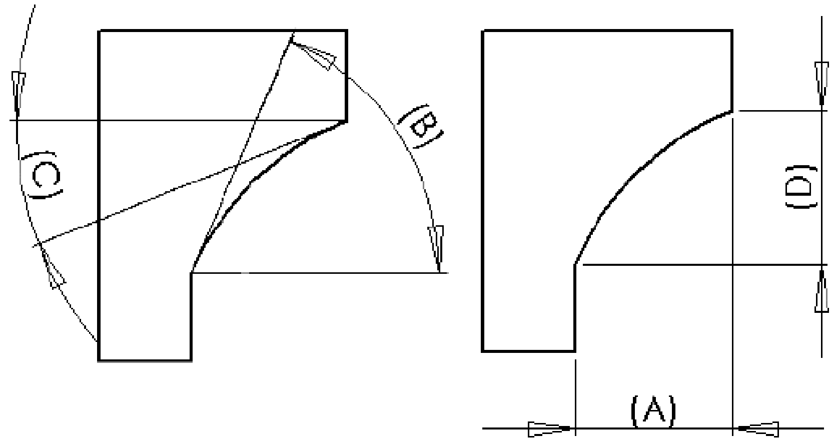


Figure 25. Geometry alteration for concave radius fillet (Thomas, 2009, p. 170).

As it can be seen from the Figure 25, (C) represents top tangent angle, (B) bottom tangent angle, (A) ledge size in mm and (D) height of radius in mm. To reduce the overhanging area the top and bottom tangent angles need to be adjusted so that the geometry comes closer to 45 degrees chamfer. When the ledge size gets larger than 5.18 mm it is suggested to use a 45 degree chamfer instead of concave radius fillet. (Thomas, 2009, p. 169–170.)

Convex radius fillet

Convex radius fillet is illustrated in Figure 26.

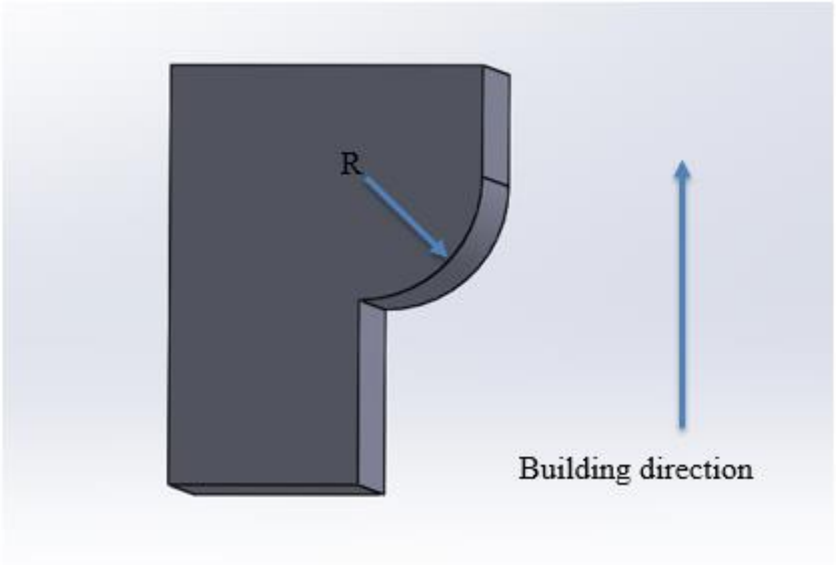


Figure 26. Tangential convex radius fillet.

As it can be seen in Figure 26, convex radius fillet resembles the concave radius fillet. Tangential radiuses up to R2 (2 mm) can be built in the building direction illustrated in the Figure 26, without using support structures and surface quality of these features will be poor as in case of small concave radius fillets. The use of support structures will prevent deformation in the process but will not enhance the surface quality of the feature. To build convex radius fillets with better surface quality and bigger than R2, the orientation of the part need to be altered or the geometry of the fillet needs to be altered as illustrated in Figure 27. (Thomas, 2009, p. 171.)

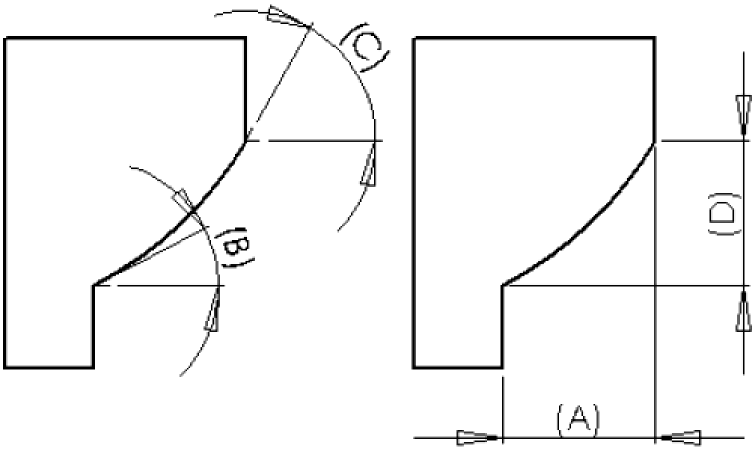


Figure 27. Geometry alteration for convex radius fillet (Thomas, 2009, p. 172).

As it can be seen in the Figure 27, (B) represents the bottom tangent angle, (C) top tangent angle, (A) ledge size and (D) height of the radius. To reduce the overhanging area the top and bottom tangent angles need to be adjusted so that the geometry comes closer to a 45 degrees chamfer. When the size of the ledge (A) becomes larger than 6.73 mm it is recommended to use a 45 degree chamfer instead of convex radius tangent fillet. (Thomas, 2009, p. 171–172.)

6.9 Round holes built parallel to building direction

Round hole built in horizontal direction is presented in Figure 28.

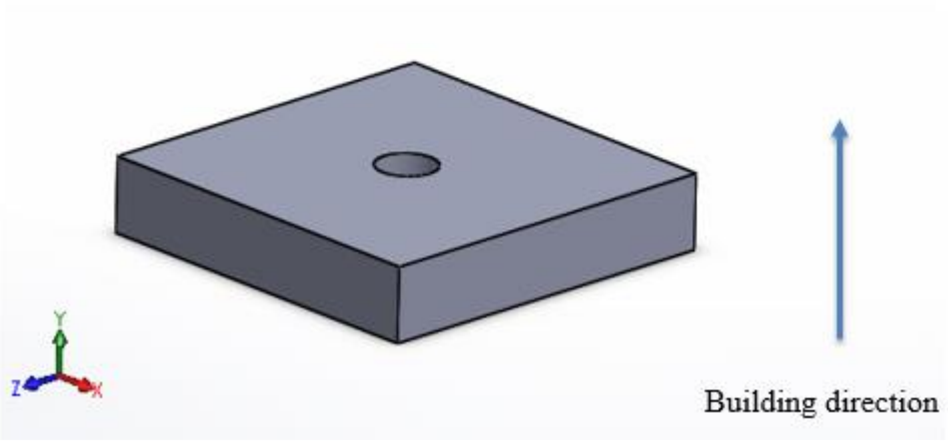


Figure 28. Round hole built parallel to building direction.

Maximum diameter for holes built in the direction illustrated in Figure 28 is 0.7 mm. Holes smaller than this will not be built successfully. (Thomas, 2009, p. 174.)

6.10 Round holes built perpendicular to building direction

Round holes perpendicular to building direction are illustrated in Figure 29.

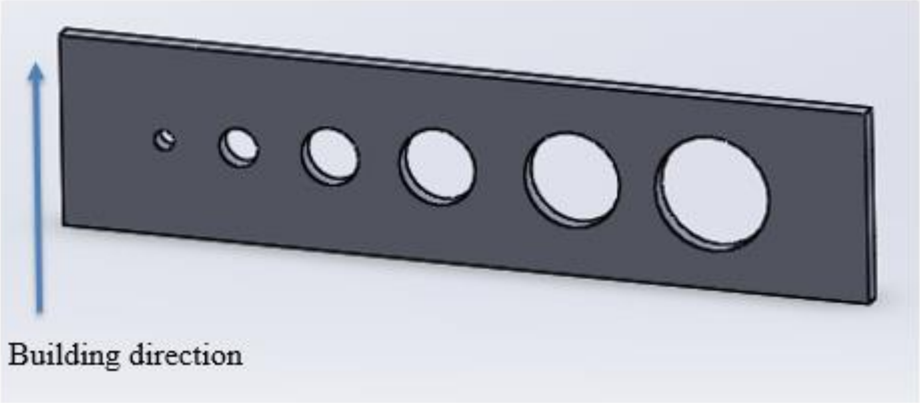


Figure 29. Round holes perpendicular to building direction.

As it can be noticed from the Figure 29, building round holes perpendicular to building direction is challenging since the geometry is not self-supporting (down-facing area in the top of the holes). Minimum diameter for a hole built without supports in this orientation is 1 mm and maximum diameter 7 mm. Holes between 1-7 mm can be built but the surface accuracy of the hole will be poor because sagging in the top of the hole. With holes larger than 7 mm, the curling effect will be so strong that the process is likely to be interrupted hence the collision of recoater and the workpiece. (Thomas, 2009, p. 175–178.)

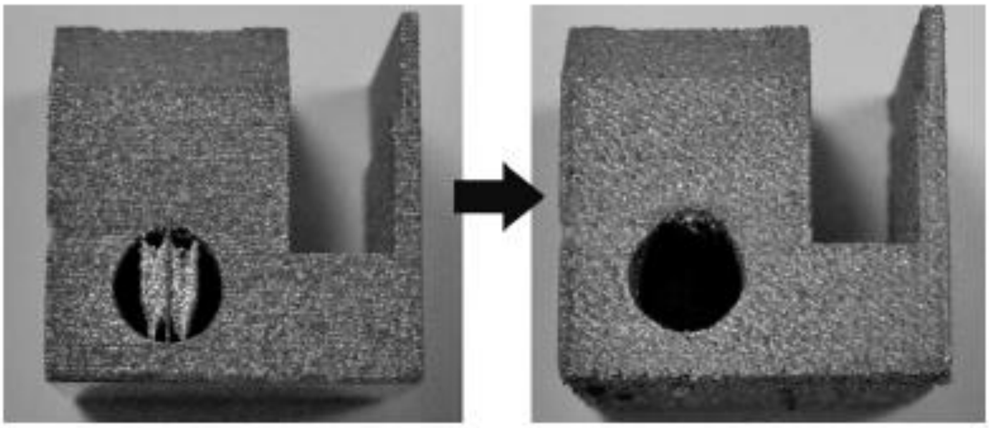


Figure 30. Round hole supported before and after support removal (Thomas, 2009, p. 64).

As it can be seen from Figure 30, adding supports enables the build of holes by controlling curling effect, but it will not prevent sagging from occurring. As a rule thumb can be said that the tolerance of round holes perpendicular to build direction will be ± 0.5 mm varying in different sections of the hole. Holes that need to be precise need to be machined during the post-processing stage. (Thomas, 2009, p. 175–178.)

Pilot drilling, reaming and tapping holes

Holes must precise for drilling, reaming and tapping, these post process operations cannot be done to holes built perpendicular to building direction without pilot drilling first. The holes need to be designed as described earlier to be accurate enough, otherwise even the pilot drilling for reaming and tapping will not be possible. (Thomas, 2009, p. 181–182.)

6.11 Self-supporting holes

As mentioned before, building round holes in parallel to building direction is complicated and sometimes without support structures not even possible. Depending on the geometry of the part it might impossible to remove the supports and even if the supports are used, the quality of the holes is not accurate. Also the procedure of building these kind of holes is not repeatable (the holes will not be copies of each other). (Thomas, 2009, p. 181–182.) Figure 31 illustrates two kind of geometries to substitute round holes.

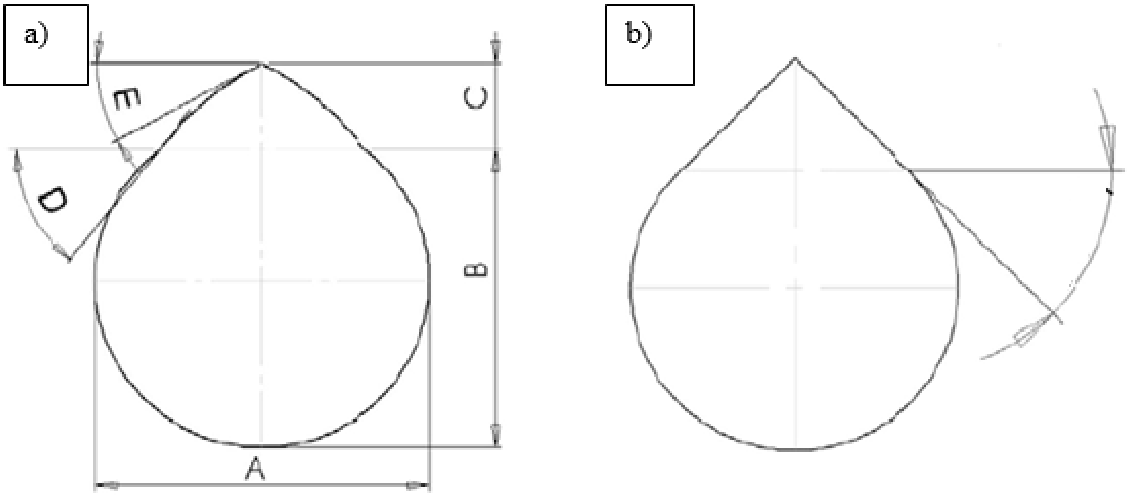


Figure 31. Self-supporting geometries for substituting round holes (Thomas, 2009, p. 180).

The geometries illustrated in Figure 31, are self-supporting and can be built repeatedly but they still contain most of the circumference of a circle. In Figure 31a, (A) presents radius of the hole, (B) height of the feature, (C) height of the peak, (D) angle at bottom of the peak and (E) angle at top of the peak. Figure 31b presents the angle of the straight lines related to building platform. The peak of the geometry on the left consist of two curves and a peak of the geometry on the right from two lines at 45 degrees angle related to building platform. The geometry on figure 31a should be used for holes between diameter of 2-14 mm and the geometry on the figure 31b for diameters larger than 16 mm. A table for holes between radiuses 2 mm and 30 mm and values for A, B, C, D and E in figure 31a minimizing the peak height the peak and retaining the circumference of the hole, can be found in doctoral thesis of Daniel Thomas. (Thomas, 2009, p. 178–181.) The table can also be found in the Appendix II of this thesis.

6.12 Hollowing of parts

Additive manufacturing enables building hollow features or completely hollow parts (Gibson et al., 2010, p. 57). An example of hollowing of a part is presented in Figure 32.

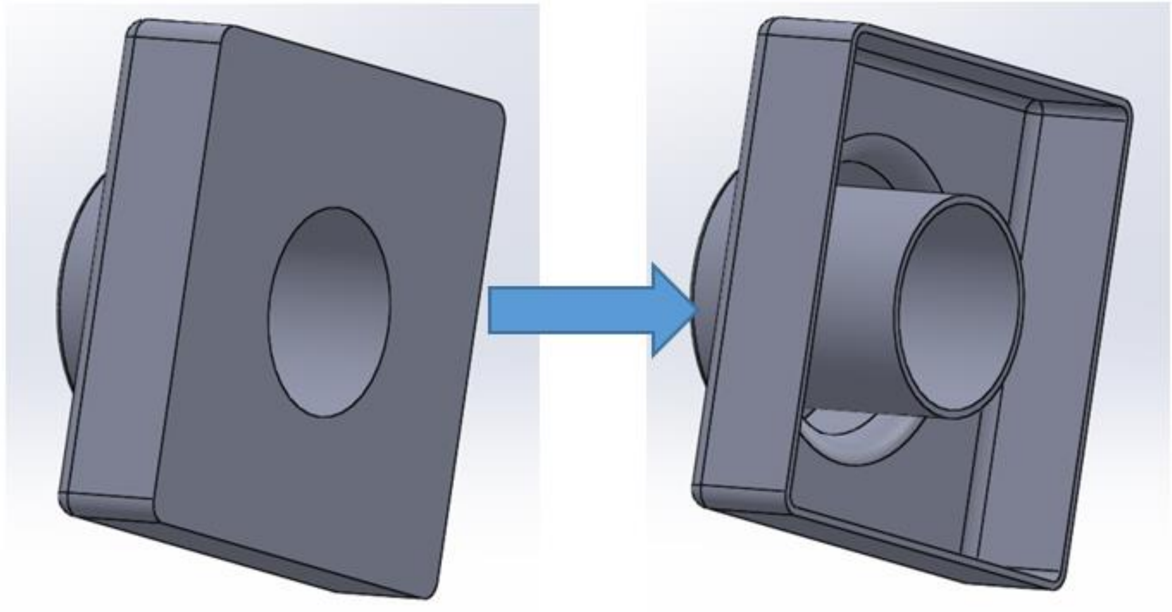
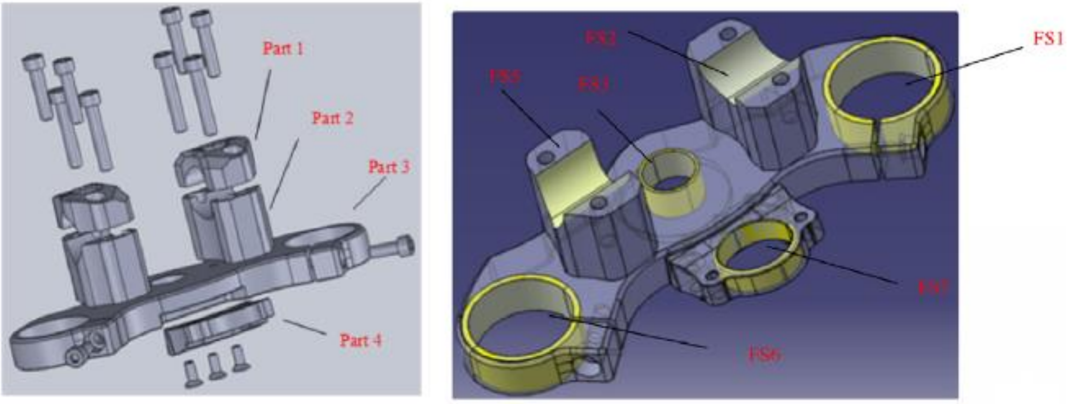


Figure 32. Hollowing of parts.

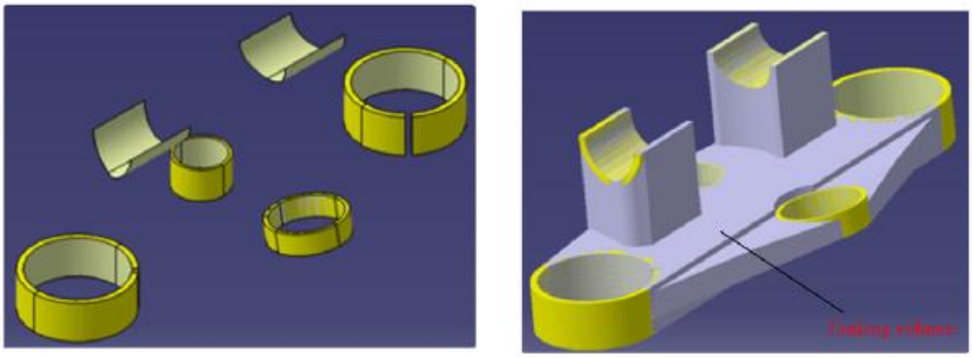
As Figure 32 shows, designing parts or features of parts to be hollow reduces building time and material usage. Hollowing of parts also reduces weight of the part, which can be the most pursued feature. Draining of excessive powder must be considered when designing hollow features. This means that the excessive powder needs to be removed from the part via drain holes or corresponding features. (Gibson et al., 2010, p. 57.)

6.13 Part consolidation

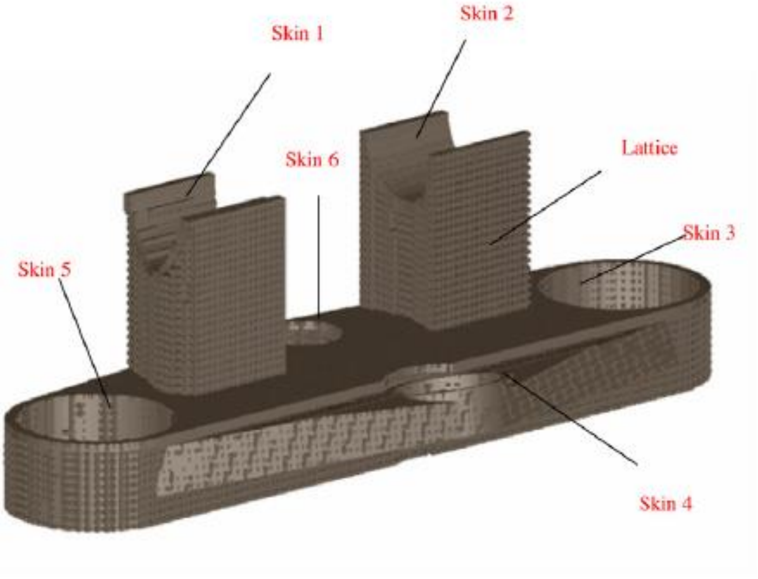
Additive manufacturing enables many possibilities to product design comparing to conventional manufacturing processes. Part consolidation, function integration and structure integration should be included in the design process to utilize this potential. (Yang, Tang & Zhao, 2015, p. 444.)



(a) exploded view (b) define functional surfaces



(c) functional surfaces extraction (d) functional volume generation



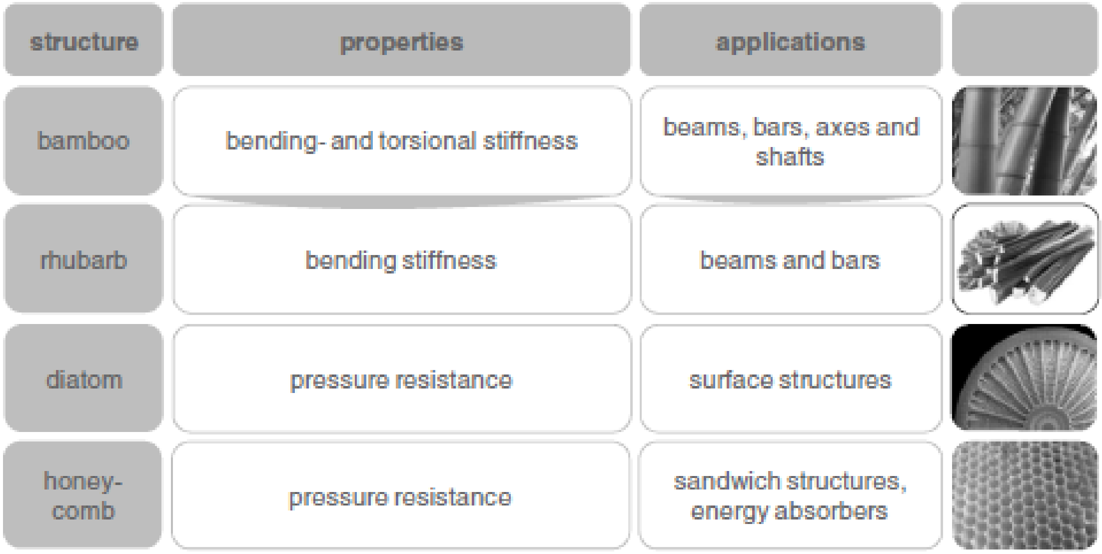
(e) homogeneous lattice structure and skin

Figure 33. Redesign of a triple clamp (modified from: Yang et al., 2015, p. 448).

As it can be seen from Figure 33, the part has been optimized as by defining functional surfaces, creating functional volume around them and creating a lattice structure. The triple clamp has now less material and weighs less, has less parts and has better performance. FEM (finite element method) analysis is essential for verifying the strength of the new part. (Yang et al., 2015, p. 448–449.)

6.14 Mimicking of structures of nature

Mimicking structures of nature i.e. biomimicry can be used to solve design problems because structures of nature have been developed and optimized by natural selection that has lasted for ages. Studying structures of nature such as bamboo, rhubarb and honeycomb structures can be used as important clues when designing light weight designs. Integrating new laser additive manufacturing technology, structural optimization tools and mimicking of structures of nature, the full potential of designing lightweight structures can be achieved. (Aziz & El Sherif, 2015, p. 1; Emmelmann et al., 2011B, p. 364–367.) Figure 34 illustrates possible solutions for a designer to approach the structural optimization and design of the structure depending on the application (Emmelmann et al., 2011B, p. 368).



structure	properties	applications	
bamboo	bending- and torsional stiffness	beams, bars, axes and shafts	
rhubarb	bending stiffness	beams and bars	
diatom	pressure resistance	surface structures	
honey-comb	pressure resistance	sandwich structures, energy absorbers	

Figure 34. Advantages and applications of structures of nature (Emmelmann et al., 2011B, p. 368).

7 SELECTING PARTS FOR ADDITIVE MANUFACTURING

Development of additive manufacturing has given companies an interest to examine if their products should be manufactured using additive manufacturing. All parts or products are not suitable for additive manufacturing. There must be a clear reasoning why a part or a product is manufactured with additive manufacturing and many things have to be considered, when deciding, which products are suitable for manufacturing. (Conner et al. 2014, p. 64–65.)

When examining system for enhancing the performance of it, the part or parts that have the greatest impact on the systems overall performance are the most important ones. These are the parts that should be taken into closer examination if they could be optimized using additive manufacturing. The selection criteria for parts to be manufactured with additive manufacturing can be divided to four main aspects (Klahn, Leutenecker & Meboldt, 2014, p. 138–139):

1. Integrated design
2. Individualization
3. Lightweight design
4. Efficient design

A part suitable for additive manufacturing does not necessarily belong only to one aspect, but several of them (Klahn et al., 2014, p. 139).

Integrated design criteria is aiming to part consolidation, which means finding an assembly that has previously consisted of several parts but can be manufactured as one part using additive manufacturing. The parts in the assembly may not be able to move in respect with each other. These original assemblies usually consist of many parts often due to manufacturing constraints, which do not apply with additive manufacturing. (Klahn et al., 2014, p. 139.)

Individualization criteria is aiming to offer the customer a benefit that bulk parts cannot offer. Individual parts and parts that are complex to manufacture with traditional manufacturing methods are often suitable for additive manufacturing. Customizing a product consisting of standard parts with individual parts manufactured with additive manufacturing can also be profitable. (Klahn et al., 2014, p. 139.)

Lightweight design criteria is aiming to enhance the performance of the part by weight reduction. This is accomplished by adding material only were it is needed reducing the use of material but making the part more complex. In additive manufacturing this does not increase the manufacturing costs conversely to machining and other conventional manufacturing methods. The parts selected to additive manufacturing are usually the parts bearing intricate loads. These parts are the ones where most material can be reduced. (Klahn et al., 2014, p. 139.)

Efficient design criteria is aiming to enhance the performance of the part in operation by reducing losses or overall performance enhancement. The parts having the largest effect in this aspect are the ones that should be examined and redesigned for additive manufacturing. These parts are often transporting mass or energy in machines or parts conversing energy in processes. (Klahn et al., 2014, p. 139.)

Design of a hydraulic manifold for additive manufacturing is an example where three different aspects encounter.

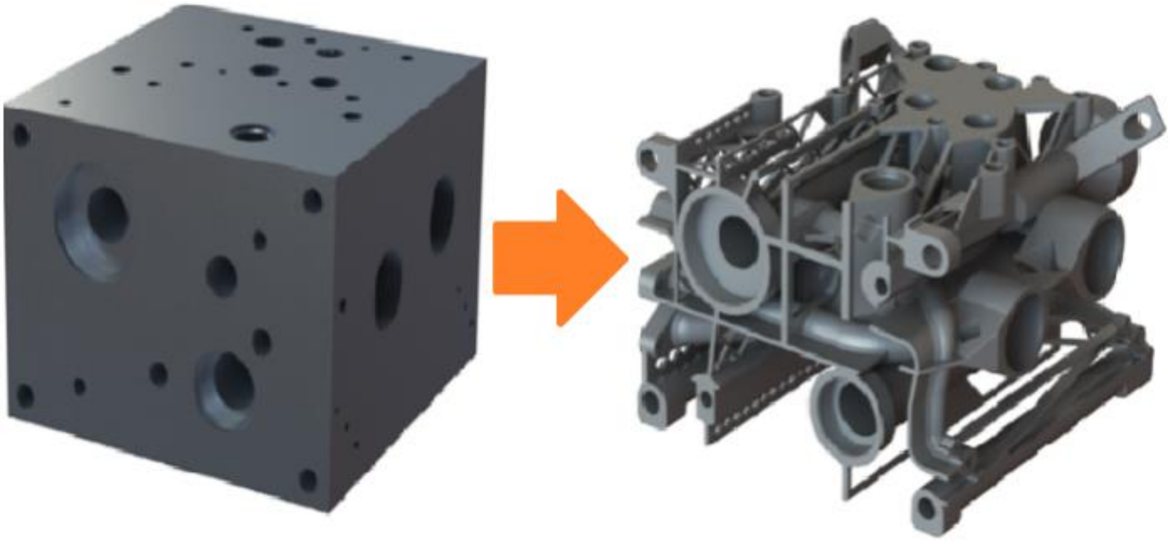


Figure 35. Conventional hydraulic block and block designed for AM (Saunders 2015).

As it can be seen from Figure 35, the hydraulic manifold could be selected for additive manufacturing by three different criteria: light weight design, integrated design and efficient design. (Klahn et al., 2014, p. 139).

As mentioned before, the parts for additive manufacturing must be chosen carefully. Parts that are easily mass manufactured with conventional methods are not suitable for additive manufacturing but when the part complexity increases and the use of conventional manufacturing methods becomes more challenging the additive manufacturing comes more profitable. However additive manufacturing can be an economical way to manufacture the tooling used in mass production with conventional manufacturing methods. (Conner et al., 2014, p. 64–66.)

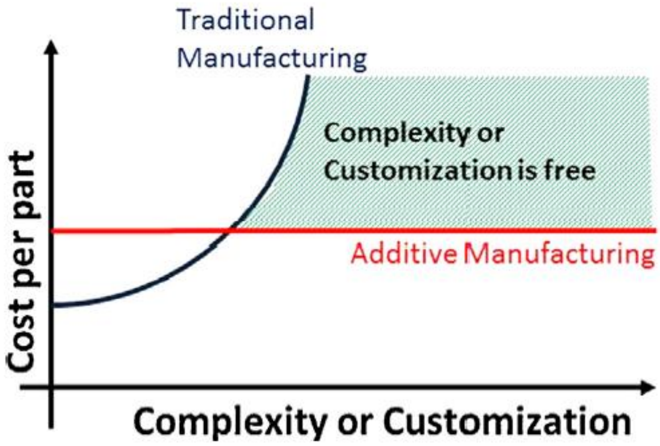


Figure 36. Cost per part on function of complexity (Conner et al., 2014, p. 71).

As Figure 36 illustrates, there is a breakeven point when complexity of the part increases and the cost pert part increases, the additive manufacturing becomes more economical than traditional manufacturing methods. This has generated the term “complexity is free” in additive manufacturing context. (Conner et al., 2014, p. 71–72.)

8 SUCCESS STORIES IN ADDITIVE MANUFACTURING

This chapter presents parts and products that have been additively manufactured successfully. Additive manufacturing has been used in many industries successfully. Success stories are presented by introducing the old and new design and comparing them.

General Electric engine bracket

The bracket was designed for GE (General Electric) by Penn State University’s Center for Innovative Materials Processing through Direct Digital Deposition. The part had to bear four load cases without alternating the position of the installation points and the part had to meet the same requirements as the original one. (Conner et al., 2014, p. 69.)

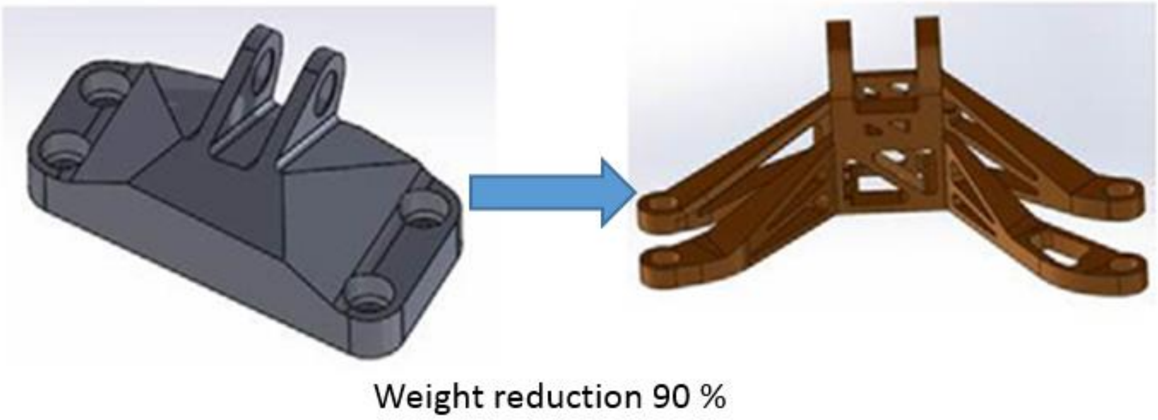


Figure 37. Re-design of an engine bracket (modified from: Conner et al., 2014, p. 69).

As Figure 37 illustrates, the re-designed bracket made for additive manufacturing (right side) has less material and weighs nearly 90 percent less than the bracket machined from cuboid (left side) (Conner et al., 2014, p. 69).

Airbus A380 bracket

The re-design of the aircraft bracket was executed by ILAS (Industrial Laser Application Symposium) by mimicking the structure of bamboo and the result is a lightweight and stiff bracket (Emmelmann et al., 2011A, p. 9).

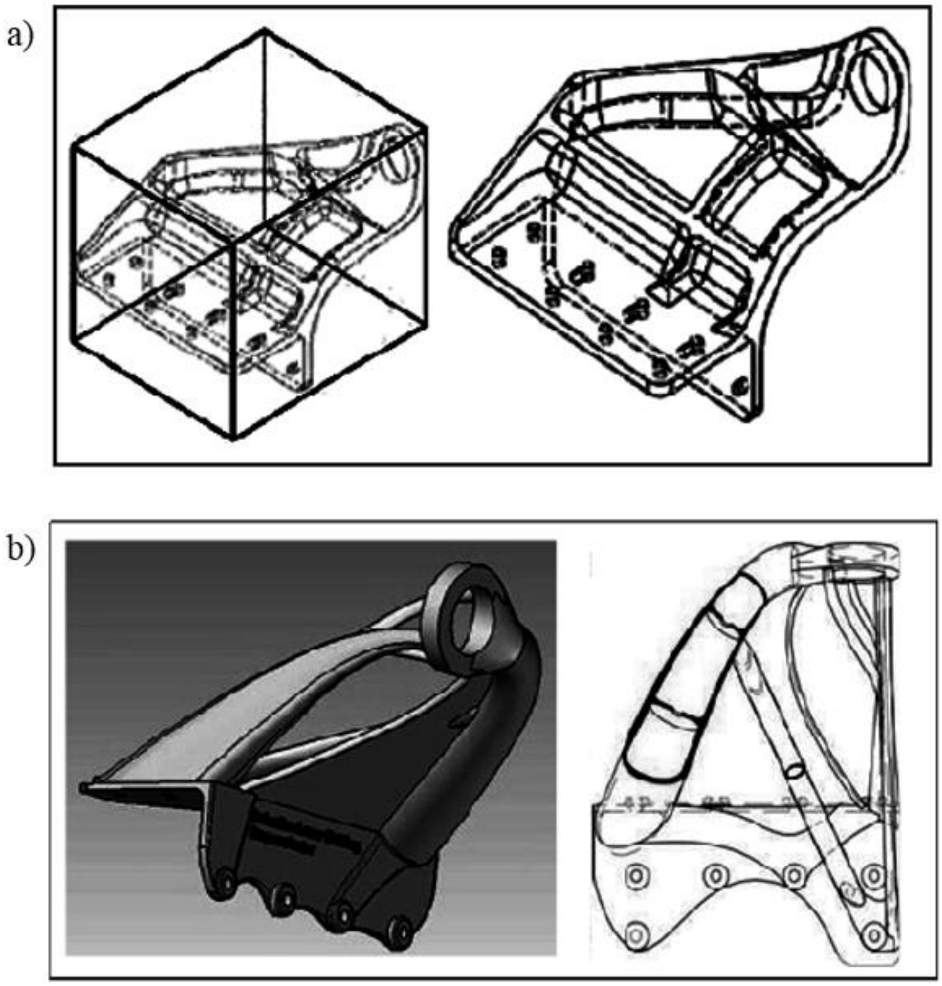


Figure 38. Aircraft bracket before and after (modified from: Emmelmann et al., 2011A, p. 10).

As it can be seen from Figure 38, the model designed for additive manufacturing (Figure 38b) uses significantly less material than the model designed for machining (Figure 38a). The new bracket weighs 50 percent less and is made from titanium. (Emmelmann et al., 2011A, p. 10.)

Hydraulic manifold

It is possible to reduce the weight and enhance the fluid flow by re-designing a hydraulic manifold (Feenstra, 2013, p. 11).

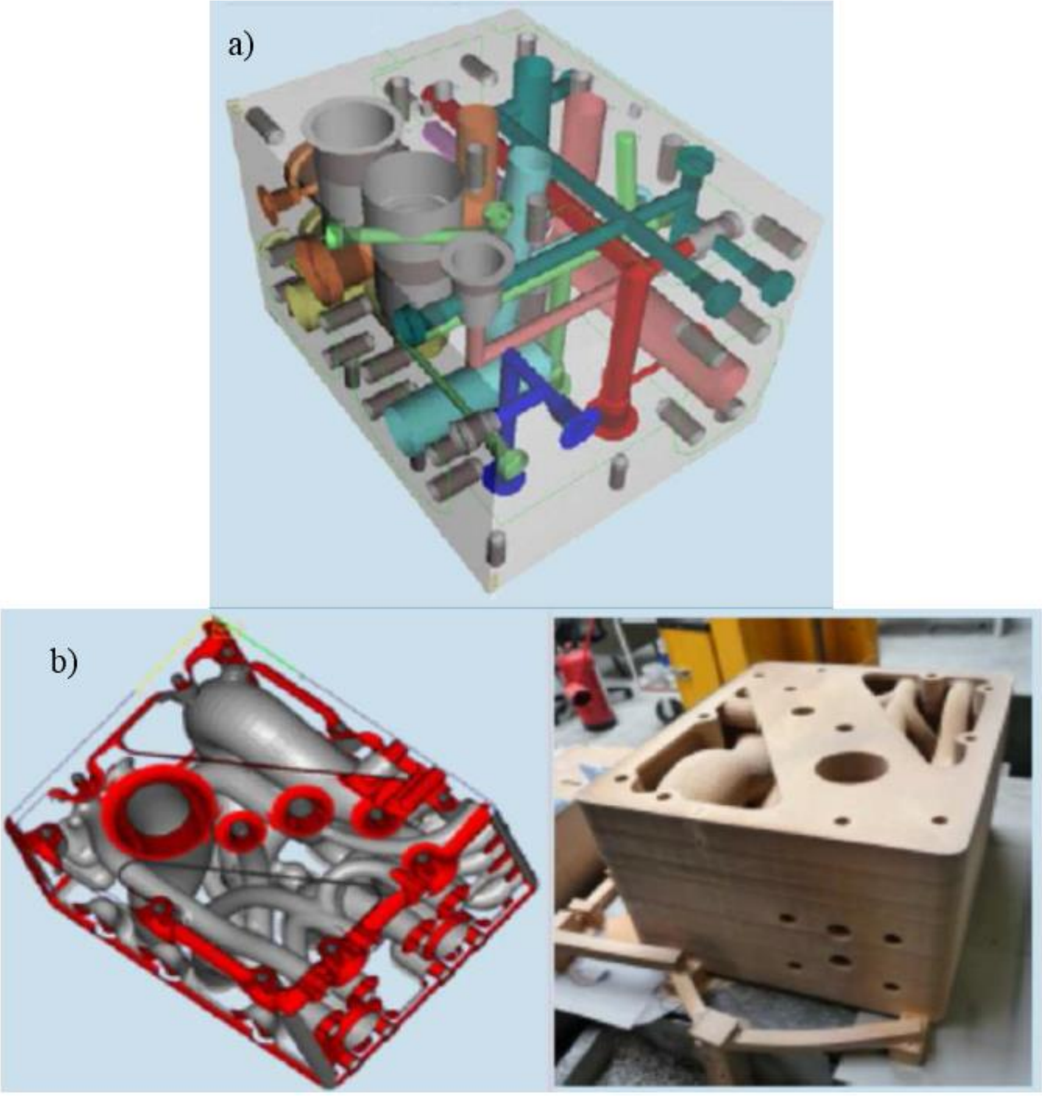


Figure 39. Hydraulic block re-designed (modified from: Feenstra, 2013, p. 11).

Figure 39a presents the original design and Figure 39b the design for additive manufacturing. The size of the original part is 26.5 cm x 20 cm x 16.5 cm and weight 55 kg. By means of additive manufacturing the size has reduced to 24 cm x 20 cm x 15cm and the weight to 18kg. (Feenstra, 2013, p. 11.)

9 AIM AND PURPOSE OF EXPERIMENTAL PART A

The experimental part A in this thesis was conducted to define a proper geometry for holes and channels used in later in experimental part B of the thesis. The aim of experimental part A is also to define suitable parameters for supports for manufacturing a component consisting of pipes in experimental part B (suitable parameters meaning parameters, which produce supports strong enough to enable safe building process but which are removable without damaging the part).

10 EXPERIMENTAL SET-UP FOR PART A

The powder bed fusion machine used in the experimental procedure is a modified research machine, which represents EOSINT-M series equipment. The size of the building area inside the building chamber is 250x250x215 mm (x-, y- and z-directions). The machine uses nitrogen as shielding gas and the oxygen concentration is 0.2 %. (Nitrogen concentration is 99.8 %). The PBF machine is presented in Figure 40.

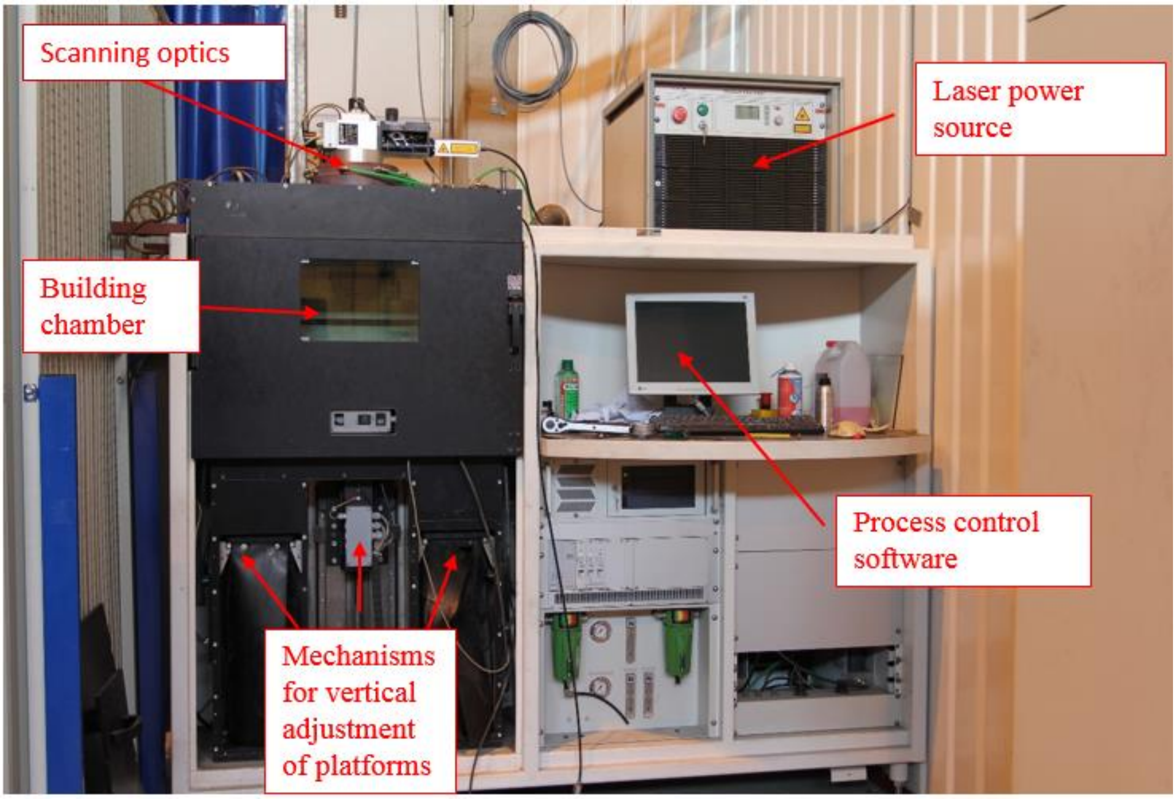


Figure 40. PBF machine used in the experimental part.

The PBF machine in Figure 40 is equipped with IPG YLS-200-SM-CW fiber laser and Scanlab hurrySCAN 20 scanning optics. Maximum scanning speed is 1000 mm/s and layer thickness is 20 µm. The building chamber and scanning optics are presented in Figure 41.

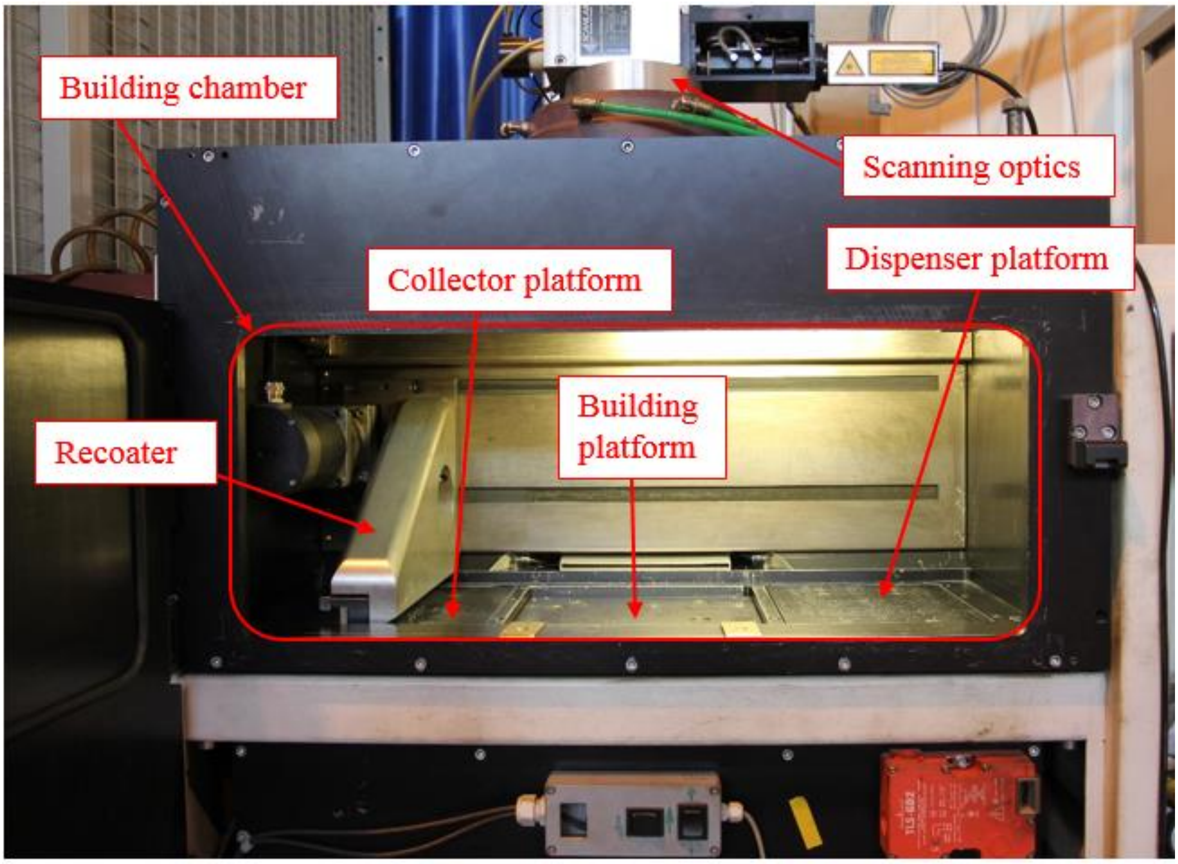


Figure 41. Building chamber and scanning optics of the PBF machine.

Laser equipment properties (IPG YLS-200-SM-CW):

- Power 200 W
- Wavelength 1070 nm
- Focal length 400 mm
- Laser spot size 100 µm

The material used was stainless steel powder EOS SS316L. Table 2 illustrates the material composition percentages (%).

Table 2. Nominal material composition of EOS SS 316L powder.

Cr	Ni	Mo	Mn	Cu	Si	O	N	P	S	C
17.9	14.2	2.67	1.48	0.01	0.51	0.03	0.03	0.01	0.007	0.009

The EOS SS316L is an iron based corrosion resistant metal alloy that is designed to be used with EOS M-series systems. It can be used in multiple purposes and it can be machined and polished. EOS SS 316L powder has been created to be used especially with EOSINT M280 series machines. The material is ideal for use in many industries such as automotive, aerospace and turbine industries. It can be used for consumer products such as jewelries and watches. The first industrial applications for the material were heat exchangers and mounting parts.

The camera used in photography of the experimental part A is a Canon EOS 60D.

11 EXPERIMENTAL PROCEDURE OF PART A

This chapter describes how the geometry and supports were designed in experimental part A. The information can be used to repeat the experiments conducted in experimental part A. Experimental part A is divided to two sections. First section presents testing of droplet shape pipes and second section testing supports for droplet shaped pipes.

11.1 Testing of droplet shaped pipes

The model designed and manufactured in experimental part B will contain pipes with larger than 8 mm internal diameter. This kind of pipes are not possible to manufacture perpendicular to the building direction without using support structures inside the geometry if the geometry is round. Thus a working shape for a self-supporting pipe geometry and working parameters for the supports for the pipes are designed and tested before designing the actual model. The self-supporting geometry designed presented in Figure 42.

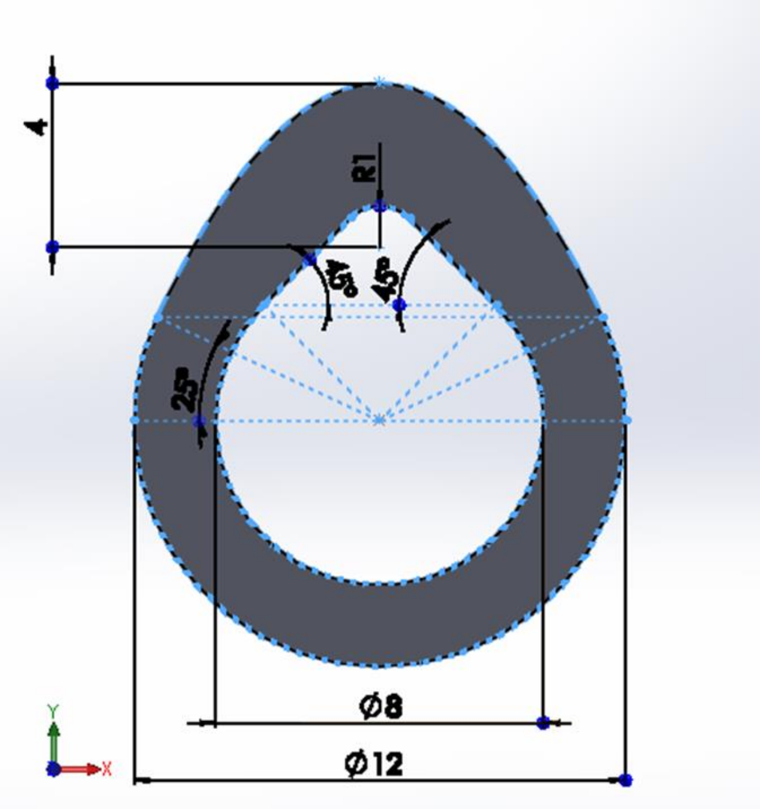


Figure 42. Self-supporting geometry of droplet shaped pipe.

The geometry for the pipe in Figure 42 was designed with SolidWorks 2015 CAD software obeying the design details for additive manufacturing presented in this thesis. A round shaped channel with an internal diameter of 8 mm would have been unsafe to build and the surface quality of it would have been unacceptable according to the information found during the process of writing literature review. Thus this version of a self-supporting hole-geometry was manufactured for test purpose.

11.2 Testing of supports for droplet shaped pipes

The supports used in this thesis are solid web supports (most suitable for PBF of metallic materials) and they were designed with DeskArtes 3Data Expert software. The software is a professional tool for manipulating 3D models for additive manufacturing. It can be used to verify and fix the STL file and for modification of the 3D model also.

The experiment was conducted by varying support parameters for 8 similar test pieces. The geometry used in test pieces is presented in Figure 43 and the length of the test pieces is 40 mm.

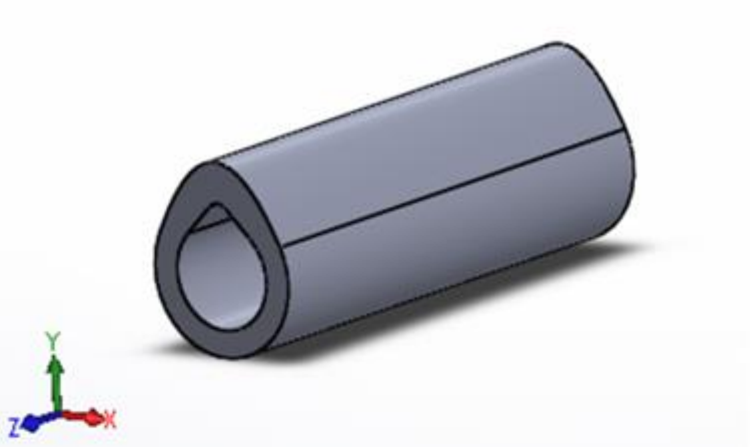


Figure 43. Illustration of the test piece.

The hole-geometry of the test piece in Figure 43 is the same than in the previous test. The length of the pipe was chosen to be 40 mm instead of a shorter length for possible problems caused by the length. After creating the 3D file with SolidWorks it was saved to STL format for creating the supports and for checking possible triangle errors.

The triangle errors of the STL file were fixed with the automatic repairing tool of DeskArtes 3Data Expert software. Next the support structures were designed with the same program using manual support creating option. The following parameters presented were varied in the test pipes.

X- and Y-spacing

Distance between bordering web hatches parallel to X- and Y-axes. This is presented in Figure 44. Red arrow is the Y-spacing and blue arrow is X-spacing. The default value for the parameter is 1.0 mm. The value was changed to 0.8 mm for test piece number 3 to test the impact of it.

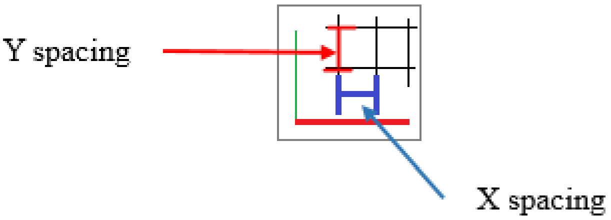


Figure 44. X- and Y-spacing.

Up overlap

This parameter defines the amount of overlap between the part and the upper part of support structure and is presented in Figure 45. The values of up overlap were varied between 0.1 mm and 0.2 mm in the test pipes.

Figure 45. Up overlap.

Down overlap

Down overlap parameter describes the amount of overlap between the part and the lower part of the support structure. This parameter was not altered because it was not used in the web supports of the test pipes. The parameter is presented in Figure 46.

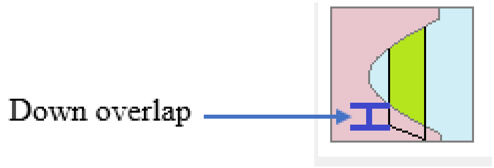


Figure 46. Down overlap.

Teeth distance

The parameter defines the distance between two successive teeth and is presented in Figure 47. The teeth distance was remained constant at 0.5 mm. Only exception was test pipe number 8 where it was changed to 0.6 mm to test the impact of it.

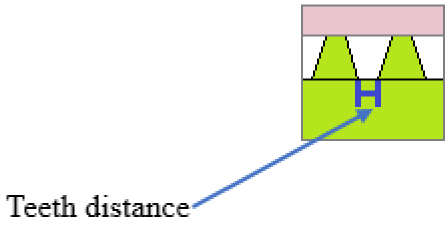


Figure 47. Teeth distance.

Teeth base length

This parameter defines the width of the bottom of the tooth. Teeth base length is presented in Figure 48. Teeth base length was varied between 0.4 mm and 0.5 mm in the test pipes to test the impact of it.

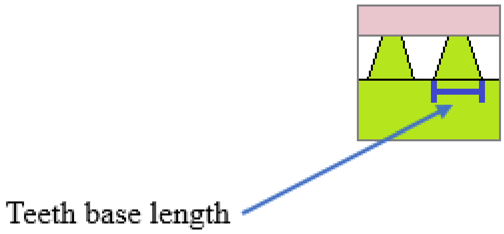


Figure 48. Teeth base length.

Teeth tip length

Teeth tip length parameter defines the width of the teeth at the top of it and is presented in Figure 49. This parameter was varied between 0.1 mm and 0.2 mm in the test pipes.

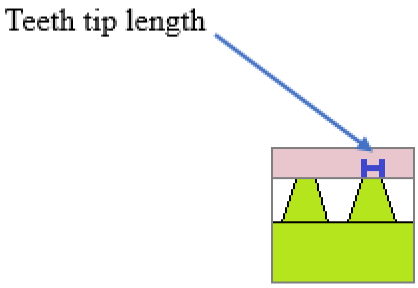


Figure 49. Teeth tip length.

Teeth height

Teeth height parameter defines the height of the teeth from the bottom to the top. The parameter is defined in Figure 50. Teeth height parameter was varied between 0.5 and 1.0 mm in the test pipes to test the impact of it.

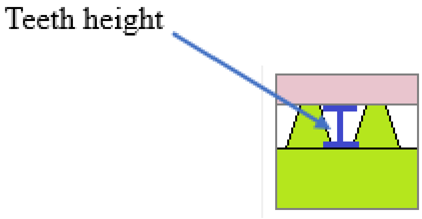


Figure 50. Teeth height.

Support angle

Support angle parameter defines maximum angle that will be supported. The value of the parameter must be between zero and ninety degrees ($0 < \alpha < 90$). The parameter is presented in Figure 51. Support angle was varied between 60 and 70 degrees in the test pipes. A value of 45 is the minimum for PBF of SS 316L but the value was increased to 60 and 70 degrees for supports wider support geometry.

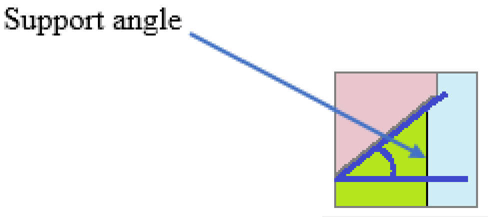


Figure 51. Support angle.

The data of the parameters that were varied is gathered in the Table 3 below. Support angle is chosen to be more than 45 degrees to obtain wider support structures below the pipes. Other parameters were varied by changing them only in small steps from the default parameters offered by the software developer DeskArtes.

Table 3. Test parameters for support structures.

Set number:	1	2	3	4	5	6	7	8
Web support parameters:								
X -and Y spacing [mm]	1.0	1.0	0.8	1.0	1.0	1.0	1.0	1.0
Up overlap [mm]	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Down overlap [mm]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Tooth support parameters:								
Teeth distance [mm]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6
Teeth base length [mm]	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Teeth tip length [mm]	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.2
Teeth height [mm]	0.5	0.5	0.5	0.5	0.7	0.8	0.5	1.0
Common support parameters:								
Support angle [degrees]	60	70	70	60	60	60	60	60

Figure 52 presents a view of parameters used in more detail. The views of individual test pipes with the supports designed is gathered together from the DeskArtes 3Data Expert software.

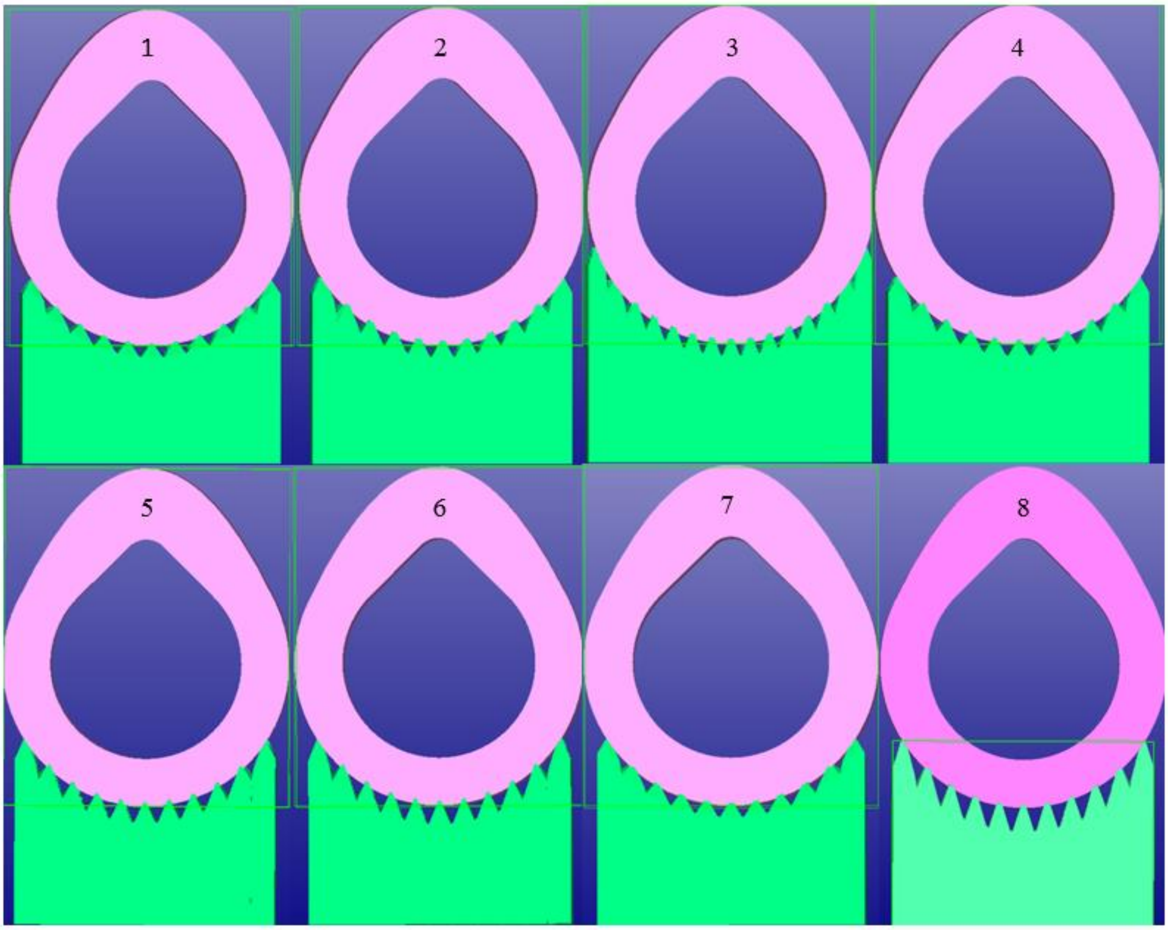
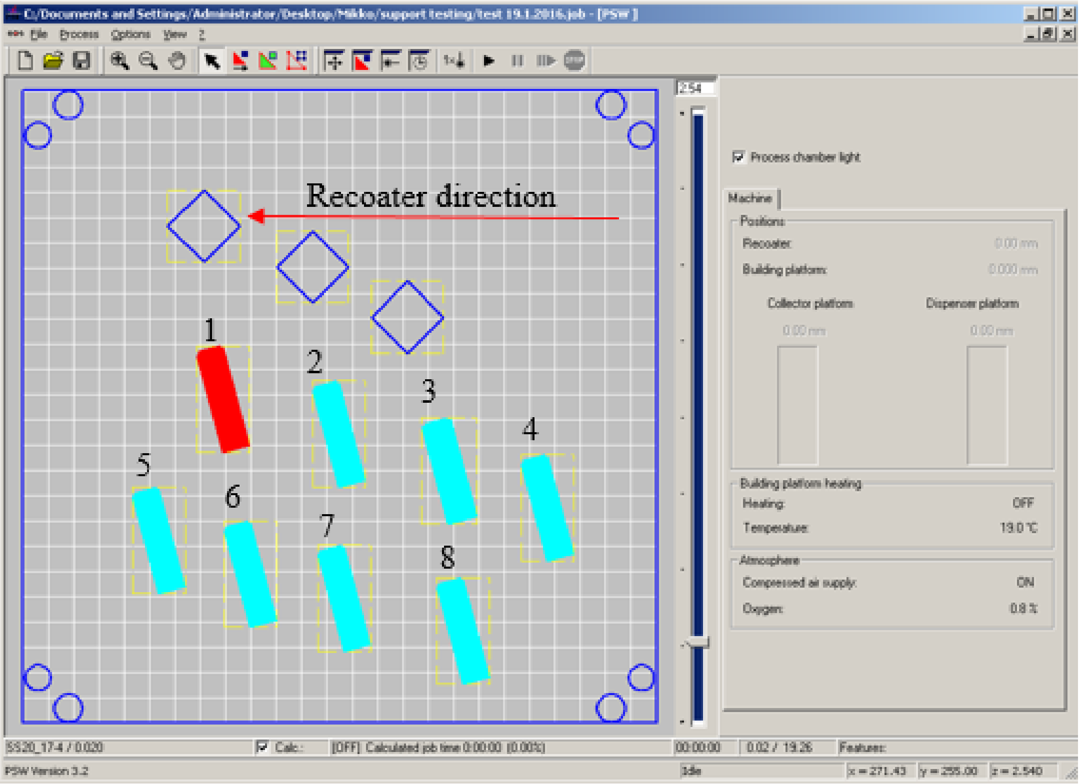


Figure 52. Representation of the designed geometries of the support structures.

As it can be seen from Figure 52, the connecting teeth and the supports of all test pieces vary from each other. The test pipes were checked for triangle errors with DeskArtes software at the same time as designing and creating the support structures. After the supports were created, the STL files were saved (each test pipe was saved as an own STL file and each support structure as an own STL file e.g. test pipe.stl and support_testpipe.stl etc.) Next phase was slicing of the STL files to SLI (Slice Layer Interface) format. This was done using Netfabb software.

After slicing the files the AM machine was prepared and the files were transferred to the AM machine control software PSW. Figure 53 presents the layout of the test pipes for manufacturing. The pipes are oriented in a way that they are not perpendicular to the recoater to avoid building defects caused by collision of recoater and test pipes.



C:/Documents and Settings/Administrator/Desktop/Mikko/support testing/test 19.1.2016.job - [PSW]

☑ Process chamber light

Recoater: 0.00 mm
Building platform: 0.000 mm
Collector platform: 0.00 mm
Dispenser platform: 0.00 mm
Heating: OFF
Temperature: 19.0 °C
Compressed air supply: ON
Oxygen: 0.8 %

SS20_17-4 / 0.020
☑ Calc.:
[OFF] Calculated job time 0:00:00 (0.00%)
00:00:00
0.02 / 19.26
PSW Version 3.2
Idle
x = 271.43
y = 255.00
z = 2.540

Figure 53. Layout for building test pipes.

The last phase of experimental part A was cleaning of the AM machine and removing the parts from the building platform for inspection.

12 RESULTS AND DISCUSSION OF EXPERIMENTAL PART A

Figure 54 presents the self-supporting geometry manufactured with PBF using EOS SS 316L powder as building material. The geometry of the test piece is successful i.e. it has no building defects visible by eye and the support structure has been appropriate. The successful build of the test piece enable the use of the geometry in experimental part B.

Figure 54. Test piece of a self-supporting hole-geometry.

SLM manufactured test pieces are presented in Figure 55. The test pieces are still attached to the building platform. There were no disturbances visible to eye during the manufacturing process.

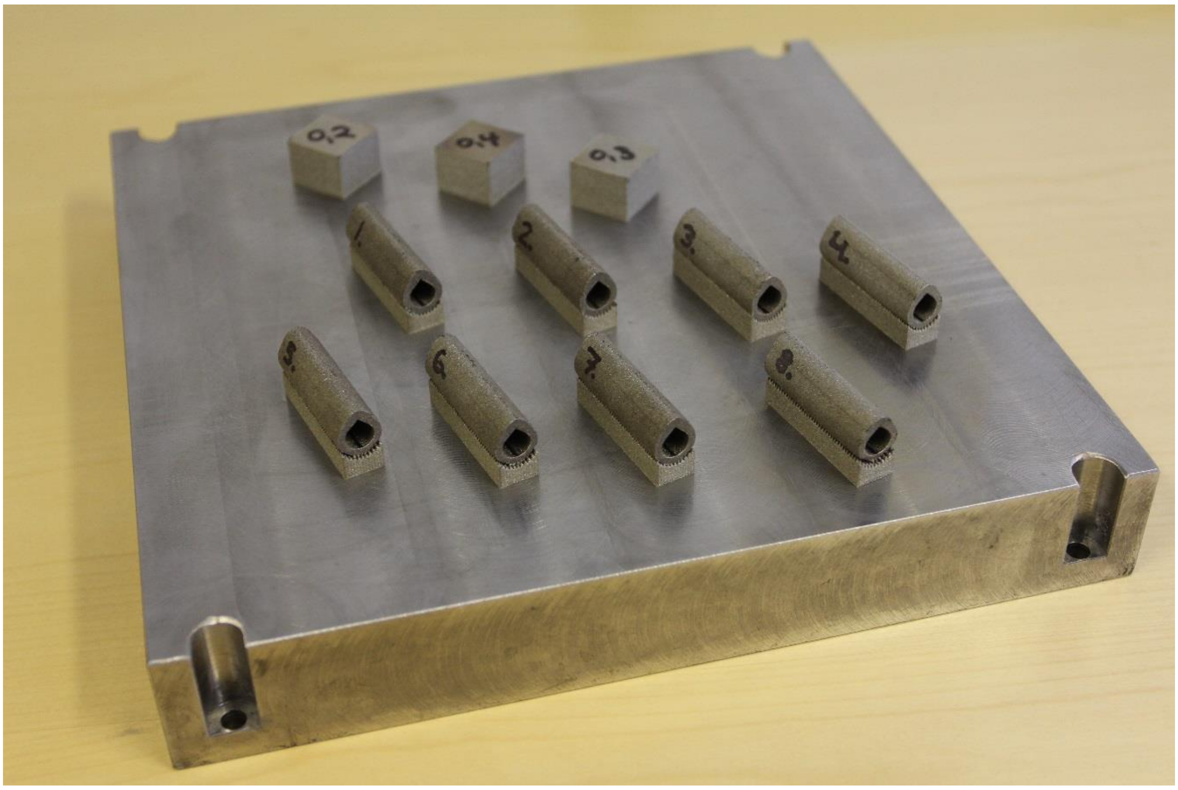


Figure 55. SLM manufactured test pipes on building platform.

Figure 56 presents one end of each test pipe and support structures of them. The parts are still attached to the building platform. The dark shadows in top of the internal hole-geometry of the workpieces is loose powder material and does not affect the quality of the pipes.

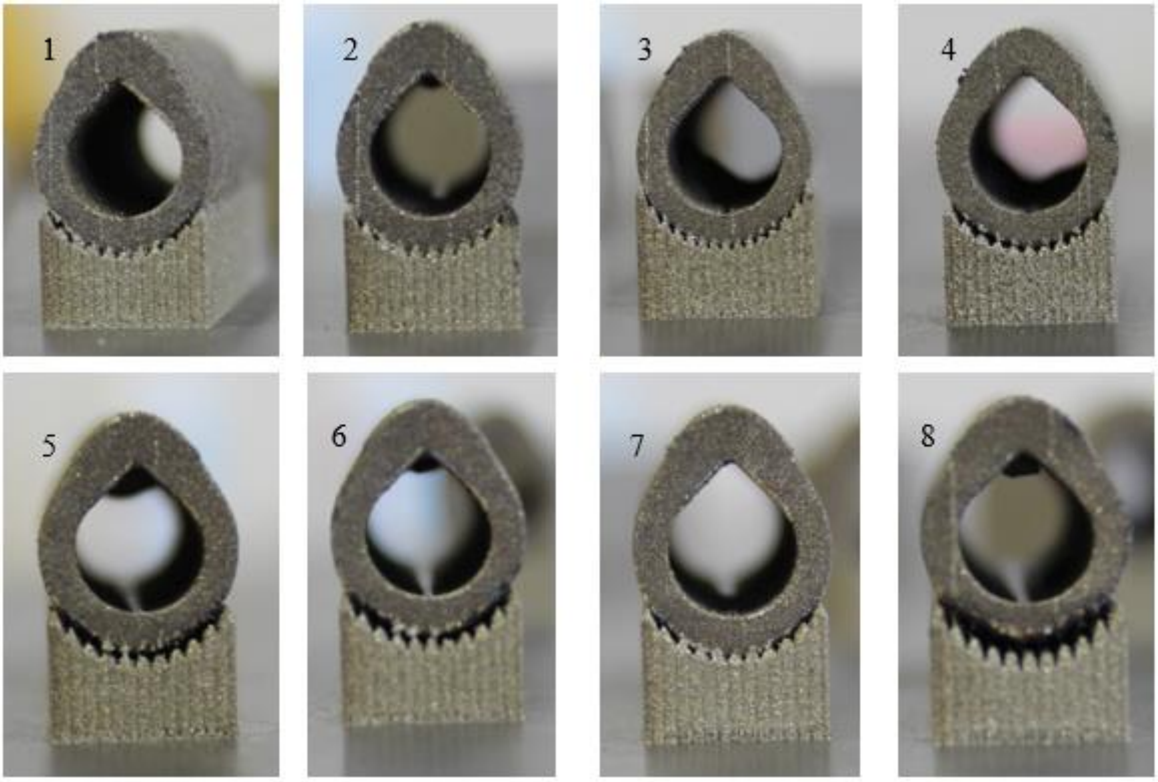


Figure 56. End view of the test pipes on platform.

As it can be noticed from Figure 56, the geometry of pipes 2, 7, 3, 1 and 4 is sufficient and the geometry of the pipes 5, 6 and 8 is not sufficient, when the evaluation is based on visual inspection of the end view of the of the test pipes. These sufficient pipes all have a proper connection between the bottom of the test pipe and the connecting teeth of the supports. This is elaborated in with help of Figure 57 by presenting the in an order from best to worst. The green arrow in pipe number 2 shows a well formed connection between the part and the connecting teeth of the supports. Conversely the red arrow in pipe number 8 shows unsuccessful connection between the test pipe and the connecting teeth of the supports. The unsuccessful connection is probably caused by curling phenomena i.e. the connection between the part and supports has been weak and the bottom of the part has curled away from the teeth of the support structure. This can be seen as deformation on the bottom of the test pipe, but it does not seem to affect the quality of the geometry in top of the pipe when evaluating it visually. The same deformation can be seen in pipes number 4, 5 and 6 also but the in these pipes the deformation is not as significant.

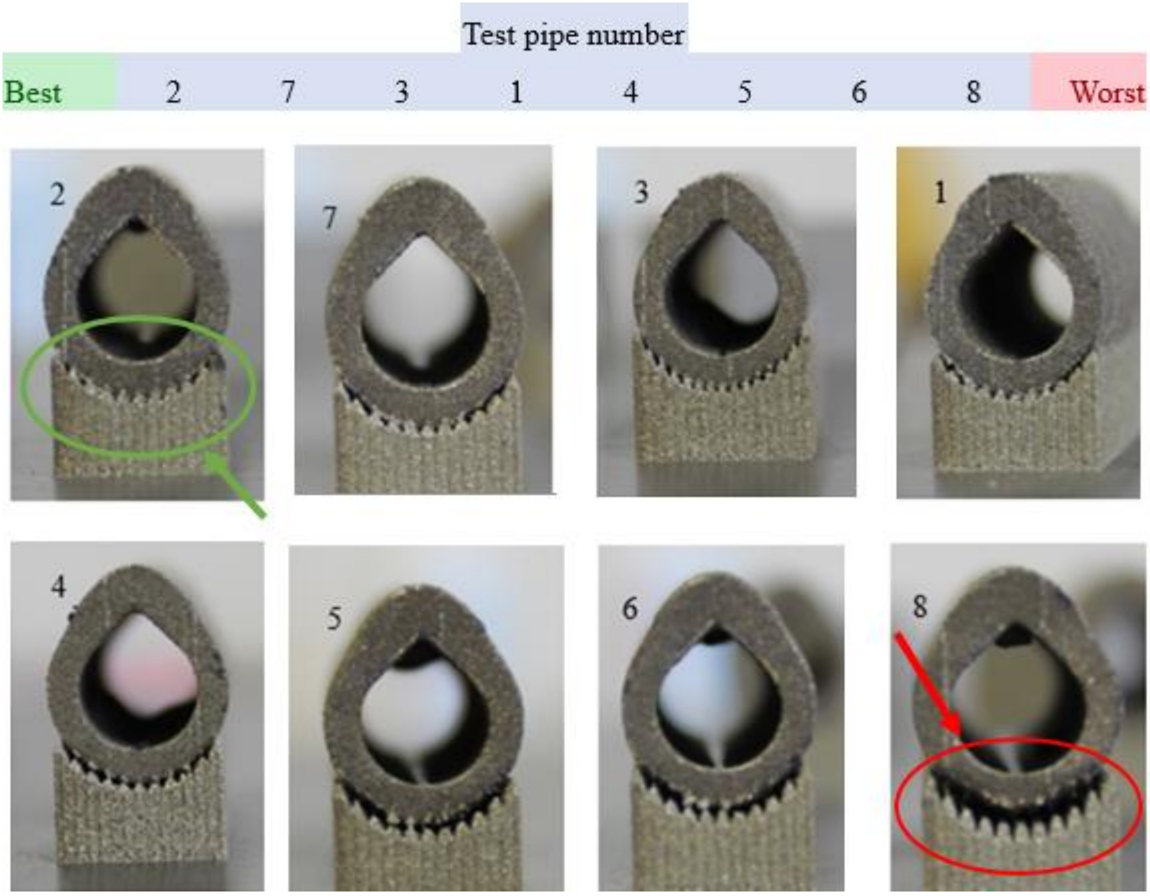


Figure 57. Visual inspection based on visual inspection of the formation of the geometry in the ends of the pipes.

In the best supports (2, 7, 3, 1 and 4) the outer geometry of the pipe is well formed and resembles the one drawn with the CAD software. However, the cost of this is that these test pipes are hard to remove from their support structures. On the contrary, the pipes having deformation in the outer geometry of the pipe are easier to remove. Figure 58 presents an example of a pipe with insufficient connection between the supports and the part, that the pipe was removed from the supports using only pliers. The droplet shaped geometry is deformed in the end of the pipe and the deformation follows all the way to the other end of the part.

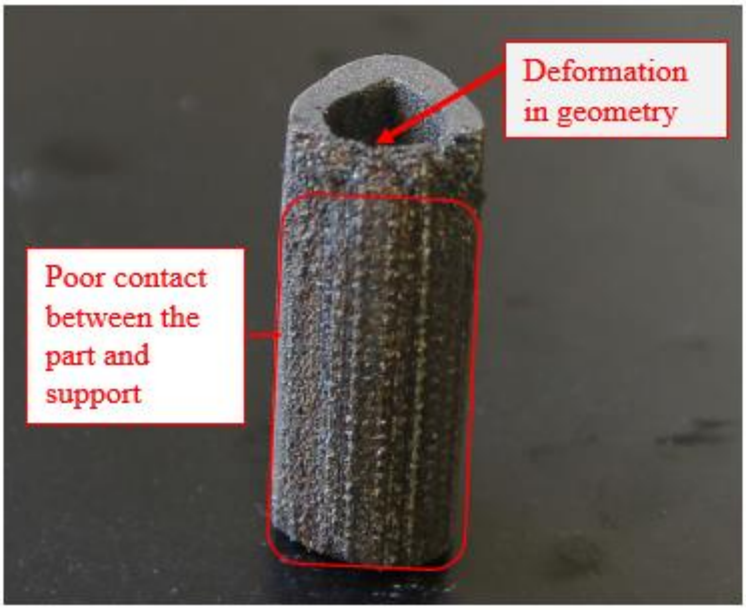


Figure 58. Example of insufficient connection between support structure and the part.

Large length of the work piece combined with insufficient support from the support structure can result the ends of the work piece to curl away from the surface. This phenomena can be seen especially in the example Figure 58 above, in the end view of test pipe number 8 but also in pipes 5 and 6 (see Figure 57). Increasing the teeth height parameter from 0.5 mm to 0.7 mm, 0.8 mm and 1 mm is likely the reason to this building defect (see Table 3).

When evaluating the test pipes from the side view all of them are successful. Only in pipes number 6 and 8, there can be seen a small building defect in the right end of the pipes. The building defect is marked with red arrows in Figure 59 and is probably caused by curling as the surface of the pipe geometry is not connected to the supporting teeth. The side view of the test pipes is presented in Figure 59. The silver and pink color in some of the pipes are traces of aluminum oxide spray used in surface analysis of the pipes, and do not affect the quality of the parts.

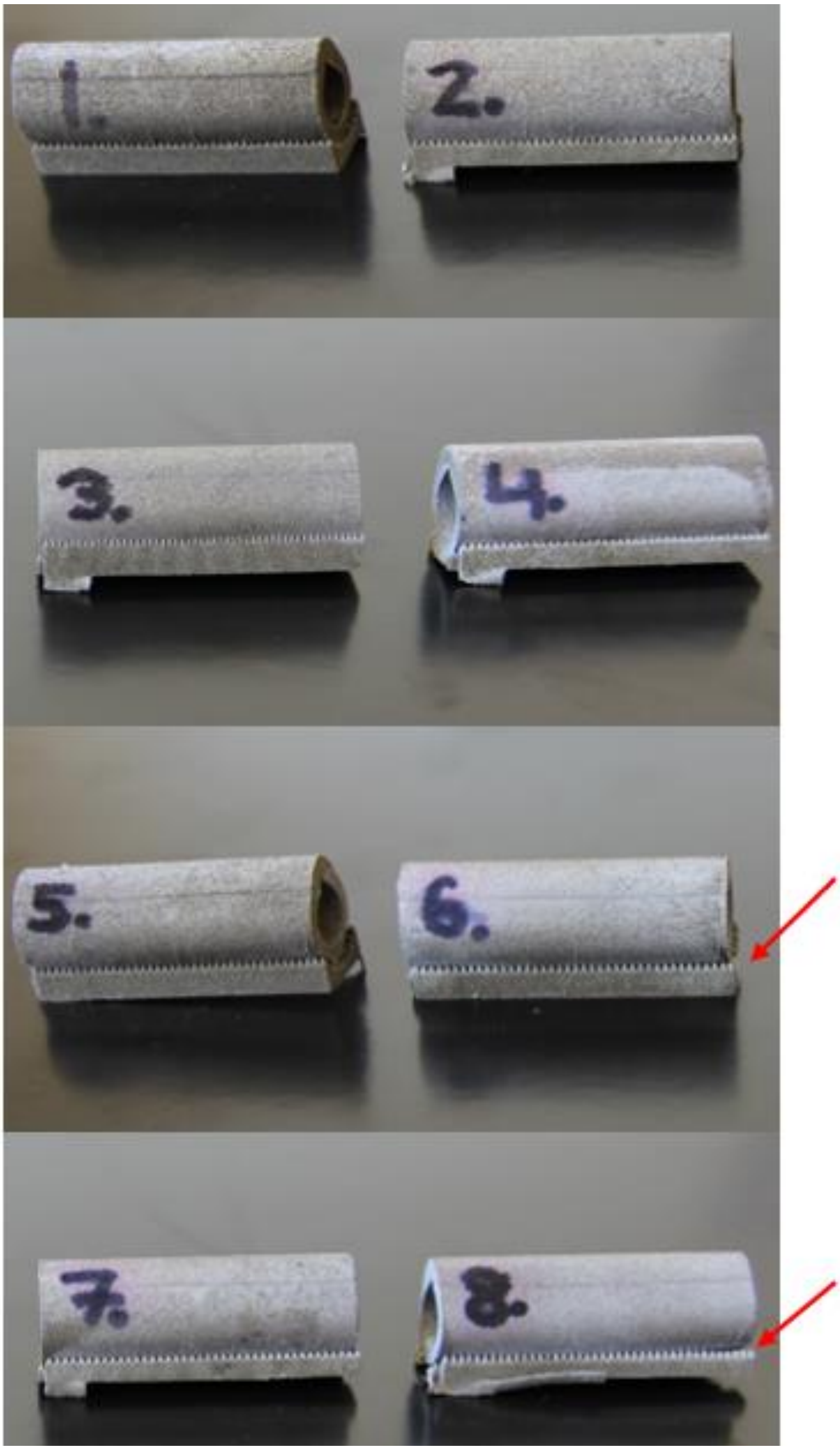


Figure 59. Side view of test pipes.

The objective of building the pipes with successful geometry was accomplished. In five of the test pieces of eight, the supports were strong enough to enable the build without deformations in geometry. The objective of building supports, which would be easily removed and strong enough to enable the build without deformations in the geometry was not achieved. All of the eight support structures were attached to the pipes so hard, that they cannot be removed without using tools.

12.1 Surface accuracy analysis of test pipes

The test pipes introduced and analyzed visually in the previous chapter were also measured using smartSCAN HE 4C scanning device. The measurements were performed in Titako Oy, Tampere. The test pipes were treated with aluminum oxide spray to get more accurate results. The measurements were compared to the volume of the original 3D model and the results are presented below in Figure 60 and in Figure 61. The scale in the figures is from -1 mm undersize to +1 mm oversize.

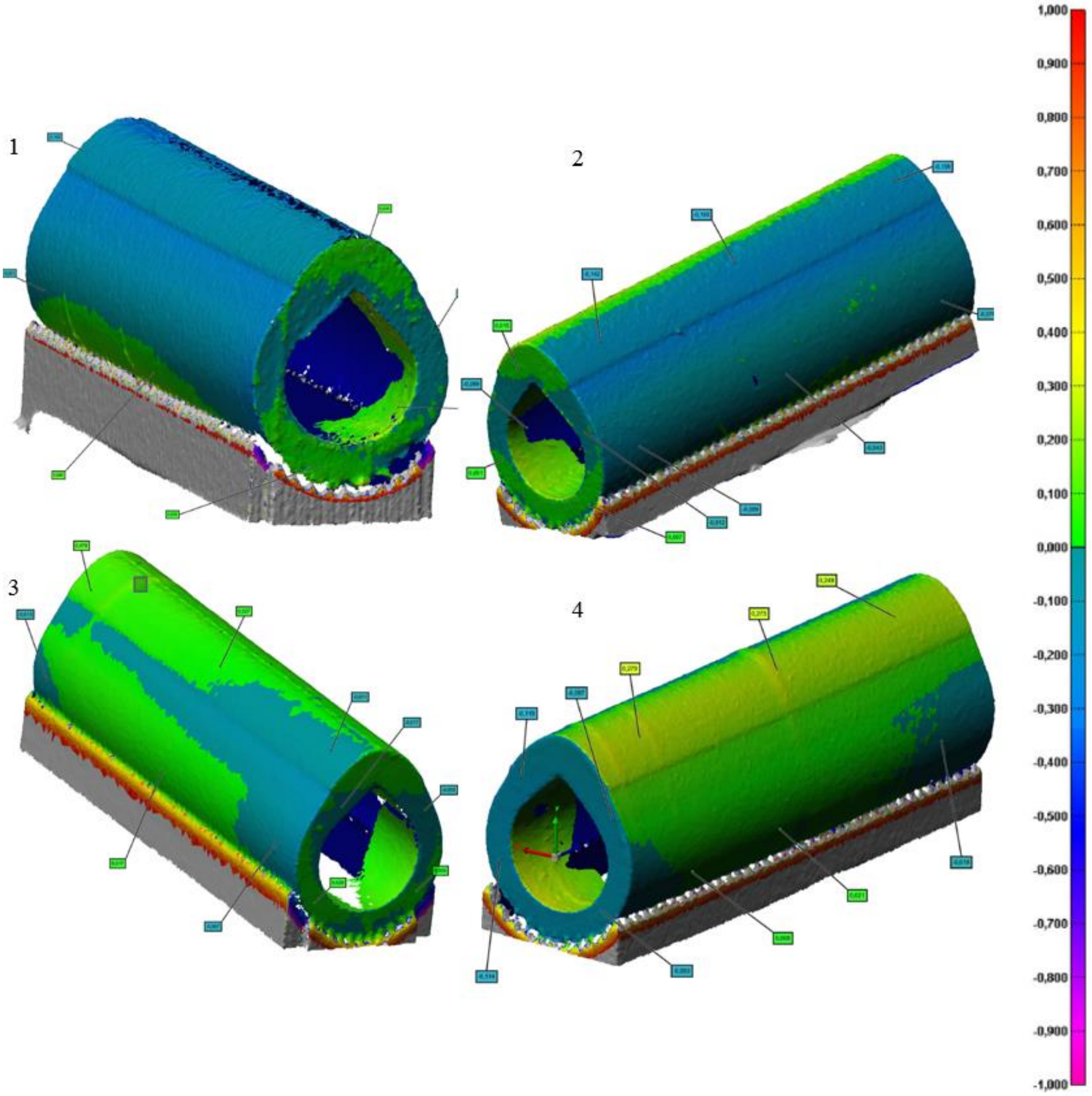


Figure 60. Surface accuracy of test pipes 1-4.

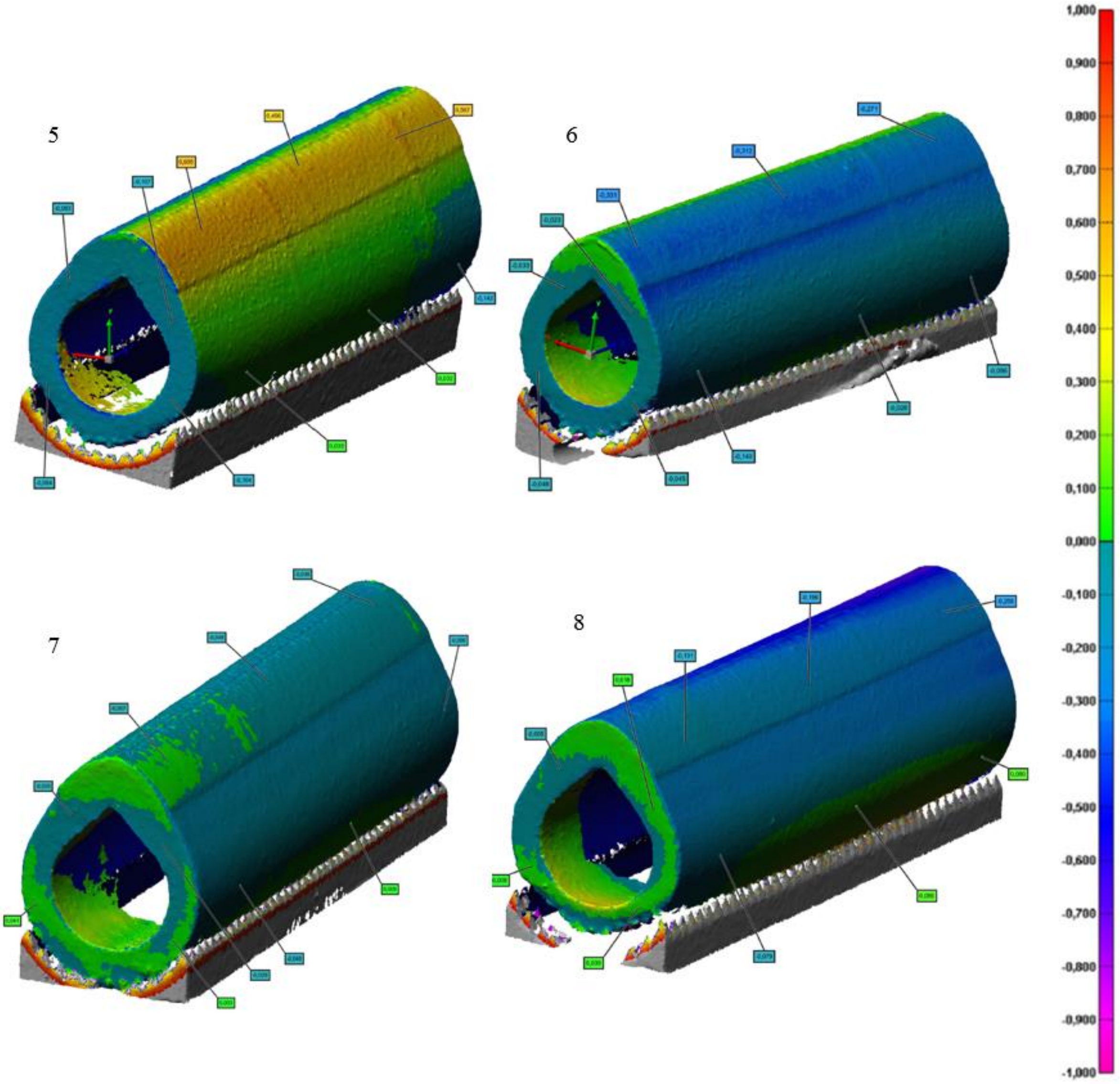


Figure 61. Surface accuracy of test pipes 5-8.

Figures 60 and 61 reveal, that the visual evaluation cannot not be used for estimate the surface accuracy of the model as the only inspection method. Comparing the scanned parts to the original CAD files reveal information, which cannot be seen by visual inspection. It can be noticed in pipes 5, 6 and 8 that the defect in the bottom of the side geometry has led to top of the geometry to be undersized. This was impossible to notice by visual inspection. Nevertheless, pipes 1 and 2 have a well formed bottom geometry and the top geometry of them is still under sized. A thing that is better visible from the surface scans than from visual inspection is that long teeth height combined with narrow teeth tip length can be the reason for oversized top geometry of pipe number 5.

13 AIM AND PURPOSE OF EXPERIMENTAL PART B

Aim of this case study is to design and manufacture a hydraulic block using PBF manufacturing method. Purpose for conducting this study is to improve the original part by applying AM design and manufacturing to it. Most important benefits, which AM can offer to this case are weight reduction and improvement of performance in the component and the whole system. More of the benefits offered by AM manufacturing technologies are described earlier in this thesis.

14 EXPERIMENTAL PROCEDURE

The case study was performed according to Figure 62.

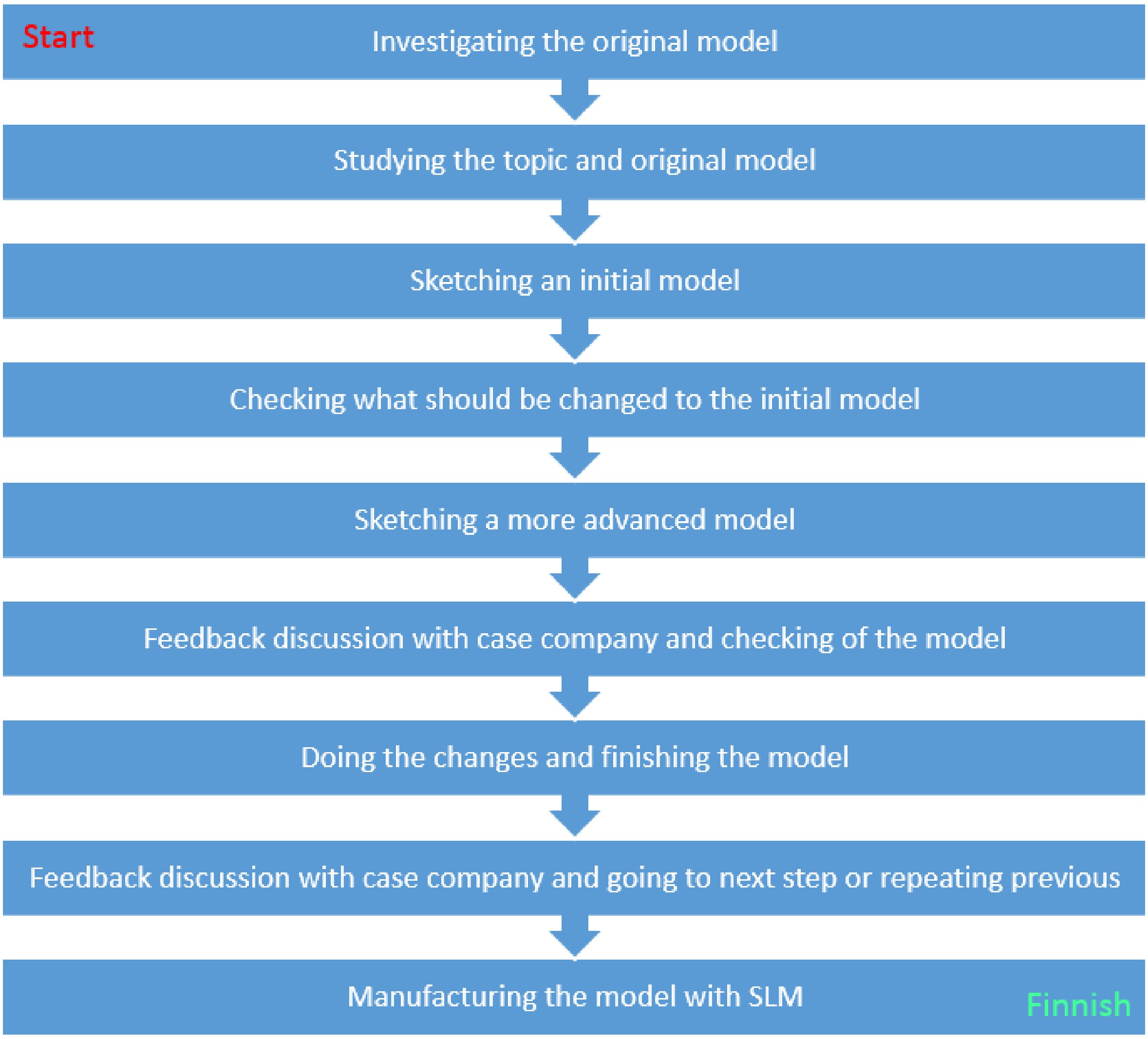


Figure 62 Flowchart of the design process.

A systematic way was created to perform the design process in organized and logical way. The design process was performed according to the pattern shown in Figure A notebook of how the design was proceeding was kept as long as the process continued.

15 RESULTS AND DISCUSSION OF EXPERIMENTAL PART B

The results of the experimental part B are explained and discussed in detail in this chapter. The progression of the design is explained with help of notes made during the design process, and with help of figures from all the most important stages of the design process. Finally the final version of the design is presented.

15.1 Investigating the original model, studying the topic and the original model

The original model was a traditional hydraulic block with several unnecessary drillings and a lot of weight due to the constraints of the traditional manufacturing technique used (machining). The original model of the hydraulic block is presented in Figure 63.

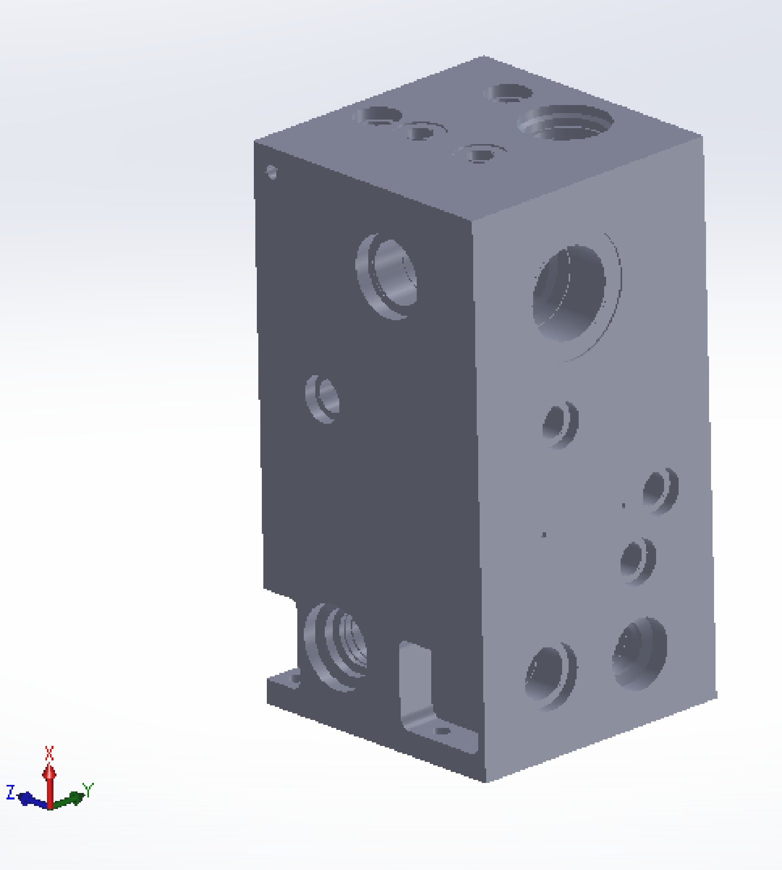


Figure 63. Original hydraulic block.

As it can be noticed from Figure 63, the original block is large and heavy (36 kg) due to the constraints from the manufacturing method used (machining). Thus the original model was not tried to be mimicked but instead, the schematic diagram was taken under investigation. Although the components and their operation principle was studied and the installation orientation of the components was checked.

Figure 64 illustrates the schematic diagram of the hydraulic block, which was used for designing the model.

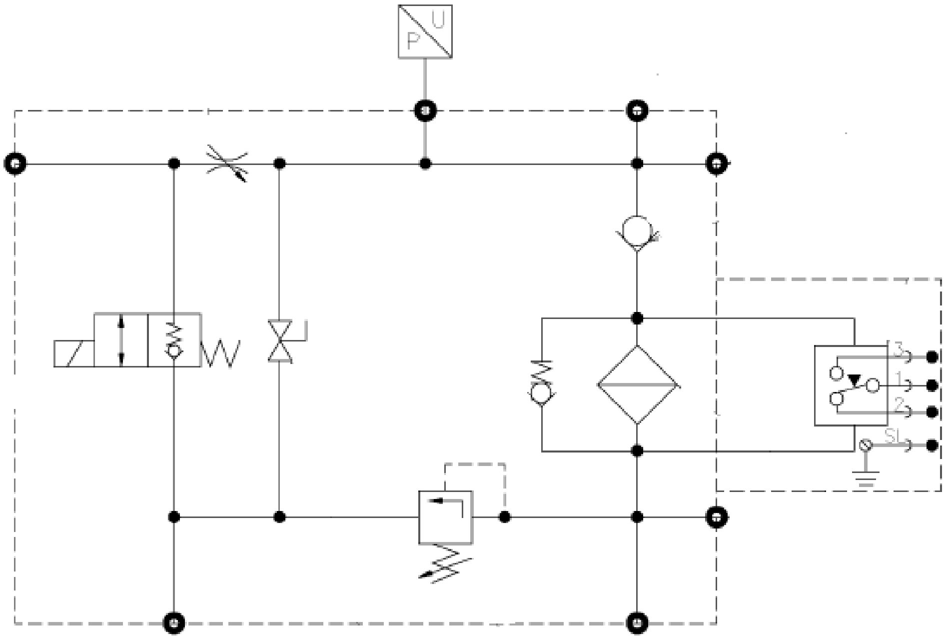


Figure 64. Schematic diagram of the hydraulic block.

15.2 Sketching an initial model

Sketching an initial model was started by mimicking the original schematic diagram. The attachment points could not be altered and the side with the connection out from the block, had to be free of other components. It was decided that the design could consist of small blocks connected to each other with pipes to exploit the benefits of additive manufacturing. The hydraulic components would be installed in the small blocks. The internal diameter of the pipes had to be 8 mm at least for sufficient fluid flow for the system and because of the complexity of the system, the orientation of the pipes could not be only parallel to building direction or perpendicular to building direction. Building round pipes with 8 mm internal diameter perpendicular to building direction would lead to building deformations (curling and sagging), caused by building on loose powder. Thus the pipes were designed to be the shape of a droplet to avoid building deformations.

The self-supporting geometry of the pipes used is presented in Figure 65.

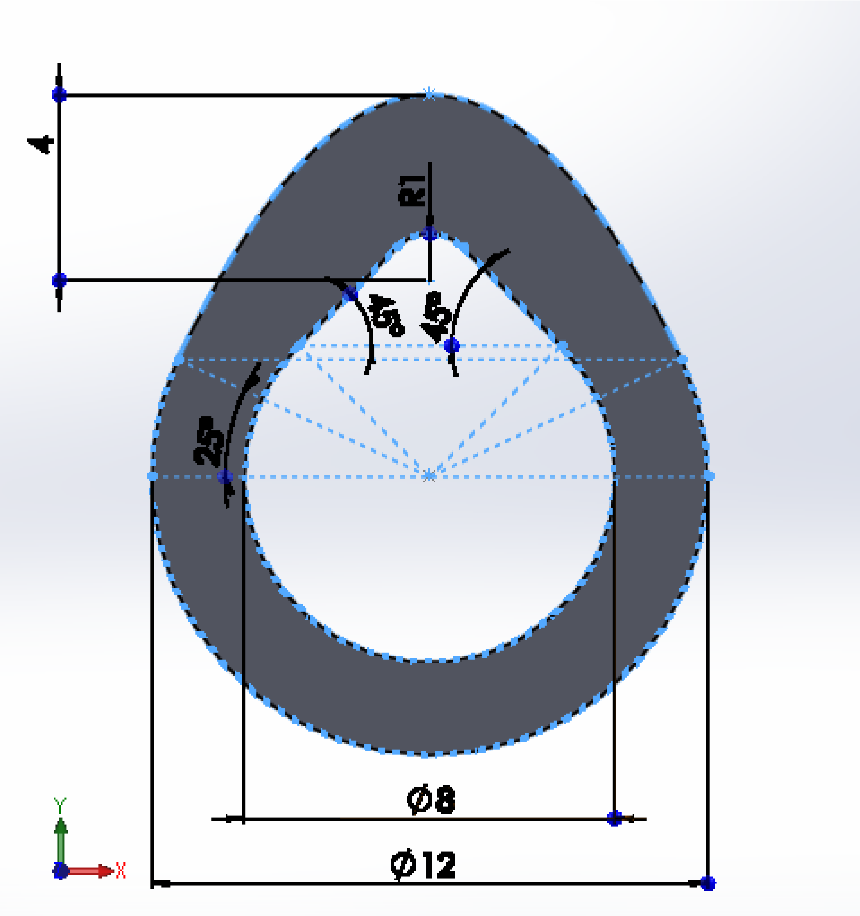


Figure 65. Self-supporting geometry of the pipes.

The chosen geometry was tested on experimental part A and the dimensions were chosen with help of the thesis of Daniel Thomas (Thomas 2009, p. 178–181). The use of round pipes parallel to building direction would have been ideal, but it was not possible due to the fact that the system consists of several blocks, which cannot be stacked up on another because they have to be supported all the way from the building platform. This lead to a design where the model is build parallel to the building platform thus minimizing the need for support structures for the blocks.

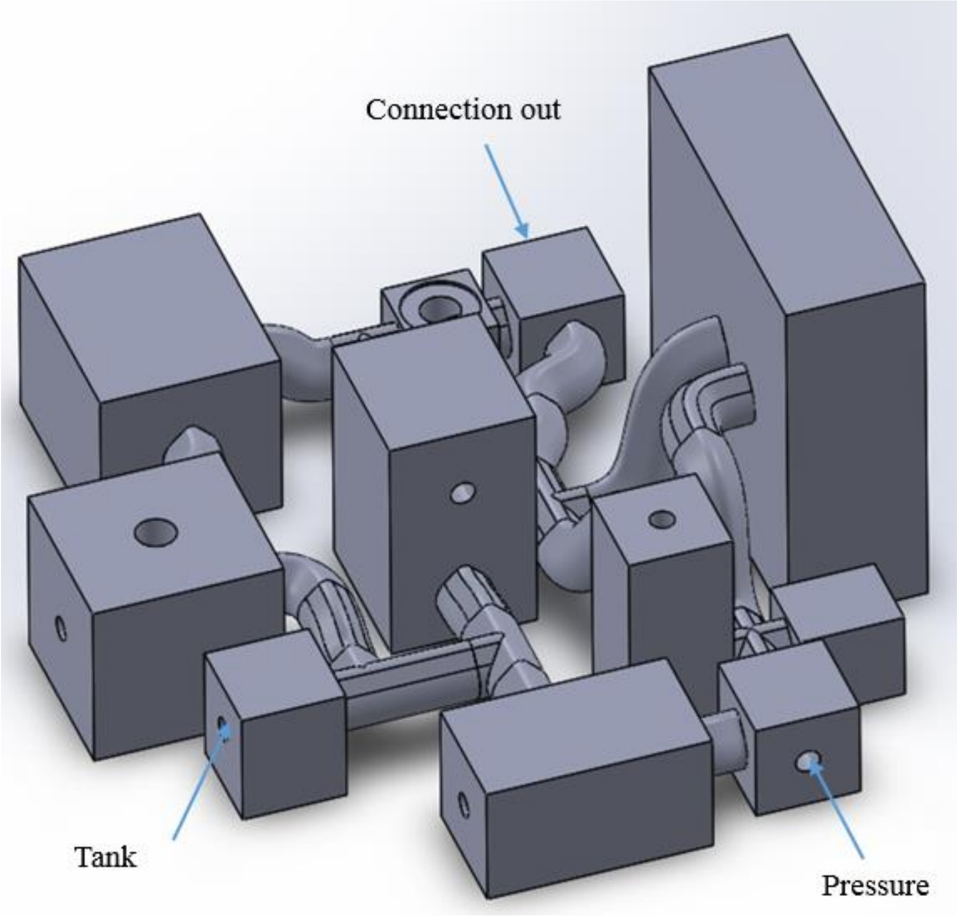


Figure 66. Initial model.

Figure 66 presents the design of the initial model. As it can be seen from Figure 66, the model resembles the schematic diagram. Blue arrows indicate where the connections are located. The blocks are designed for specific hydraulic components and they dimensions are chosen with help of the cavity machining instructions offered by the component manufacturers.

15.3 Checking what should be changed and sketching a more advanced model

The model was examined and many propositions for improving the model rose up. Figure 67 presents the most critical issues in the initial model (marked with red arrows). The filter housing is heavy and large in size, there is an unnecessary curve and some blocks have poor access for machining cavities for the hydraulic components.

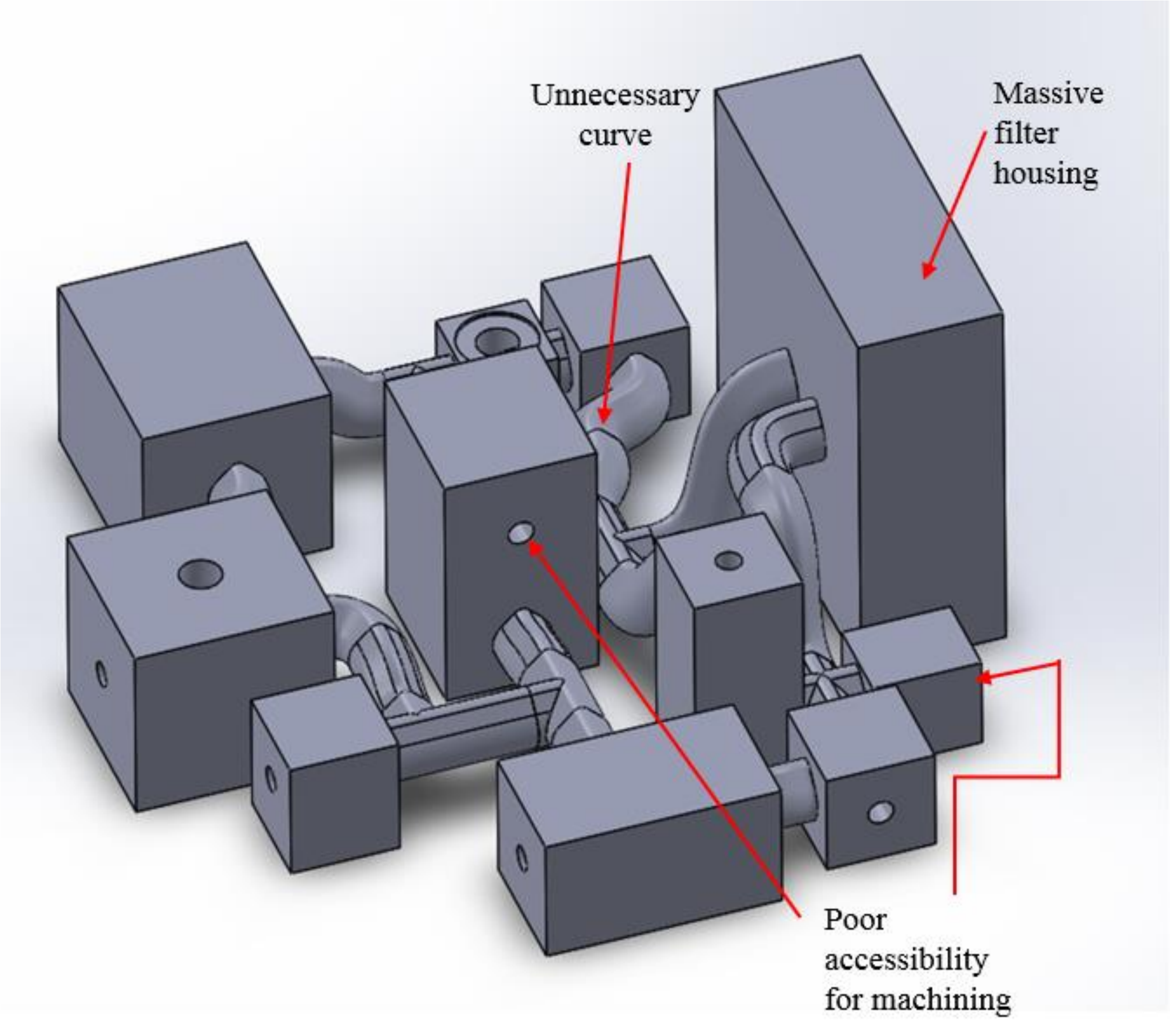


Figure 67. Problems in the initial model.

15.4 Sketching a more advanced model

The filter used was changed to a different model that contains the filter itself and other components used in the assembly reducing the size and weight of the system and making it simpler. The filter is assembled to the hydraulic circuit before the pressure connection to the redesigned hydraulic block. The model was then fitted to the place of the original hydraulic block in the system and it was noticed that it should be rotated around the building axis and that some of the components can be fitted into a same blocks reducing the weight and size of the model again. The model was redesigned in a way that most of the components could be installed from the upper side of the model.

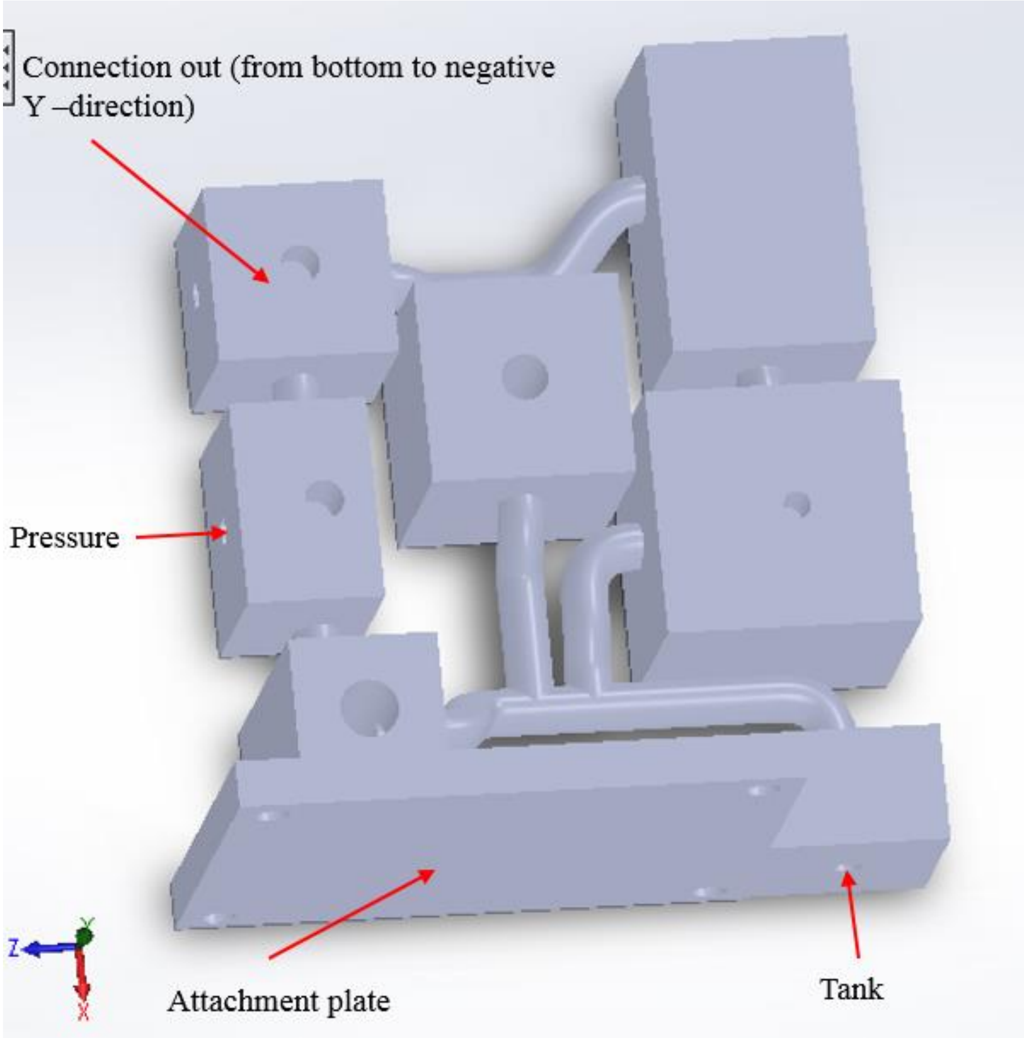


Figure 68. Advanced model.

Figure 68 presents the more advanced model, which is simpler, lighter and smaller than the previous model. Red arrows indicate the most important connections and the added attachment plate. It was decided that the final design of the blocks (removing excessive material with fillets) and designing the final shape of the attachment plate will be done when the model is ready in functional point of view.

15.5 Feedback discussion with engineers of case company, checking and changing the model

The model needed some adjustments for the small blocks for cavity machining and the attachment plate for reducing the mass of it.

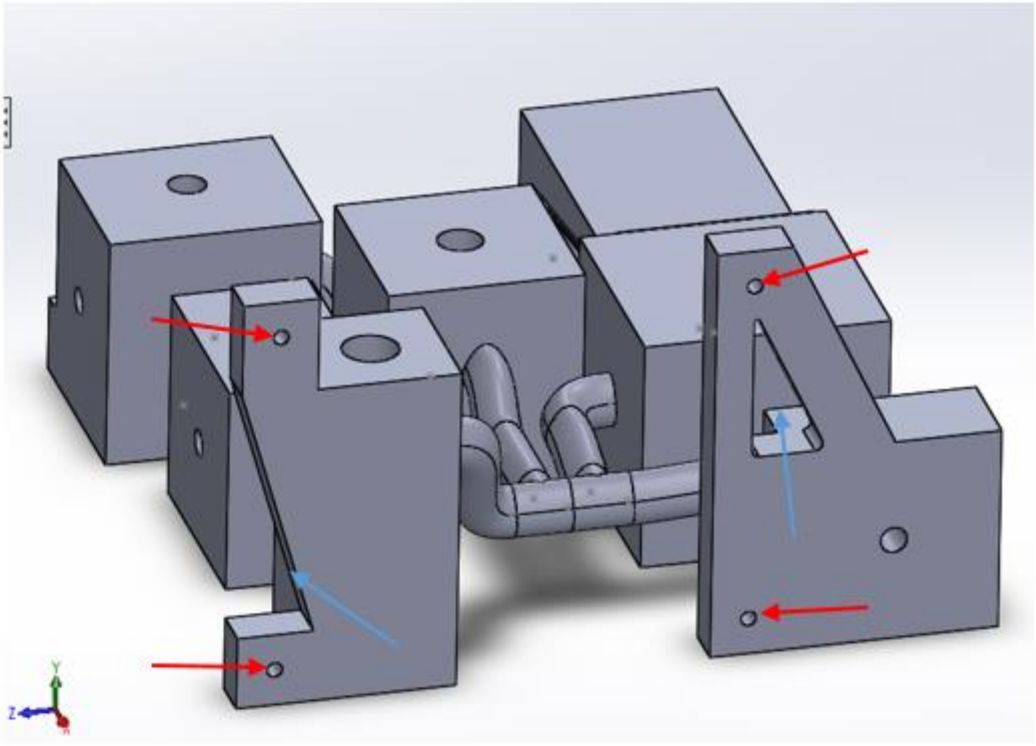


Figure 69. Advanced model with attachment points

Figure 69 presents the advanced model with the attachment points consolidated in the design (red arrows) of the model itself. This part consolidation reduces weight and building time. The blue arrows indicate the parts where design for additive manufacturing was used to save material and reduce weight and building time by removing excessive material from the model. The holes in the small blocks will be cavity machined for installation of hydraulic components. The diameter of holes perpendicular to building direction (Y-axis in Figure 69) are 7 mm for enabling safer building process. The diameter of holes parallel to building direction vary depending on the diameter of the cavity to be machined.

Figure 70a presents the external supports added to enhance the rigidity of the model. Figure 70b presents the supports marked with green arrows in detail and figure 70c the supports marked with red arrows. Supports in figure 70b are better when the length of the support (distance in X-axis direction) is large and supports in figure 70c, when the length is short.

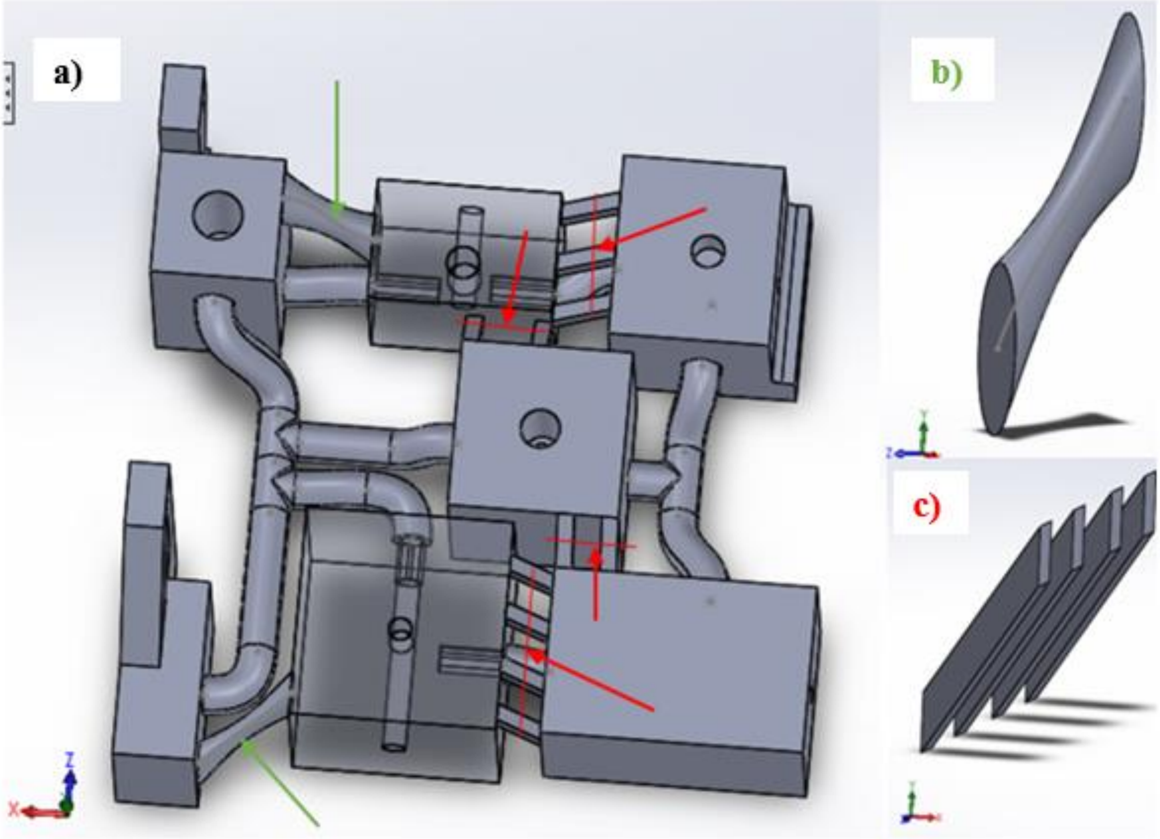


Figure 70. Advanced model with added supports. Green arrows refer to b) and red arrows to c).

Support structures will be generated between the bottom of the pipes and the building platform. Leaving the supports there will enhance the rigidity of the system even more. Support structures will be generated to the bottom of the blocks also for easier removal from the building platform.

Design for additive manufacturing was used where it was possible to be used. The restrictions having the most influence in the design of the model were the volume required around the hydraulic components and the challenges in designing the routing of the pipes with SolidWorks 3D modelling software. A more compact design would have been ideal, but it could not be implemented with the design software. Using droplet shaped pipes retaining their geometry as the pipes turn was a complicated task to do in tight space. Therefore all the individual blocks are not attached to each other or at imminent distance from each other.

15.6 Final adjustments to the model before manufacturing

Fillets were applied to the small blocks in the model. Some features were filleted less than the others to avoid compromising the strength of the system. After the filleting it was noticed that the supports added manually to strengthen the system for cavity drilling, were misplaced and had to be altered. This can be seen in Figure 71. The misplaced supports are indicated with red arrows.

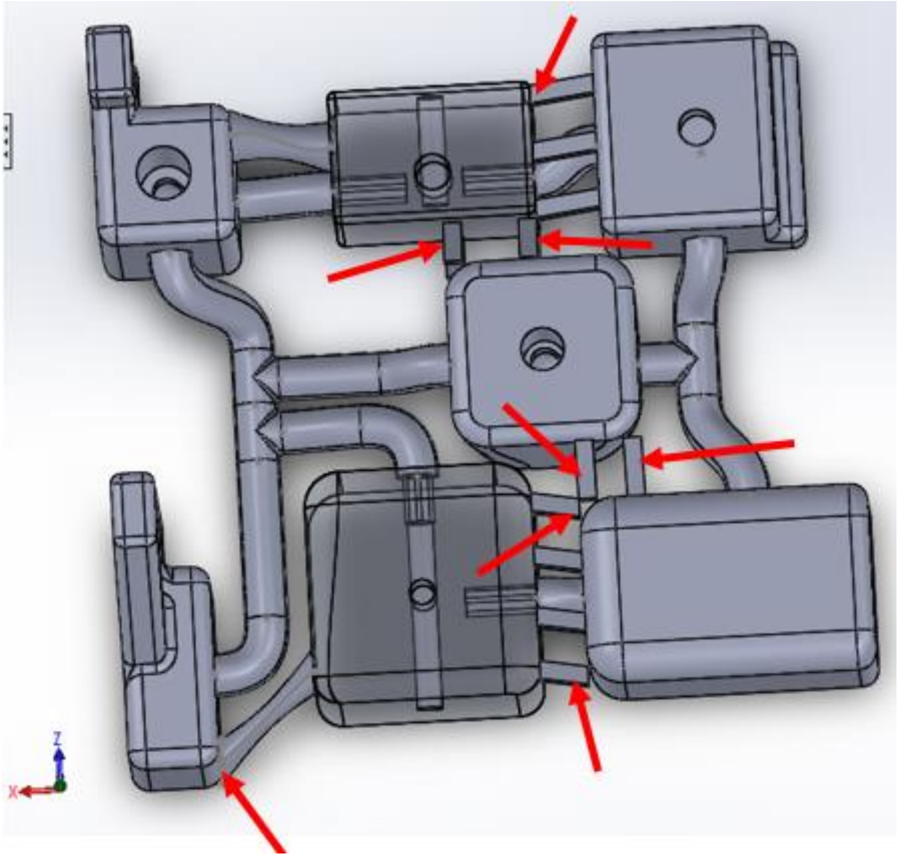


Figure 71. Advanced model with misplaced supports after filleting.

The supports were designed using X shaped self-supporting geometry, which can be seen in Figure 72. The dimensions of the geometry vary on the model depending on the location.

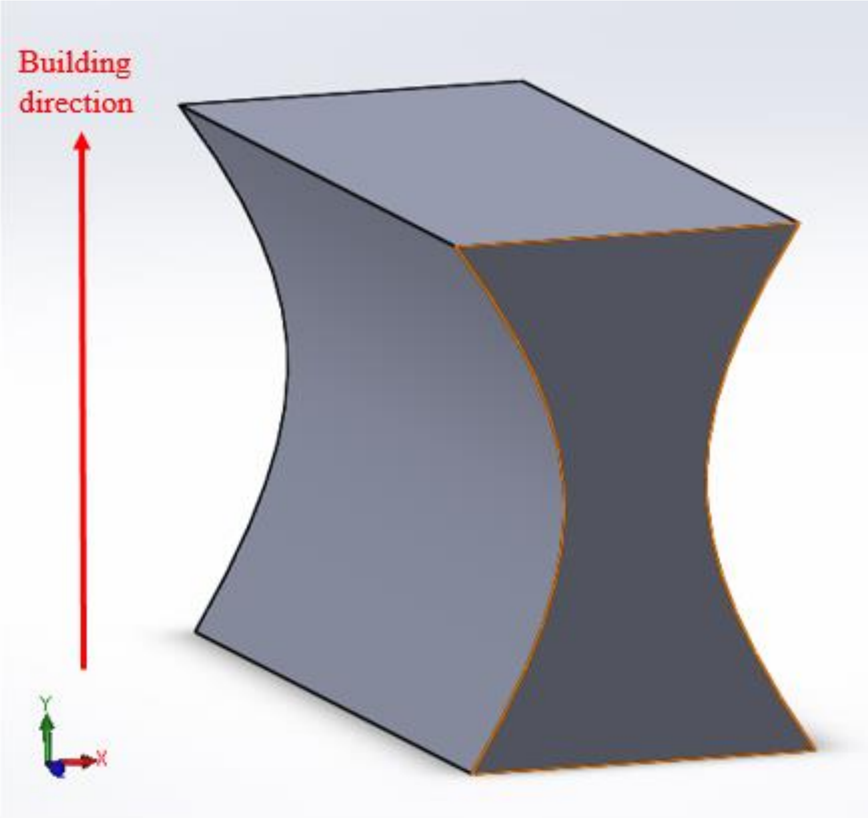


Figure 72. X shaped support geometry.

The new supports were positioned against the forces, which will be caused by cavity machining after the manufacturing process. The supports are presented in figure 73 and are pointed out with red arrows. The end of the supports were also filleted for smoother binding to the blocks. This is at the same time the final model in this thesis. Due to the time limitations of the thesis the model could no more be altered or improved even though there could have been several ways to improve the model. The manufacturing of the model had to be let out of this thesis because of the time limitations also. The model will be manufactured and the cavities machined in spring 2016.

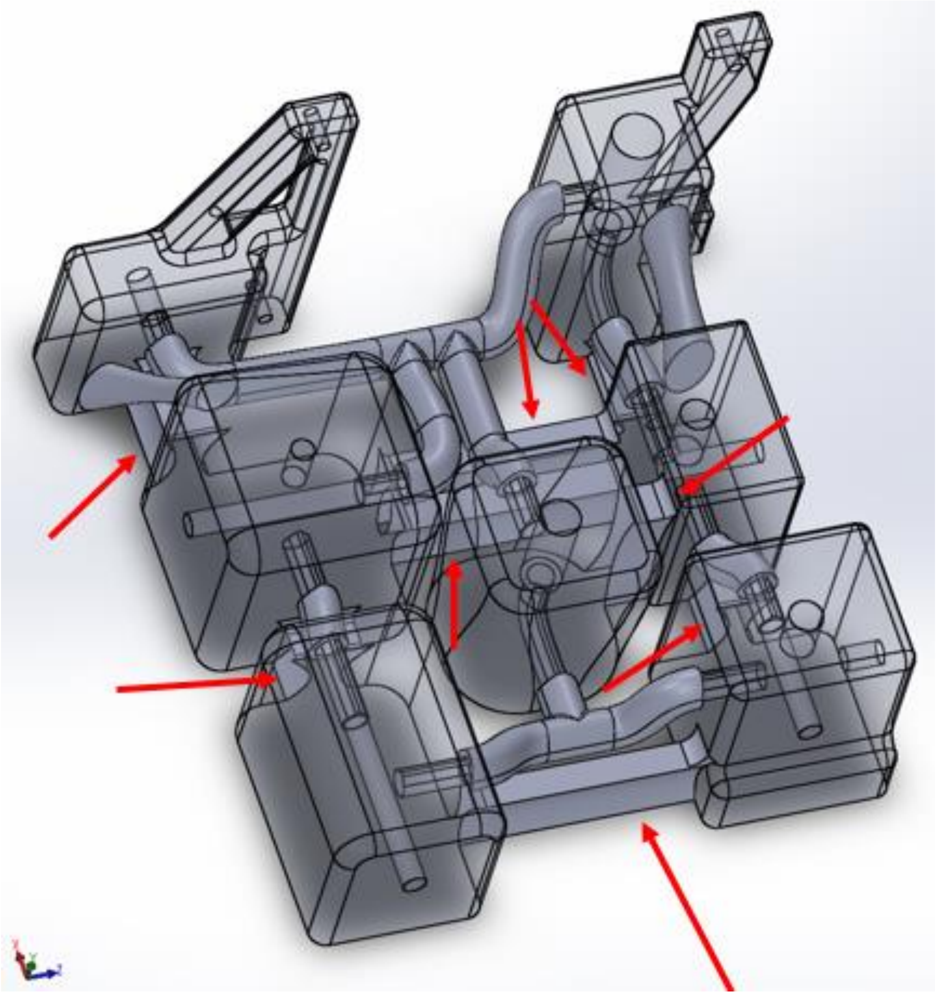


Figure 73. Advanced model with new supports.

The weight and dimensions of the conventionally manufactured hydraulic block were 36 kg and 145x145x275 mm. The weight and dimensions of the additively manufactured block will be 9.7 kg and 197.5x208.5x115 mm. The weight of the models designed for additive manufacturing was estimated using the mass properties tool in SolidWorks software. The weight of the additively manufactured model will be increased by the support structures built for the manufacturing process. However the cavity machining will remove material from the model so the increase of the weight of the model will not be significant. The weight reduction achieved with the new design is 72 % and it is illustrated in Figure 74.

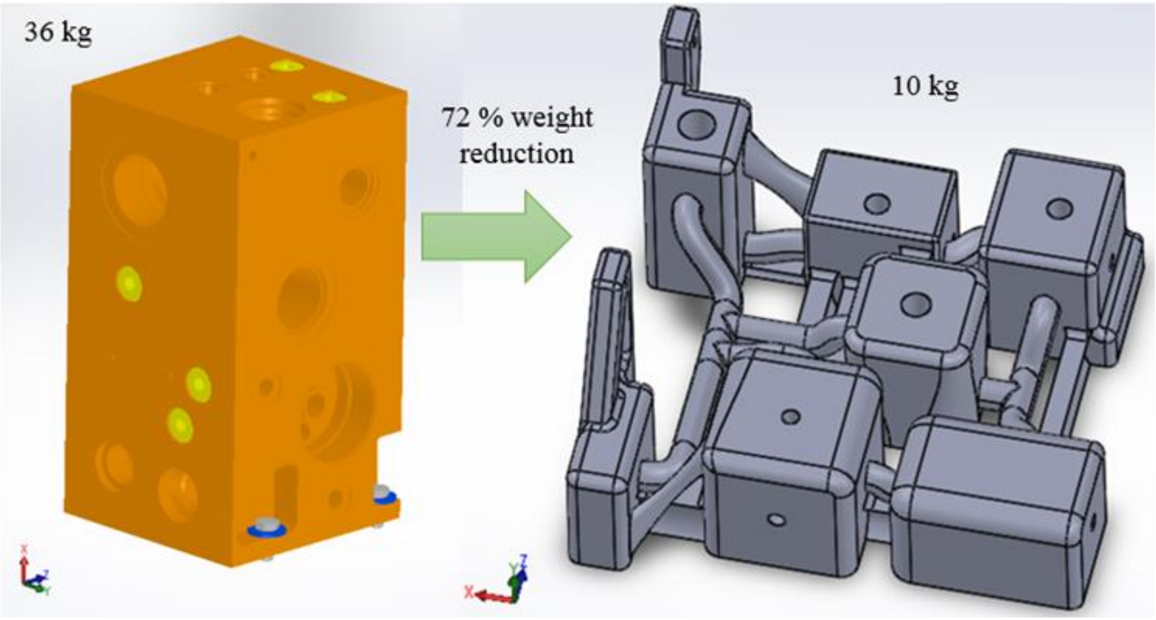


Figure 74. Comparison between the old and the new model.

The channels and pipes inside the new model have no sharp angles and there are no unnecessary drillings in the system. On the contrary all the channels inside the old model have sharp angles due to the manufacturing method. The amount of unnecessary drillings is reduced from 7 to 0, as 2 of the plugs are located in the sides hidden in the Figure 74. Therefore the fluid dynamics of the system should be improved from the original model. Part of these unnecessary drillings can be seen in the Figure 74 above, as they are clogged with the yellow plugs. The analysis of the fluid dynamics were let out of the thesis due to time and resource limitations. Figure 75 presents another view of the final design.

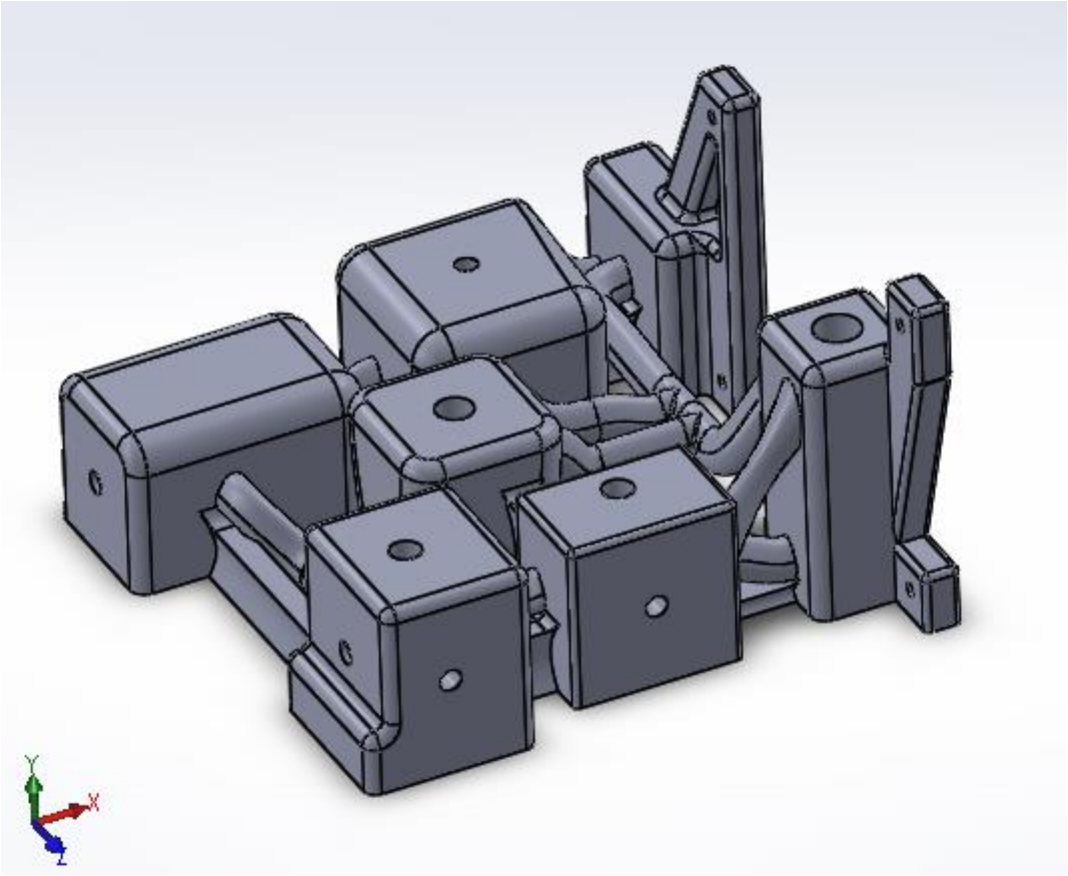


Figure 75. Final version of the design.

16 CONCLUSIONS

The aim and purpose for conducting this study was to re-design a hydraulic block to reduce the weight of the part, increase the functionality of the part and to enhance the performance of the part. The study was carried out in Laboratory of Laser Processing of Lappeenranta University of Technology. The study was conducted by planning the design process and designing the new part with SolidWorks 2015 CAD software. A flowchart of the design process is presented in Figure 76.

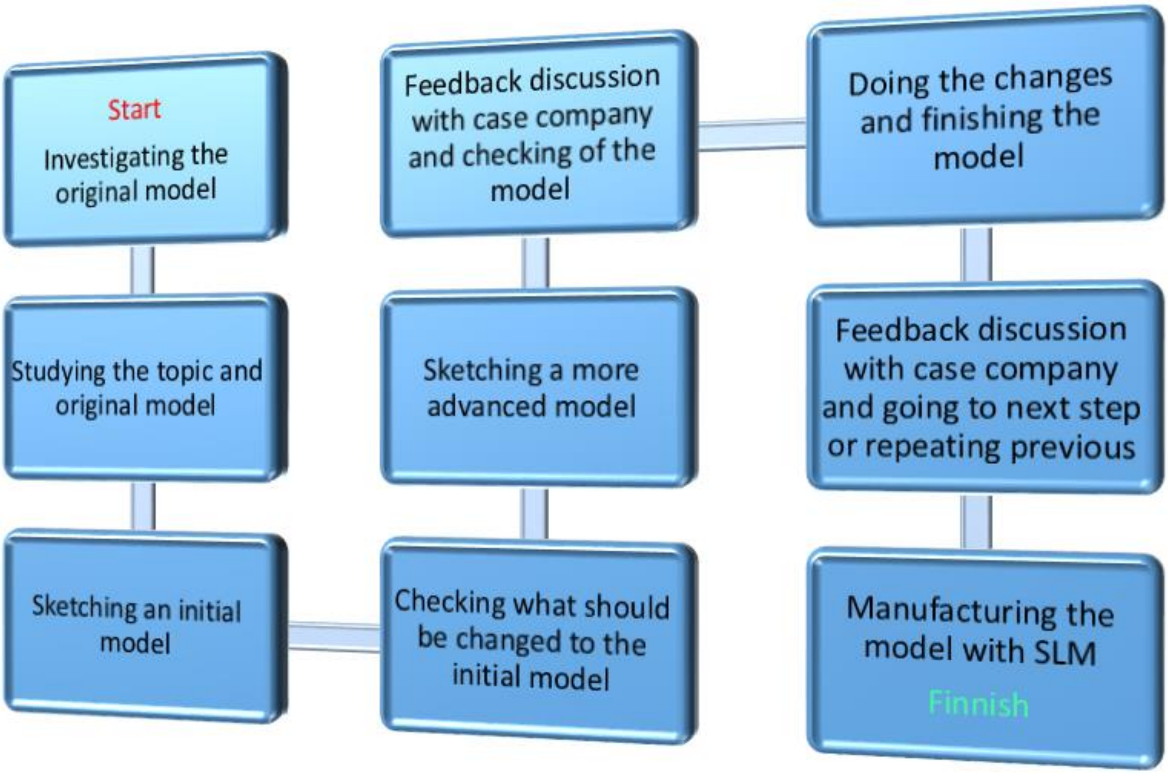


Figure 76. Flowchart of the design process.

The design process was partly conducted in co-operation with design engineers of the case company. It can be concluded that the achieved weight reduction of 72 % is remarkable. It can be also concluded that the performance of the hydraulic block should be improved as a result of absence of the unnecessary drillings and as a result of smoother geometry of the channels and pipes. The hydraulic components at the market at the present are designed to be installed in large hydraulic blocks instead of minimal AM hydraulic blocks. By reducing the size of the components and the material needed around them, this and other AM designed hydraulic blocks could be designed even more efficiently.

Designing a product for powder bed fusion of metallic materials is a challenging project. Design for additive manufacturing has many limitations and only a small amount of products are suitable for additive manufacturing. Nevertheless additive manufacturing has significant potential in manufacturing products suffering from limitations caused by the conventional manufacturing methods. The designer must approach the assignment in a new perspective. The limitations of conventional manufacturing methods must be forgotten to fully utilize the potential of additive manufacturing. Using this approach requires deep knowledge of the design for additive manufacturing. The designer must have a profound knowledge from the additive manufacturing process, which will be used for manufacturing and also about the process chain of the process in question. Powder bed fusion of metals as the most challenging additive manufacturing method has several strict design limitations. Even though having the knowledge from additive manufacturing the designer must also be aware that the product will be most likely also machined or treated with conventional manufacturing methods in the post processing stage of additive manufacturing. In the case study of this thesis, the product will be machined for creating the cavities for the hydraulic components to be installed in it. This had to be taken into consideration when designing the product. The small blocks were designed using the instructions given by the component manufacturers for cavity machining.

As pointed out in the thesis, DFAM procedure includes several phases and things to consider. An approach for beginning a new study for DFAM is presented in Figure 77. This kind of approach could be used when beginning a design of another hydraulic block for AM with more time and resources. This kind of approach would improve the functionality, shape and weight of the hydraulic block even more as it would utilize also FEM analysis and CFD (computational fluid dynamics) analysis. The importance of individual phases is case dependent and the order of the phases cannot be completely predetermined.

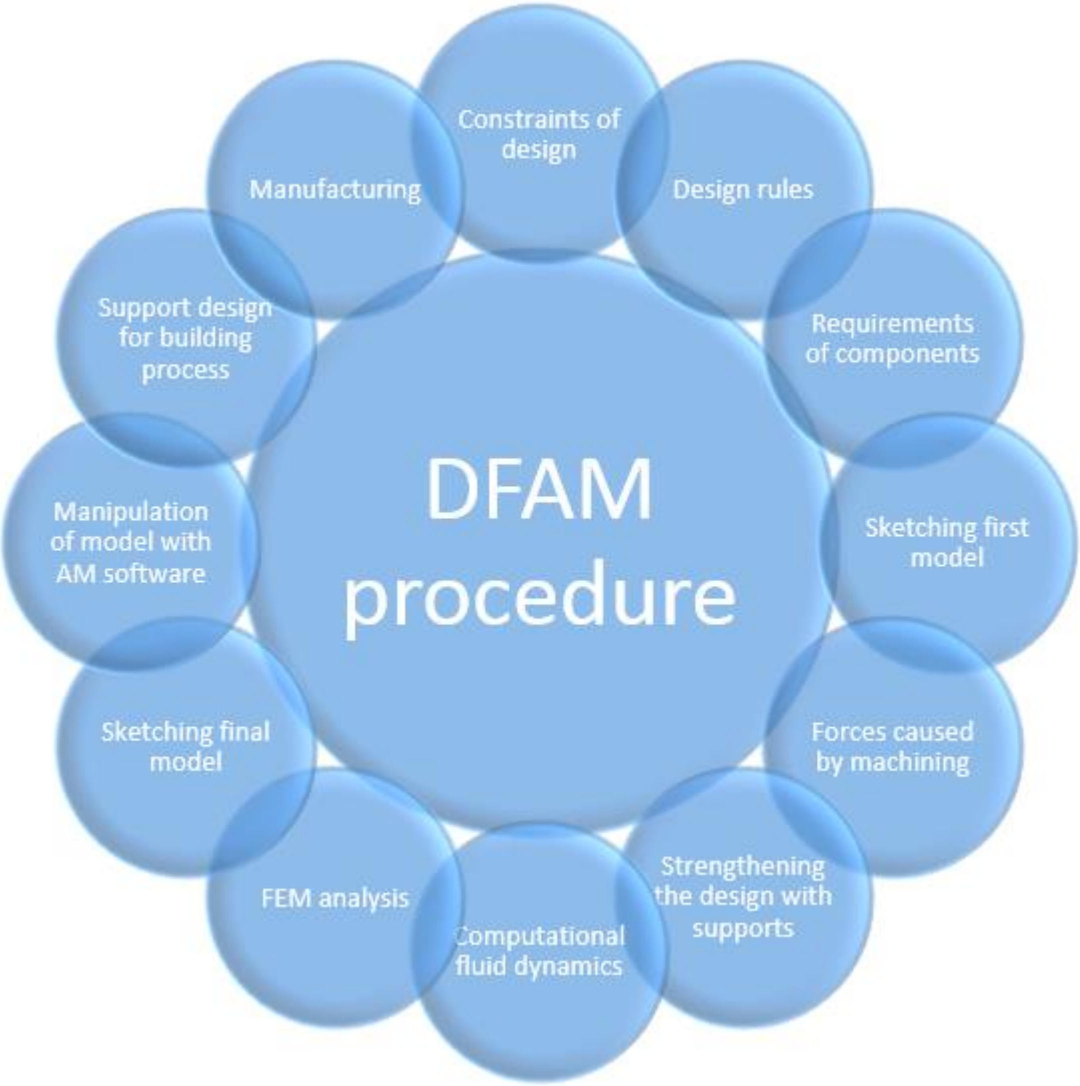


Figure 77. Possible DFAM procedure for future research.

It was noticed that designing a product for additive manufacturing is a time consuming process that needs several iteration loops. The expertise of several engineers was needed to design the product. The knowledge from additive manufacturing came from Laboratory of Laser Processing Technology at LUT and the knowledge of designing hydraulics from Metso Minerals Inc.

It can be concluded that the weight saving in the additively manufactured model compared to the conventionally manufactured model is significant. The results are promising and indicate that universities and companies can design improved products for Finnish industry in co-operation.

17 FURTHER STUDIES

The development of the model was left where it is due to the time and resource limitations of the thesis. Therefore the development of the model could be continued and the model could be improved in several ways. The fluid flow inside the channels and pipes of the model could be optimized using CFD, machining of the cavities could be simulated and the shape and geometry of the model analyzed with FEM for optimizing the geometry and shapes of the model. The whole structure of the model could be as well optimized using topology optimization.

The support structures for the model can be created automatically with DeskArtes 3Data Expert software and this was experimented shortly for the model. The supports could also be manually designed with detail for minimizing the use of the support material and for achieving better build quality. The supports could be also be designed with another software (such as Magics) and the results could be compared.

The model designed in this thesis and other hydraulic blocks designed for additive manufacturing could be investigated at the same time, compared and the pros and cons of them enlisted.

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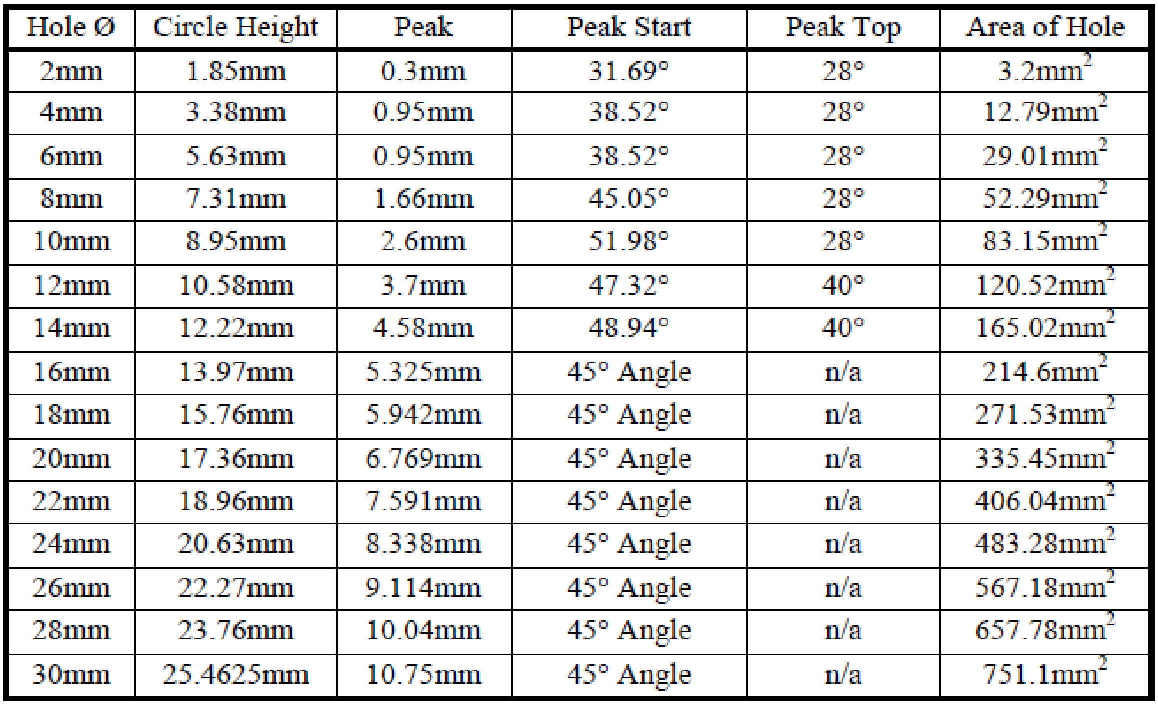
APPENDIX I

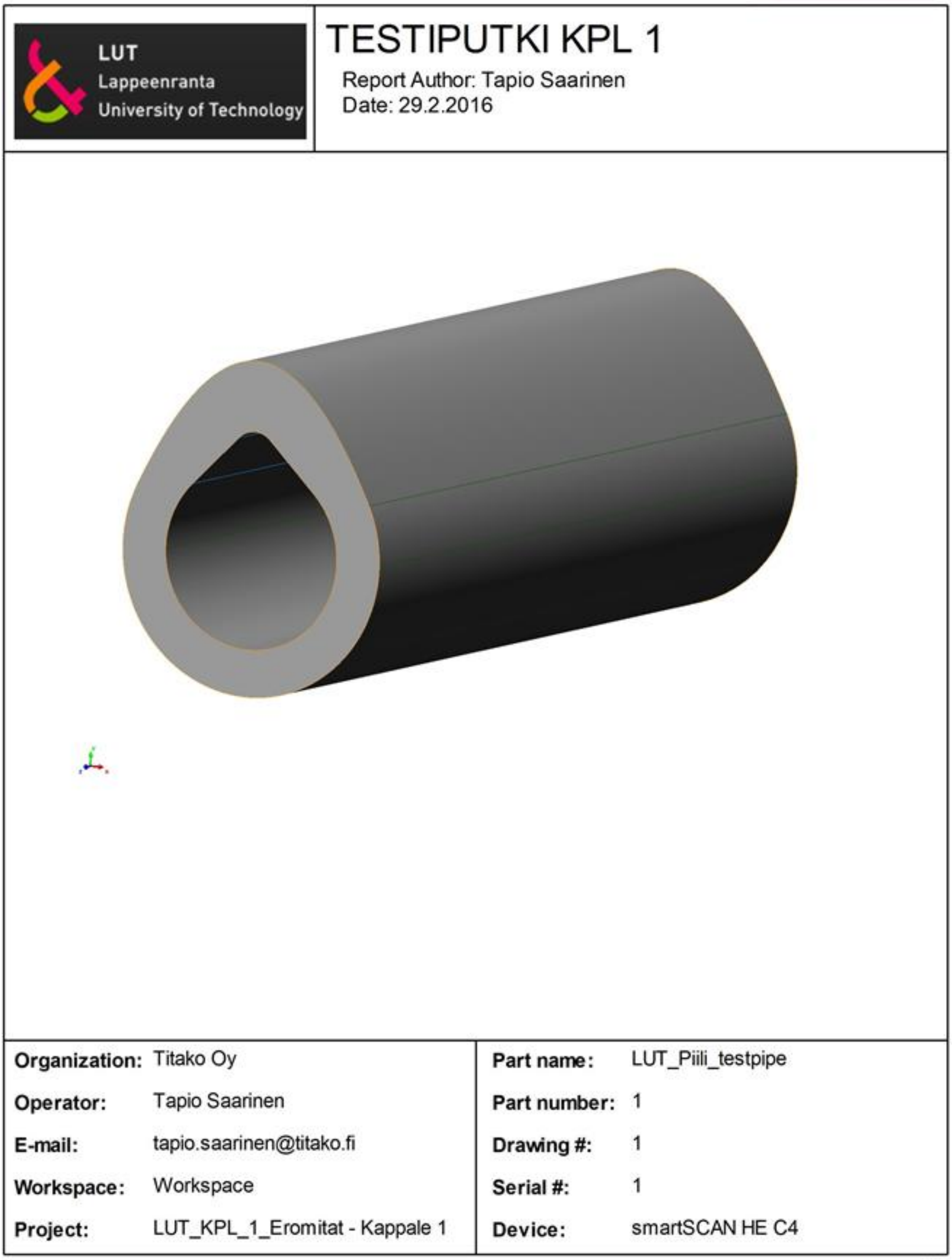
Parameters for self-supporting holes.

Parameters for self-supporting holes from 2 to 30 mm radiuses (Thomas 2009, p. 181).



Hole Ø	Circle Height	Peak	Peak Start	Peak Top	Area of Hole
2mm	1.85mm	0.3mm	31.69°	28°	3.2mm^2
4mm	3.38mm	0.95mm	38.52°	28°	12.79mm^2
6mm	5.63mm	0.95mm	38.52°	28°	29.01mm^2
8mm	7.31mm	1.66mm	45.05°	28°	52.29mm^2
10mm	8.95mm	2.6mm	51.98°	28°	83.15mm^2
12mm	10.58mm	3.7mm	47.32°	40°	120.52mm^2
14mm	12.22mm	4.58mm	48.94°	40°	165.02mm^2
16mm	13.97mm	5.325mm	45° Angle	n/a	214.6mm^2
18mm	15.76mm	5.942mm	45° Angle	n/a	271.53mm^2
20mm	17.36mm	6.769mm	45° Angle	n/a	335.45mm^2
22mm	18.96mm	7.591mm	45° Angle	n/a	406.04mm^2
24mm	20.63mm	8.338mm	45° Angle	n/a	483.28mm^2
26mm	22.27mm	9.114mm	45° Angle	n/a	567.18mm^2
28mm	23.76mm	10.04mm	45° Angle	n/a	657.78mm^2
30mm	25.4625mm	10.75mm	45° Angle	n/a	751.1mm^2

3D scanning results.



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University of Technology

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Report Author: Tapio Saarinen
Date: 29.2.2016

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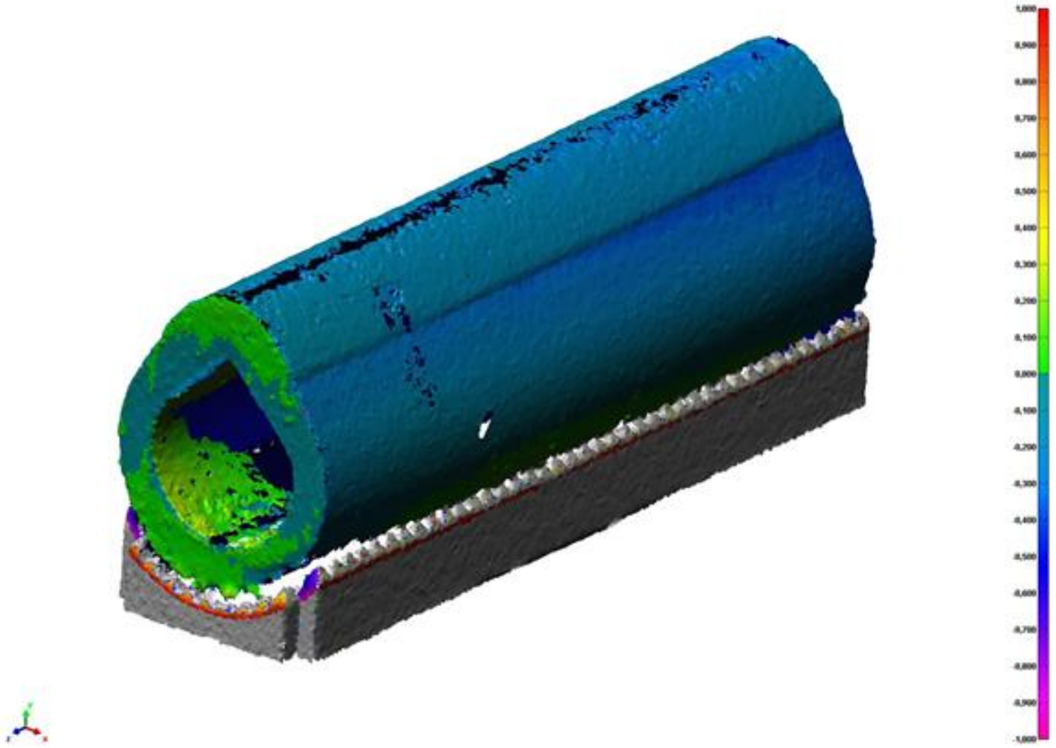

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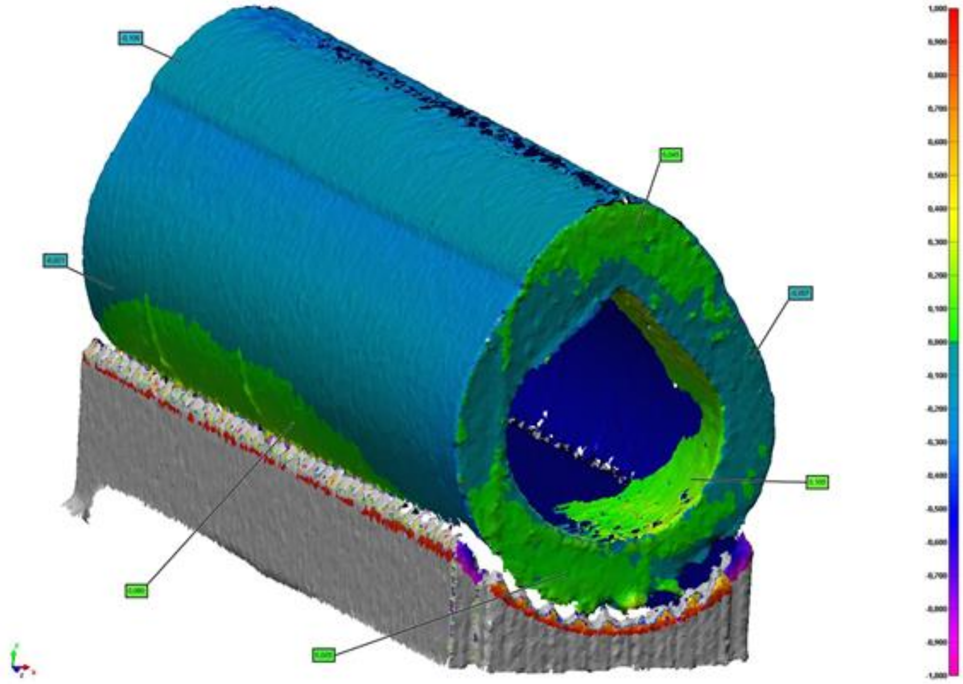

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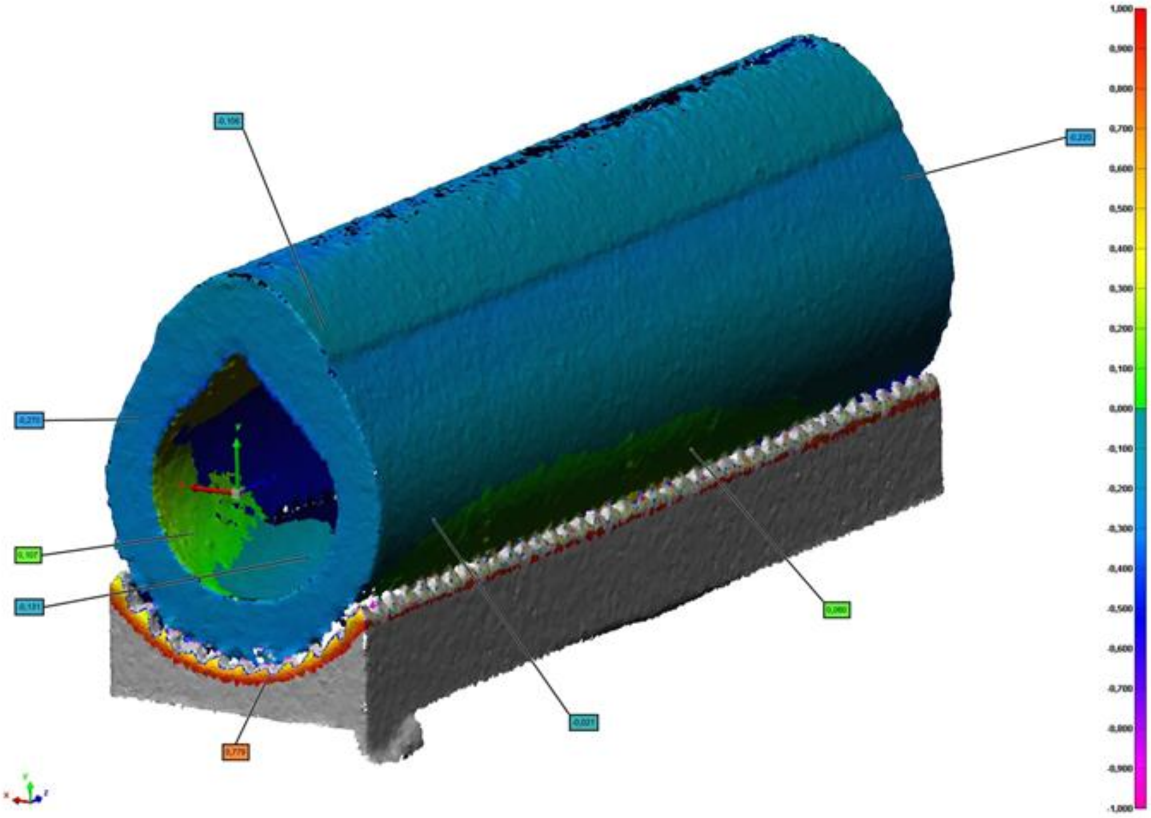

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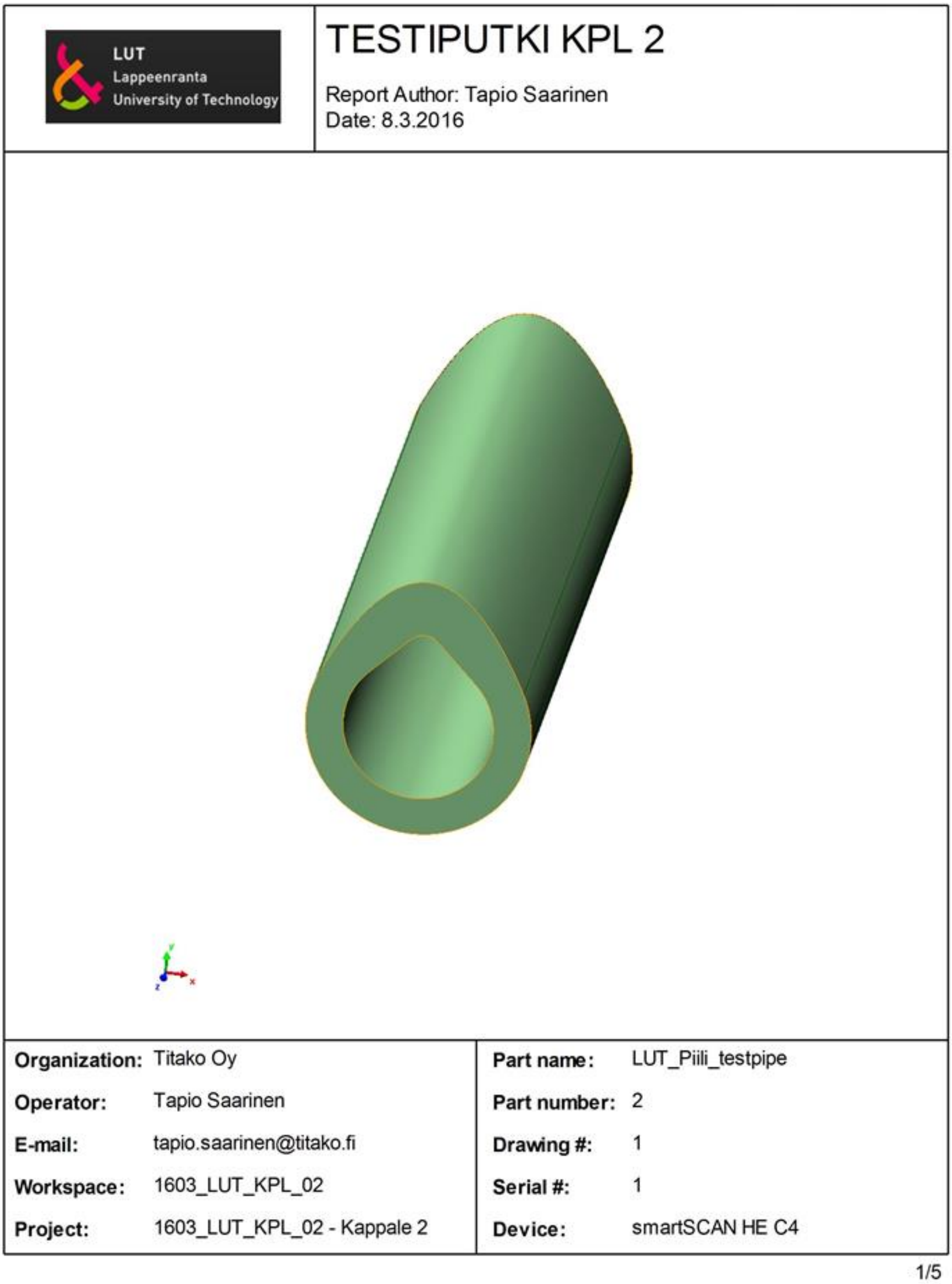

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Date: 8.3.2016

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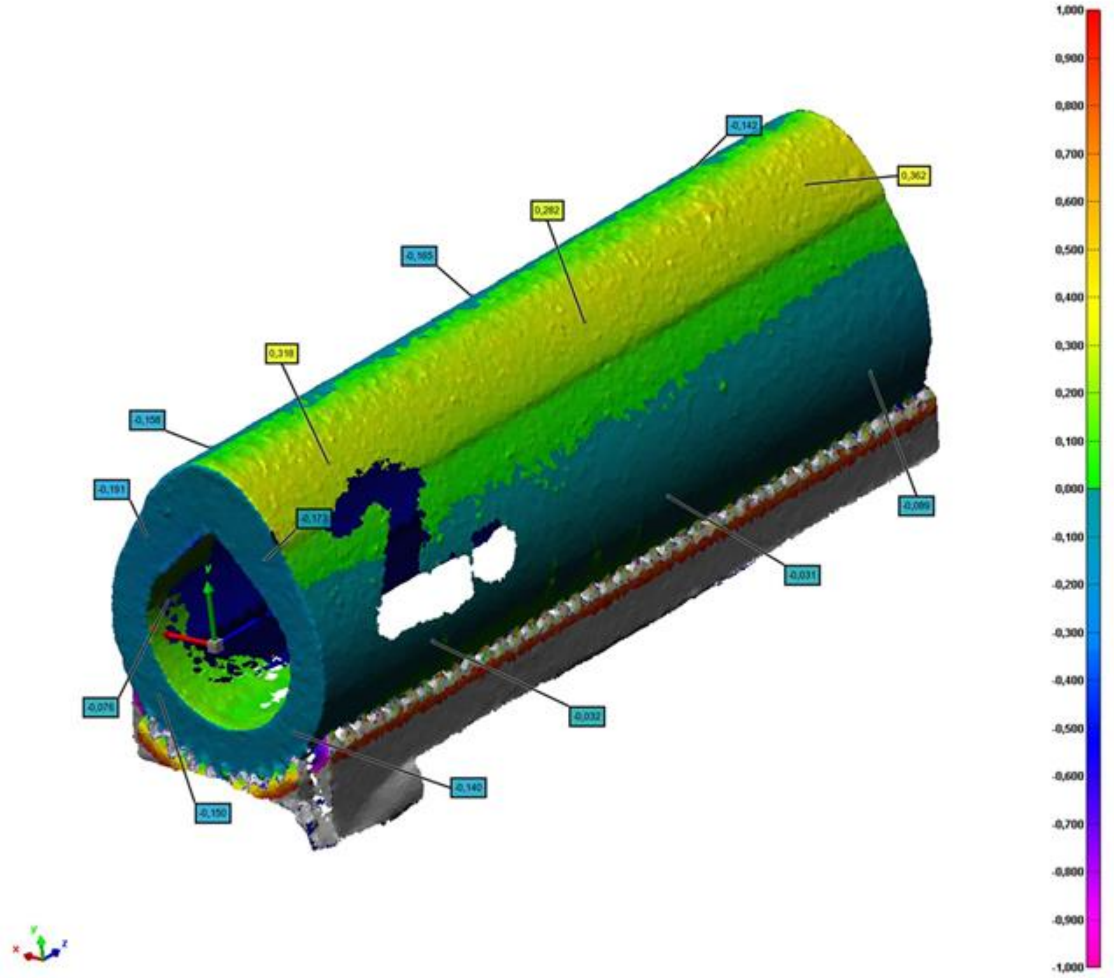

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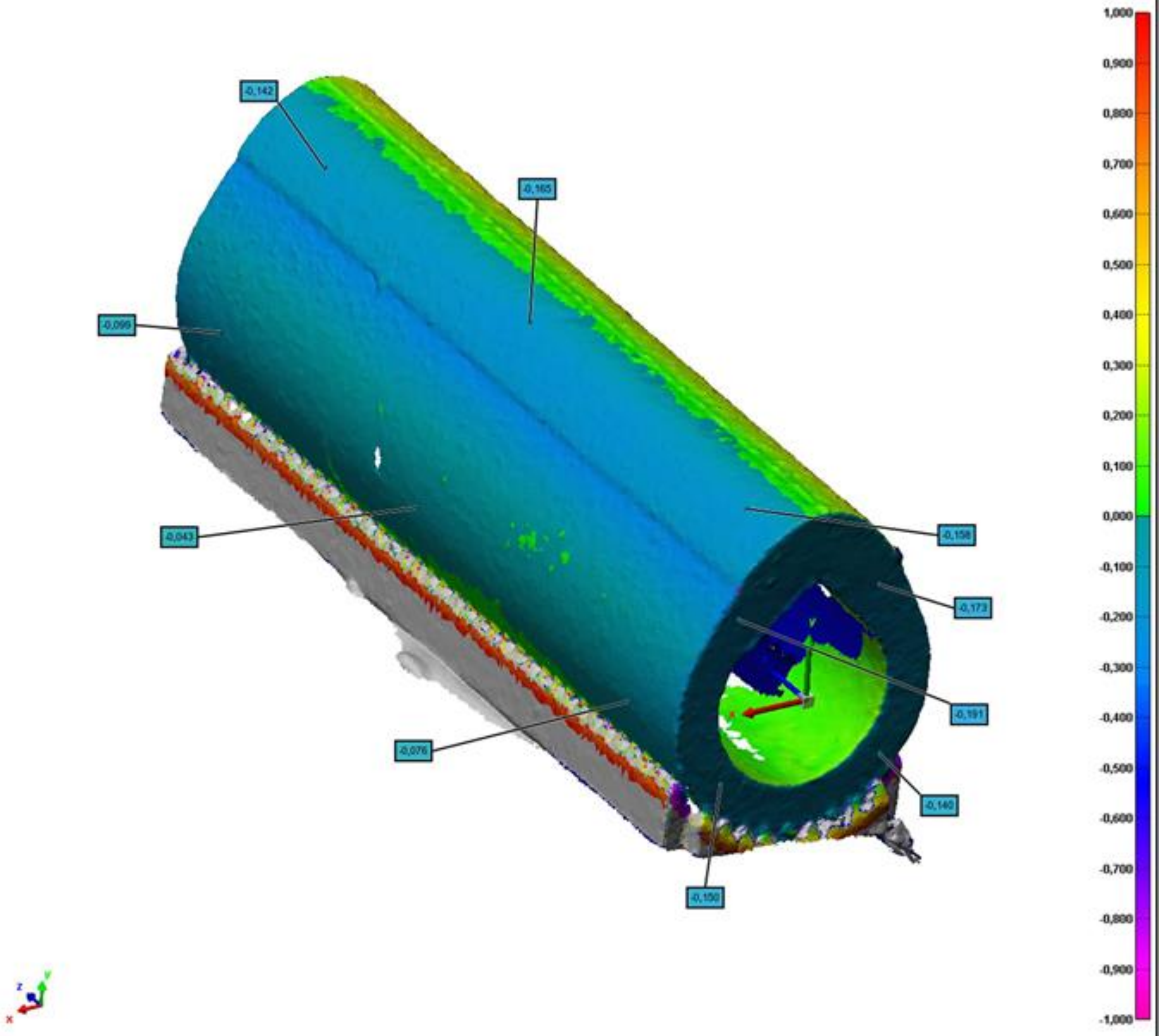

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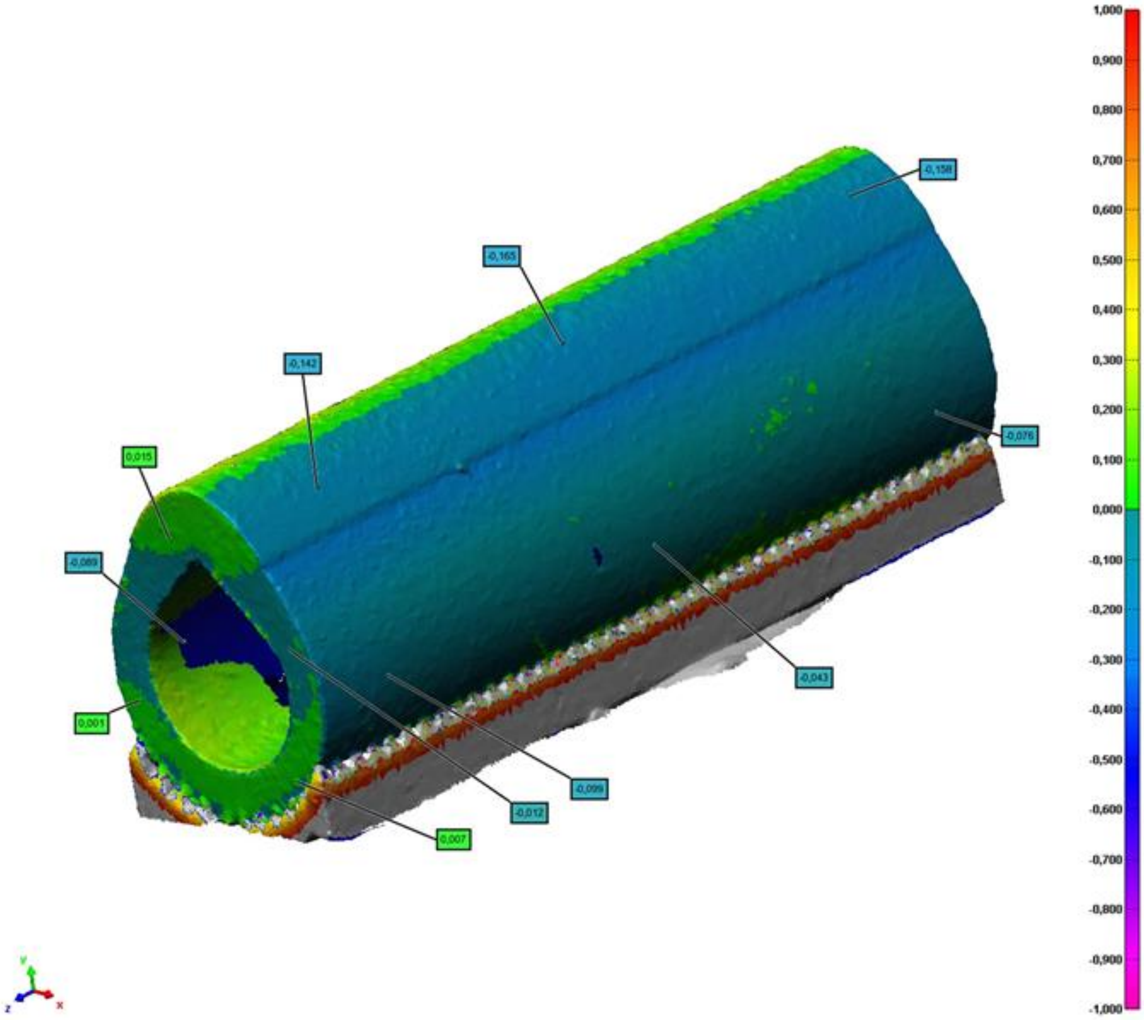

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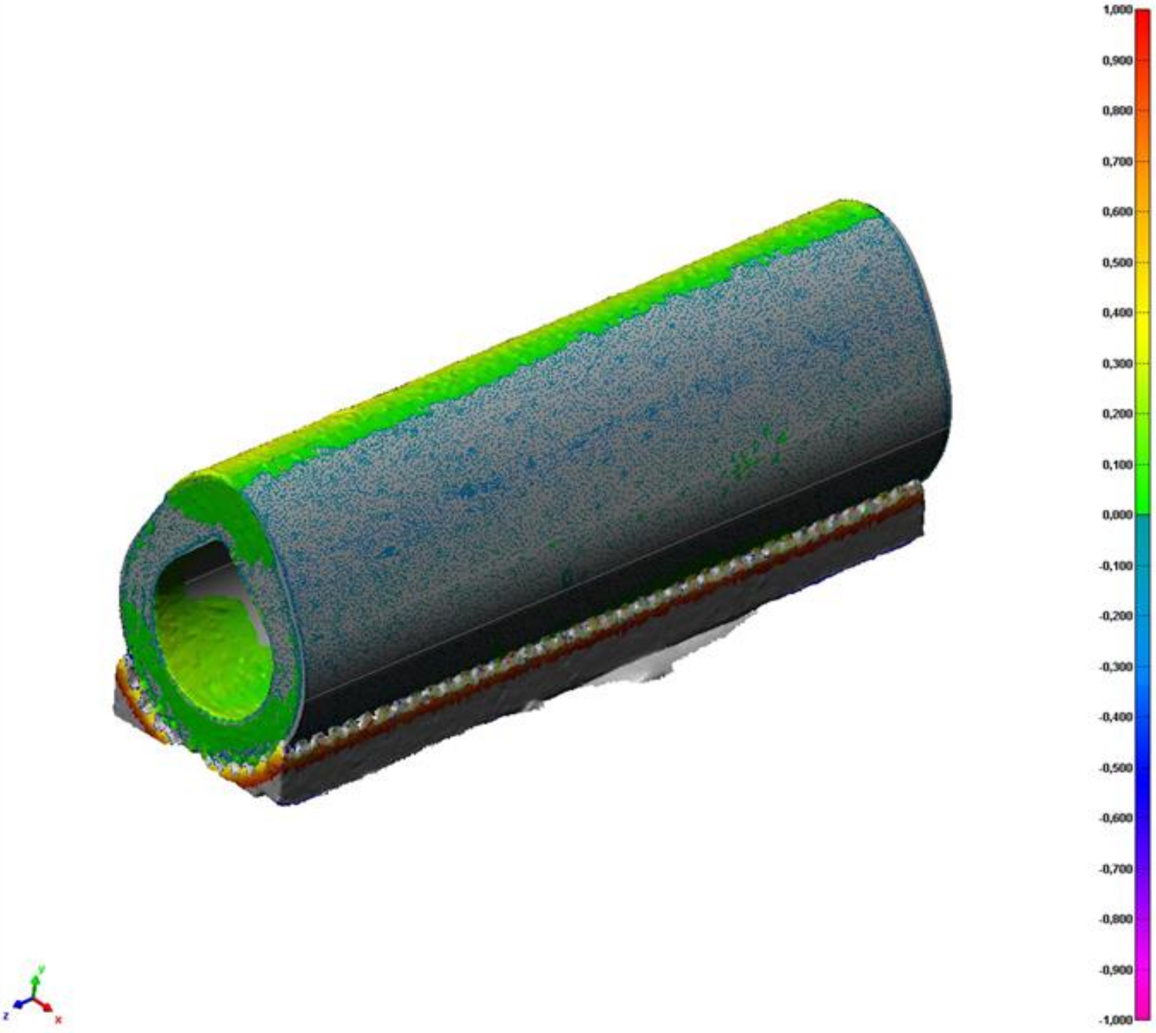

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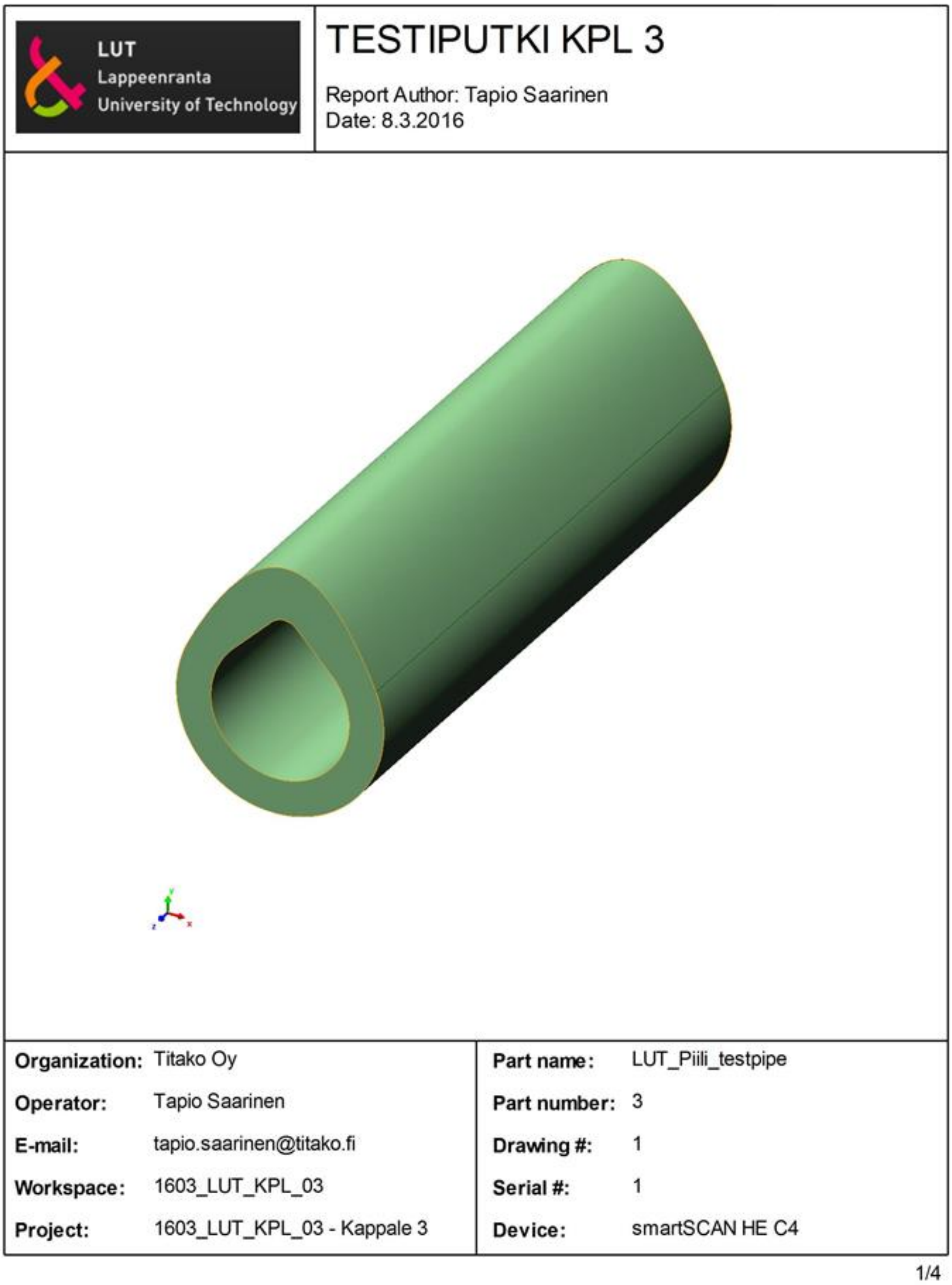

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TESTIPUTKI KPL 3

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Date: 8.3.2016

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Operator:	Tapio Saarinen	**Part number:**	3
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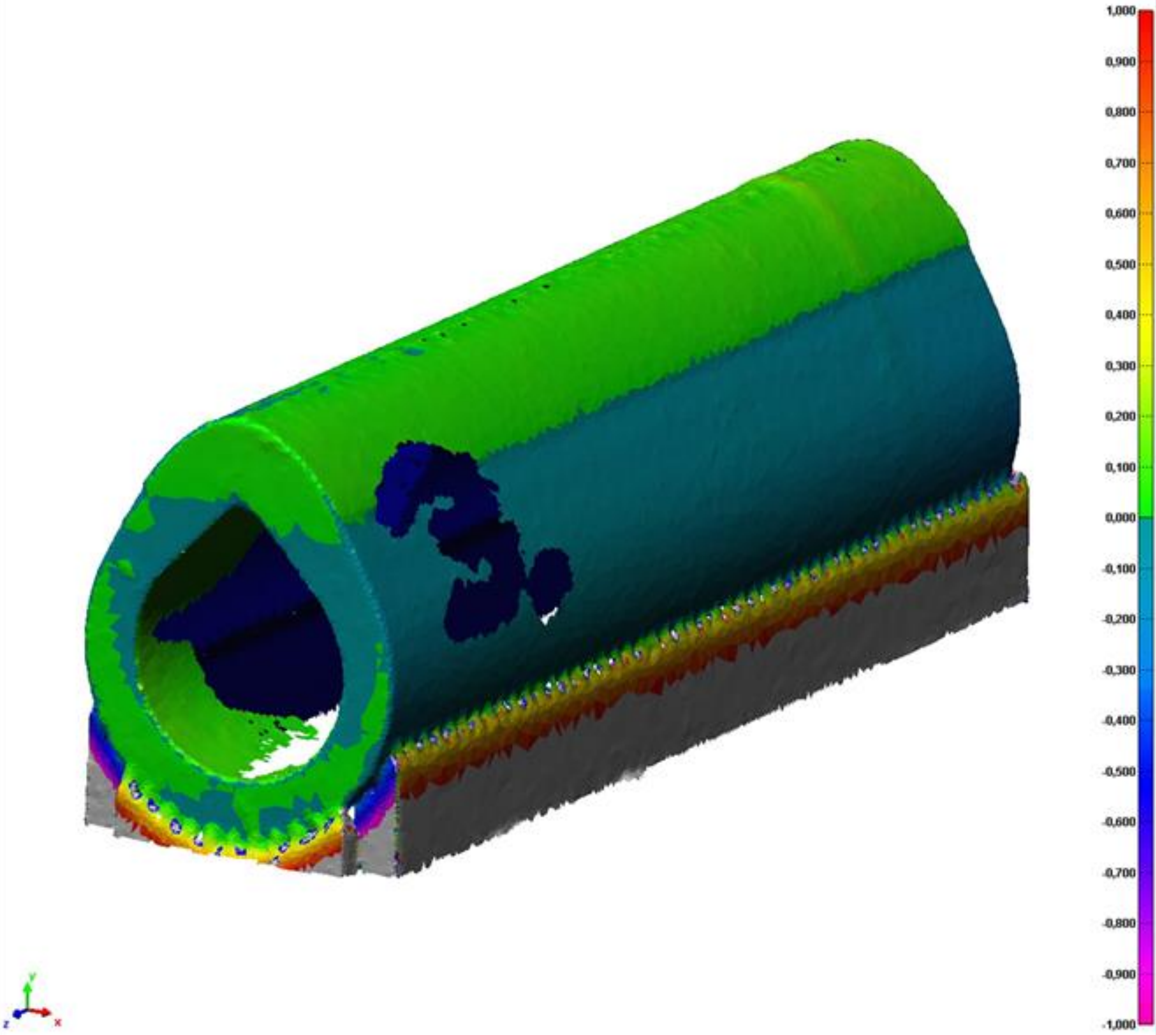

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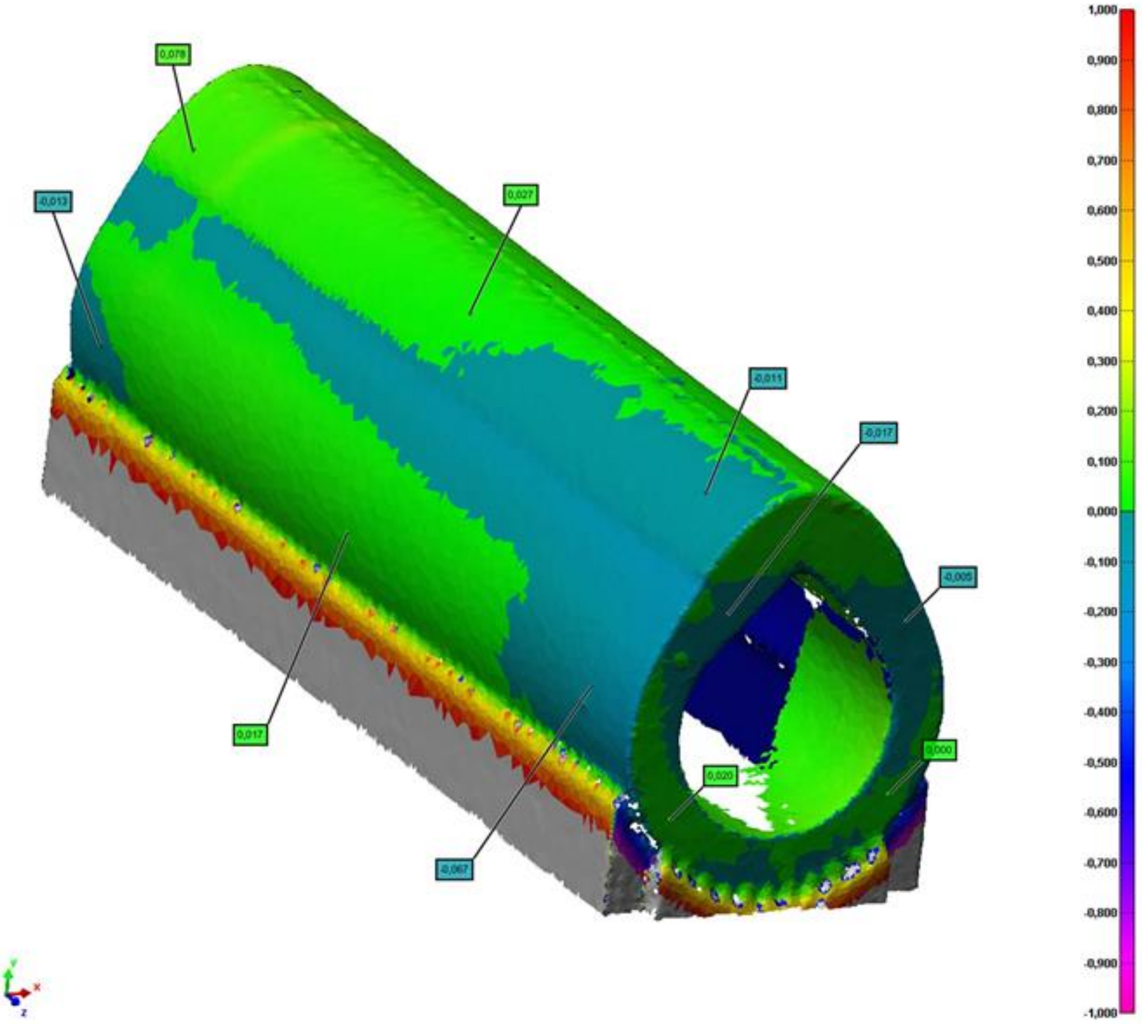

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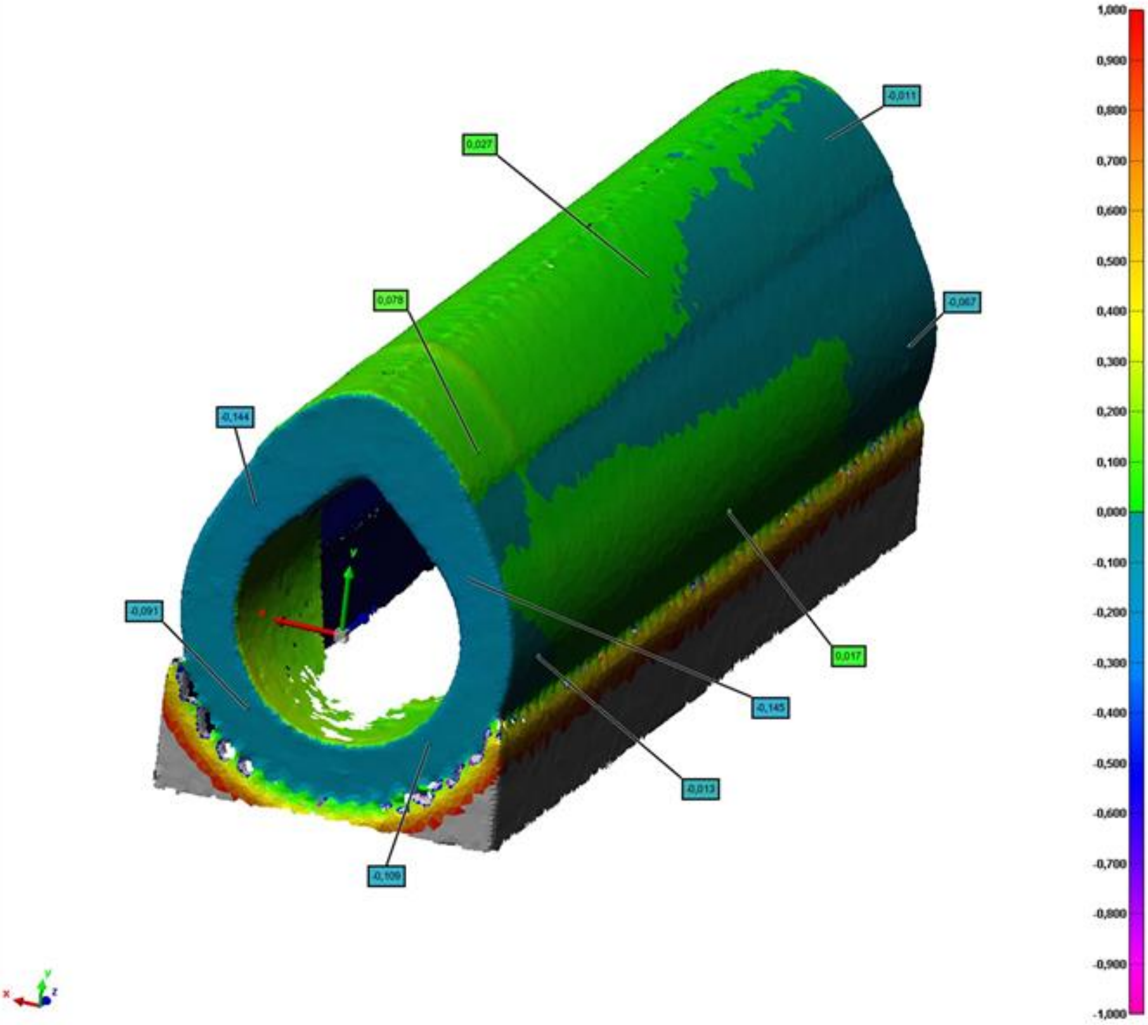

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TESTIPUTKI KPL 4

Report Author: Tapio Saarinen
Date: 8.3.2016

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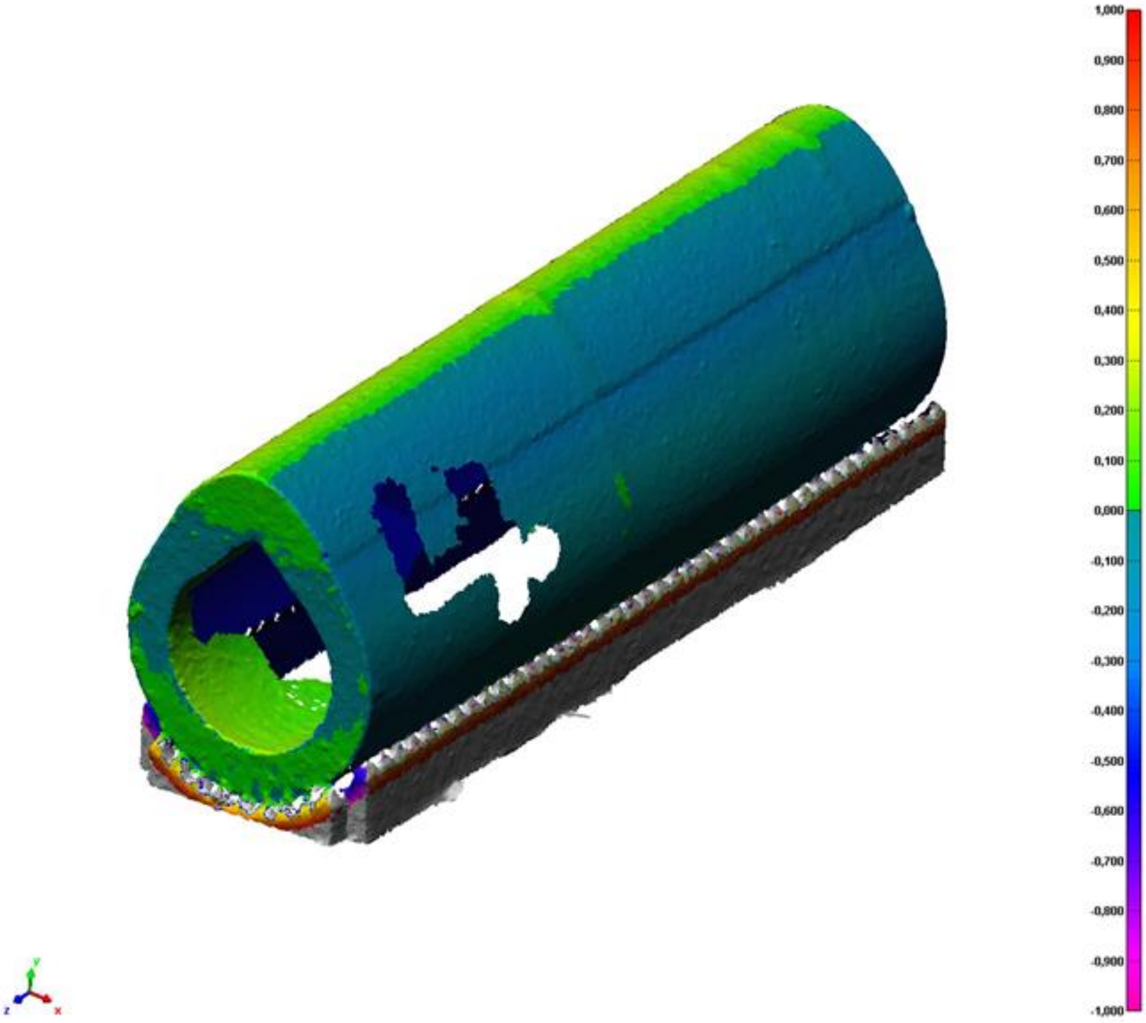

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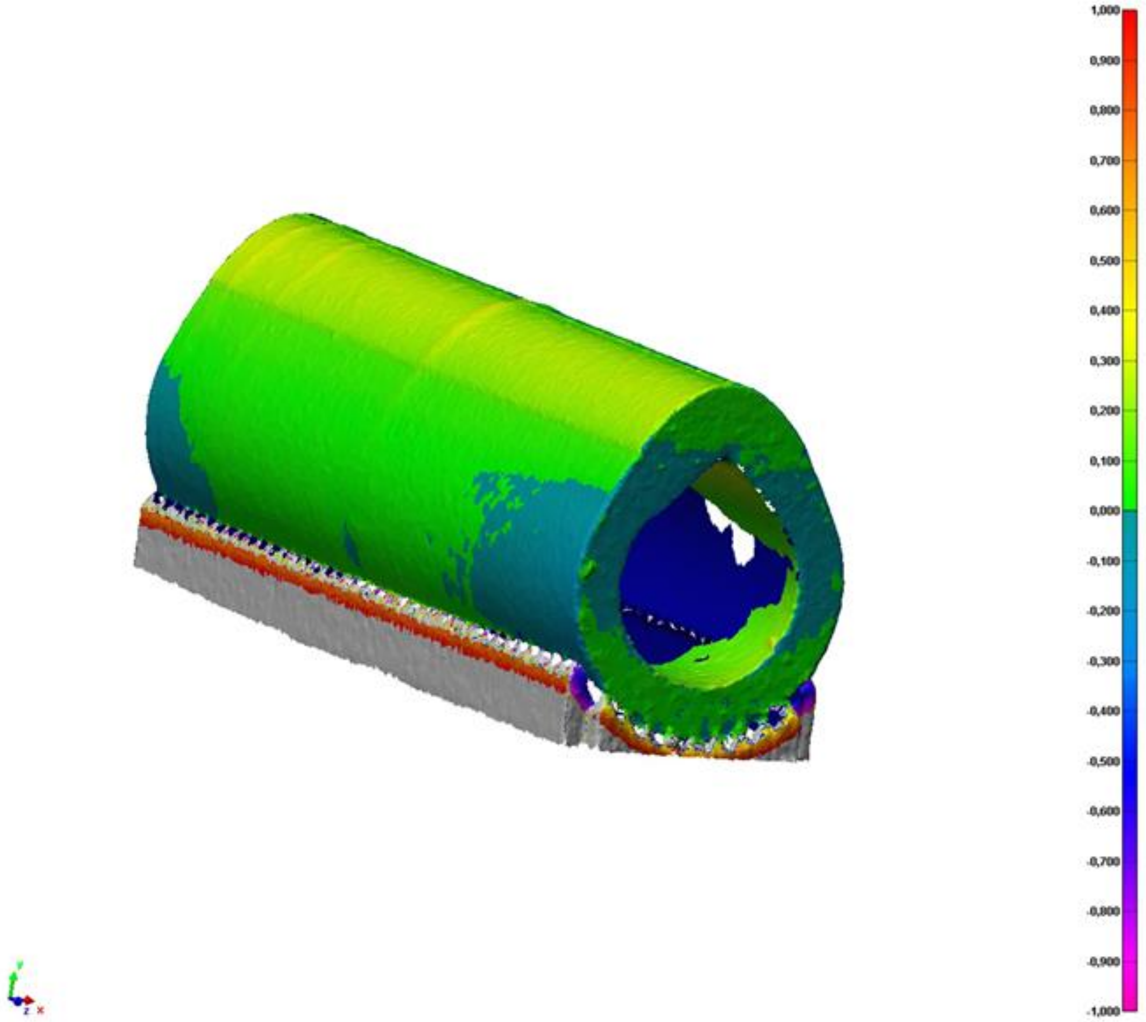

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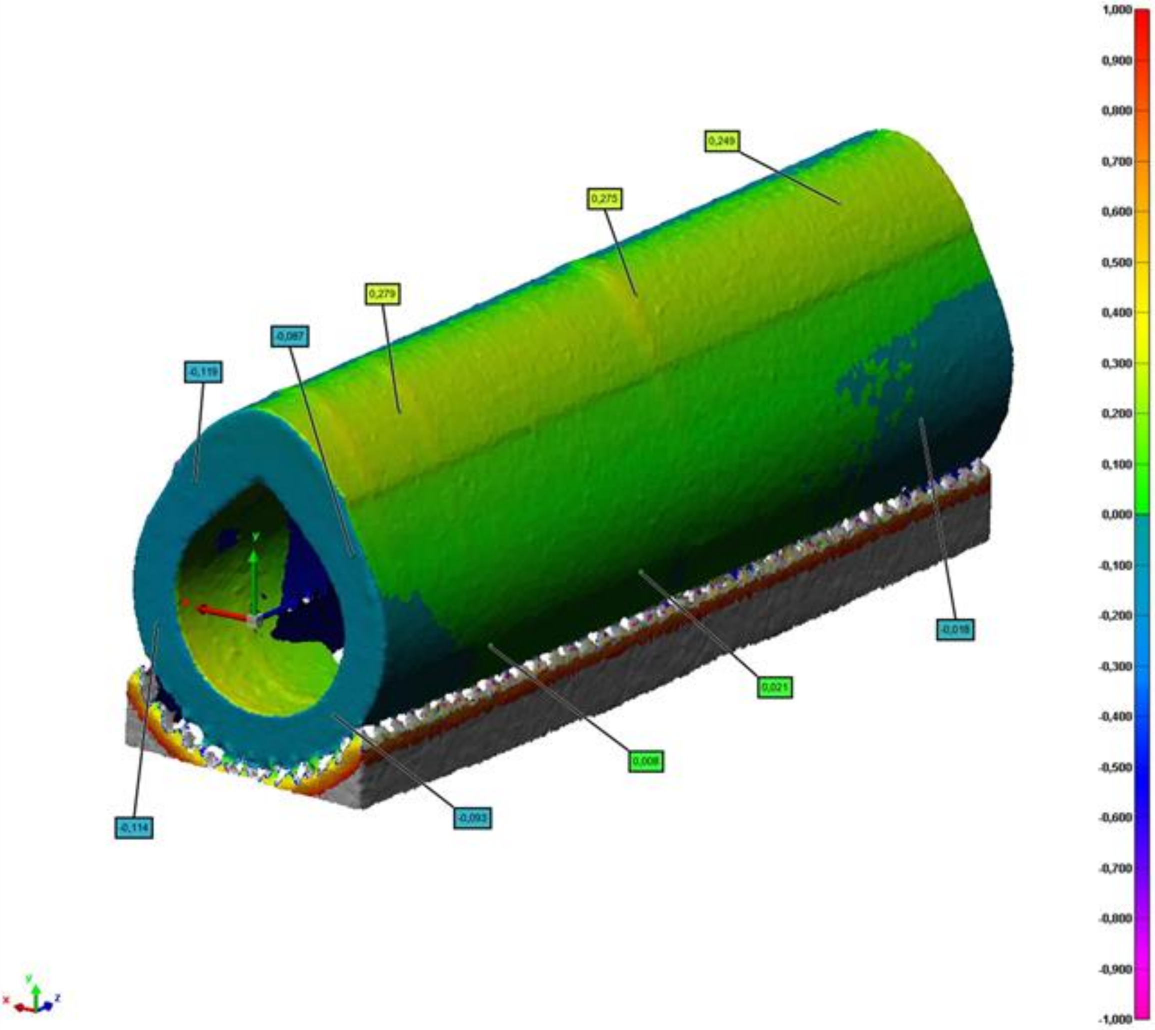

Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	4
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 4

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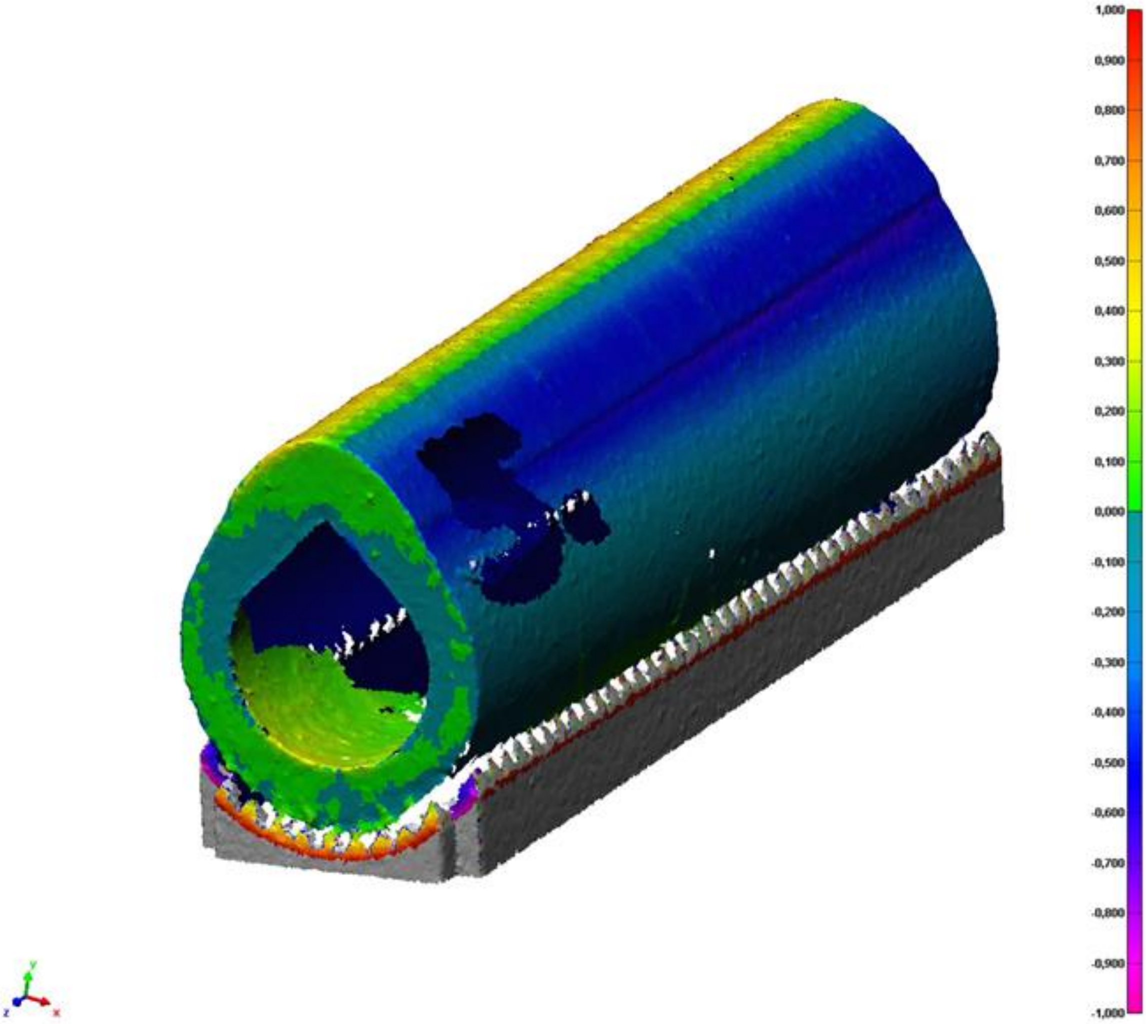
TESTIPUTKI KPL 5

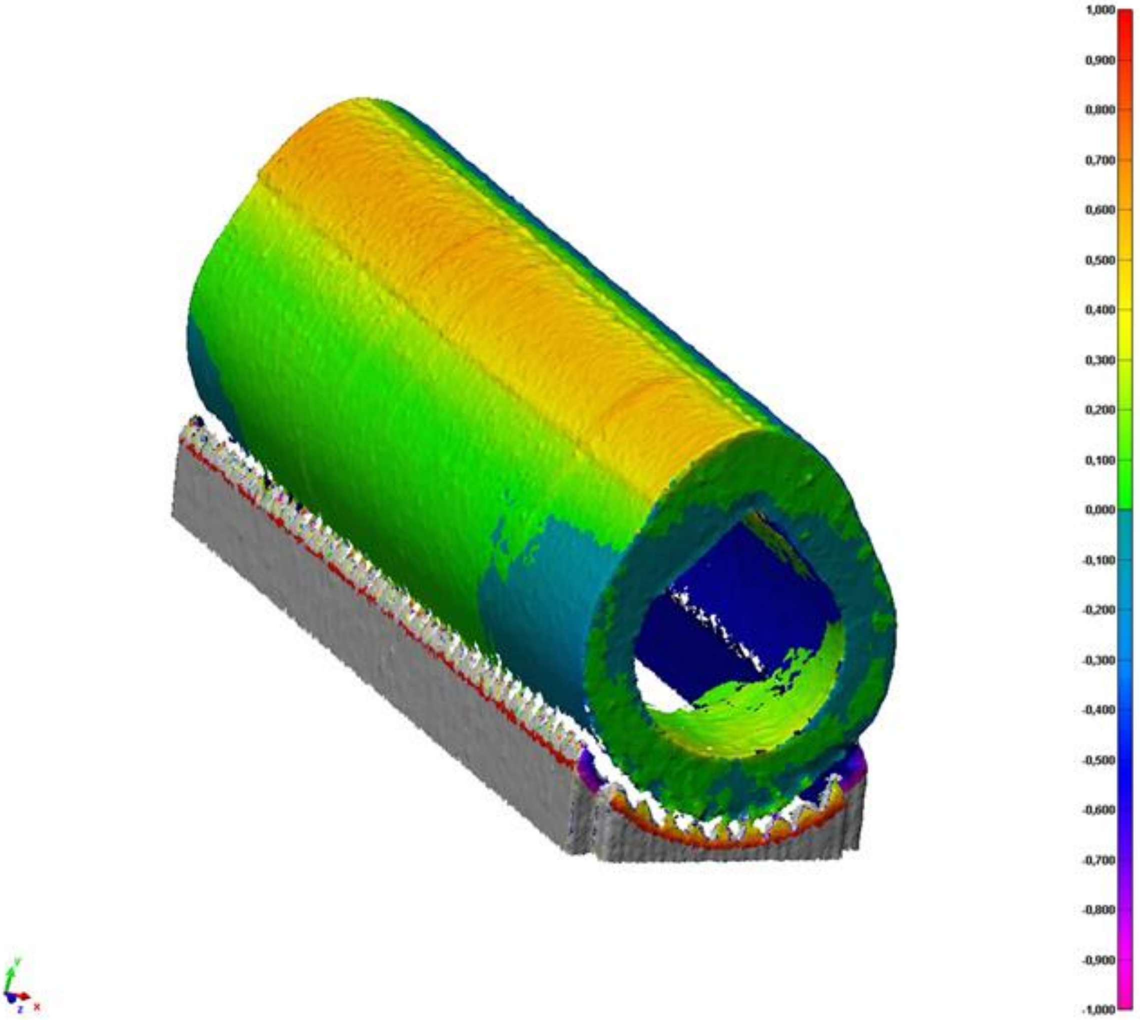
Report Author: Tapio Saarinen
Date: 8.3.2016

Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	5
E-mail:	tapio.saarinen@titako.fi	**Drawing #:**	1
Workspace:	1603_LUT_KPL_05	**Serial #:**	01
Project:	1603_LUT_KPL_05 - Kappale 5	**Device:**	smartSCAN HE C4



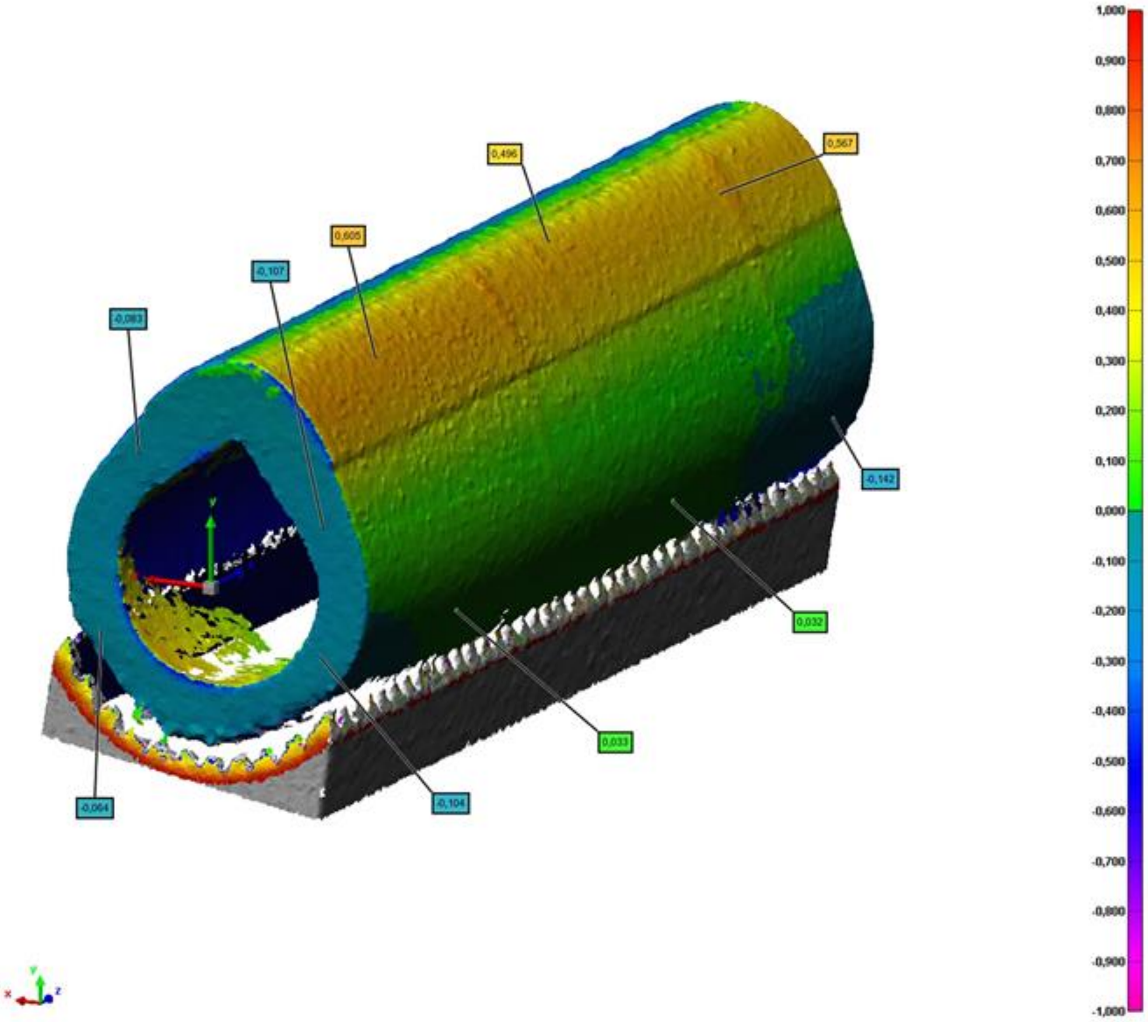
Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	5
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 5

8.3.2016

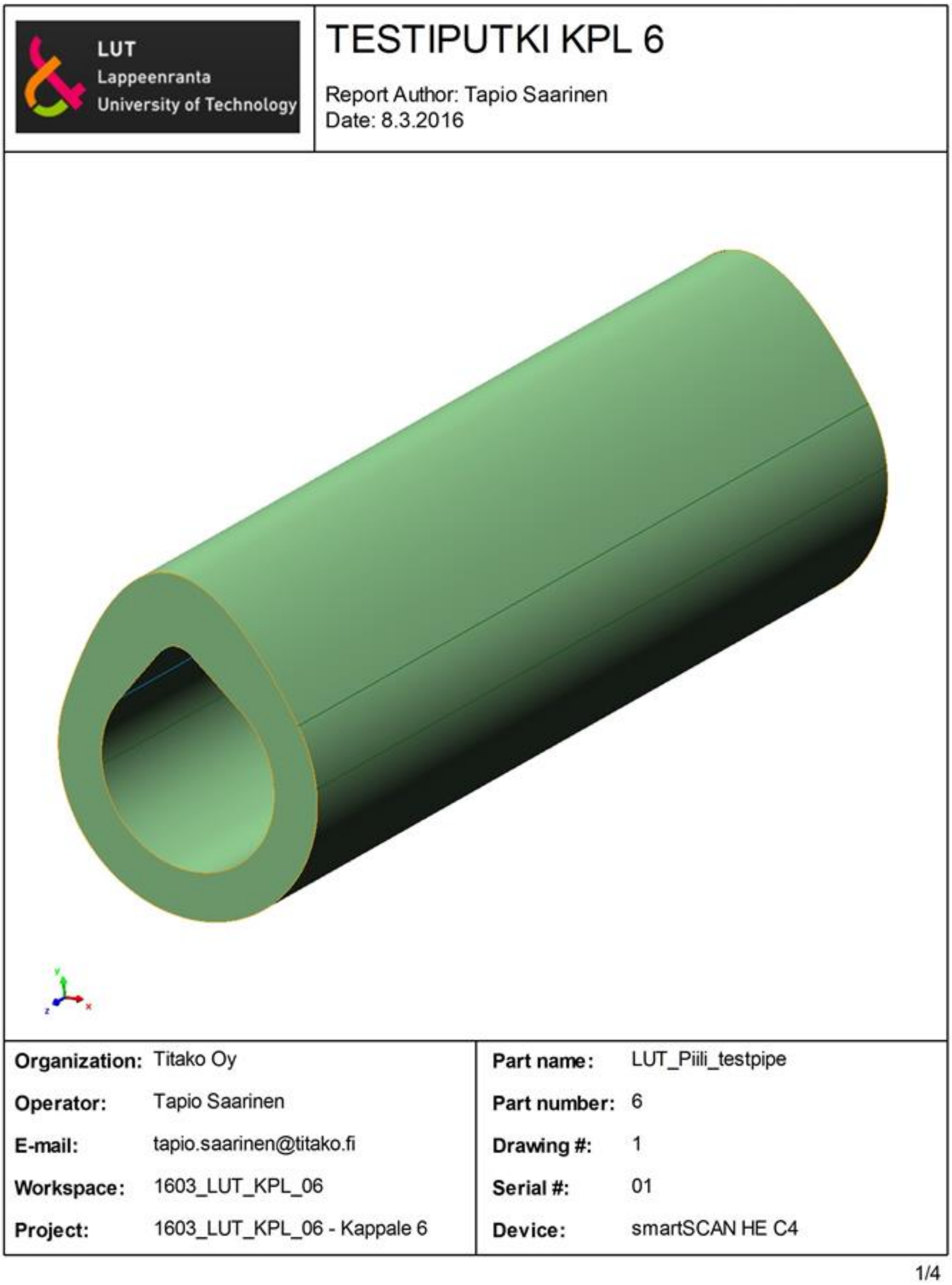


Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	5
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 5

8.3.2016



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	5
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 5



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TESTIPUTKI KPL 6

Report Author: Tapio Saarinen
Date: 8.3.2016

Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	6
E-mail:	tapio.saarinen@titako.fi	**Drawing #:**	1
Workspace:	1603_LUT_KPL_06	**Serial #:**	01
Project:	1603_LUT_KPL_06 - Kappale 6	**Device:**	smartSCAN HE C4

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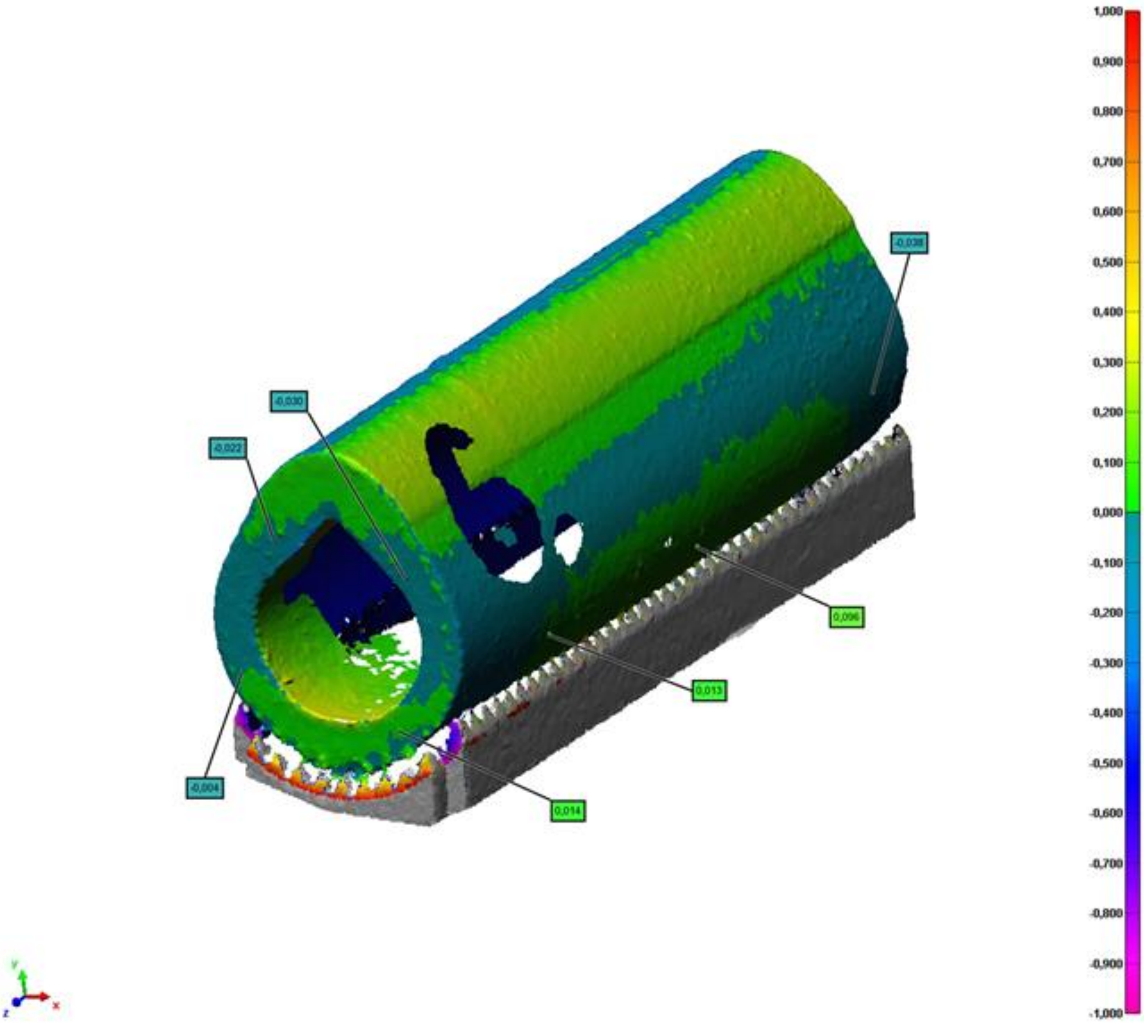
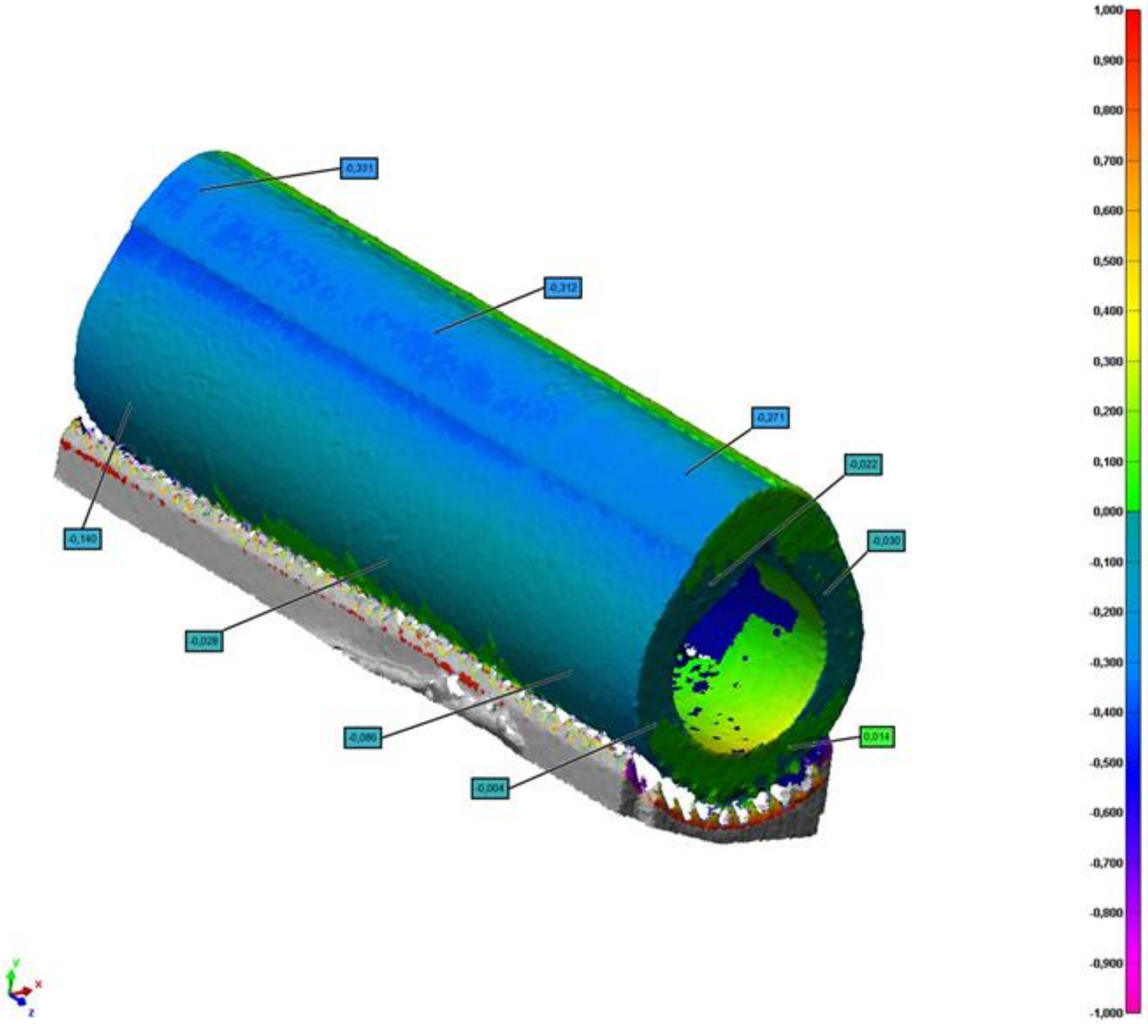
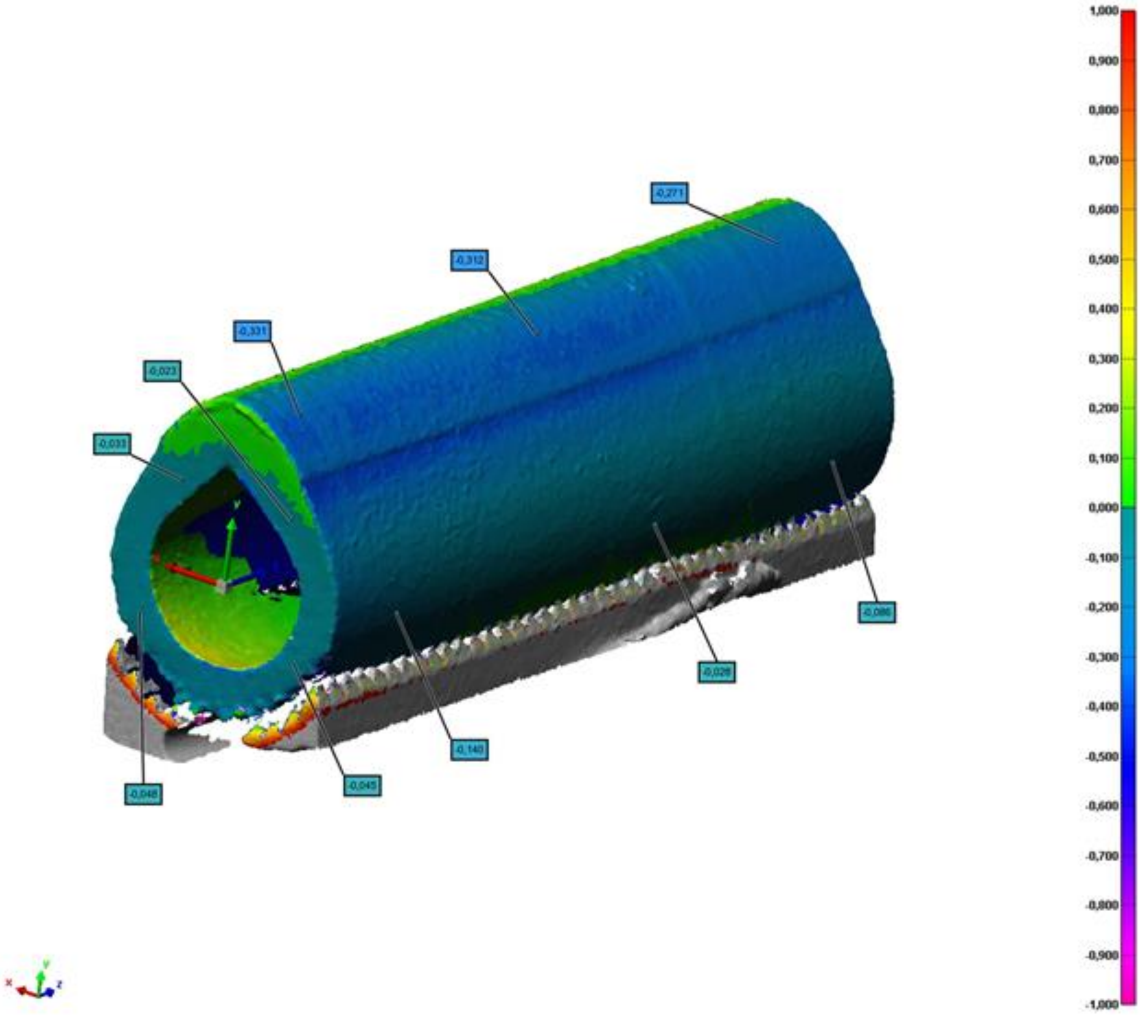


Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	6
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	6
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	6
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6

8.3.2016

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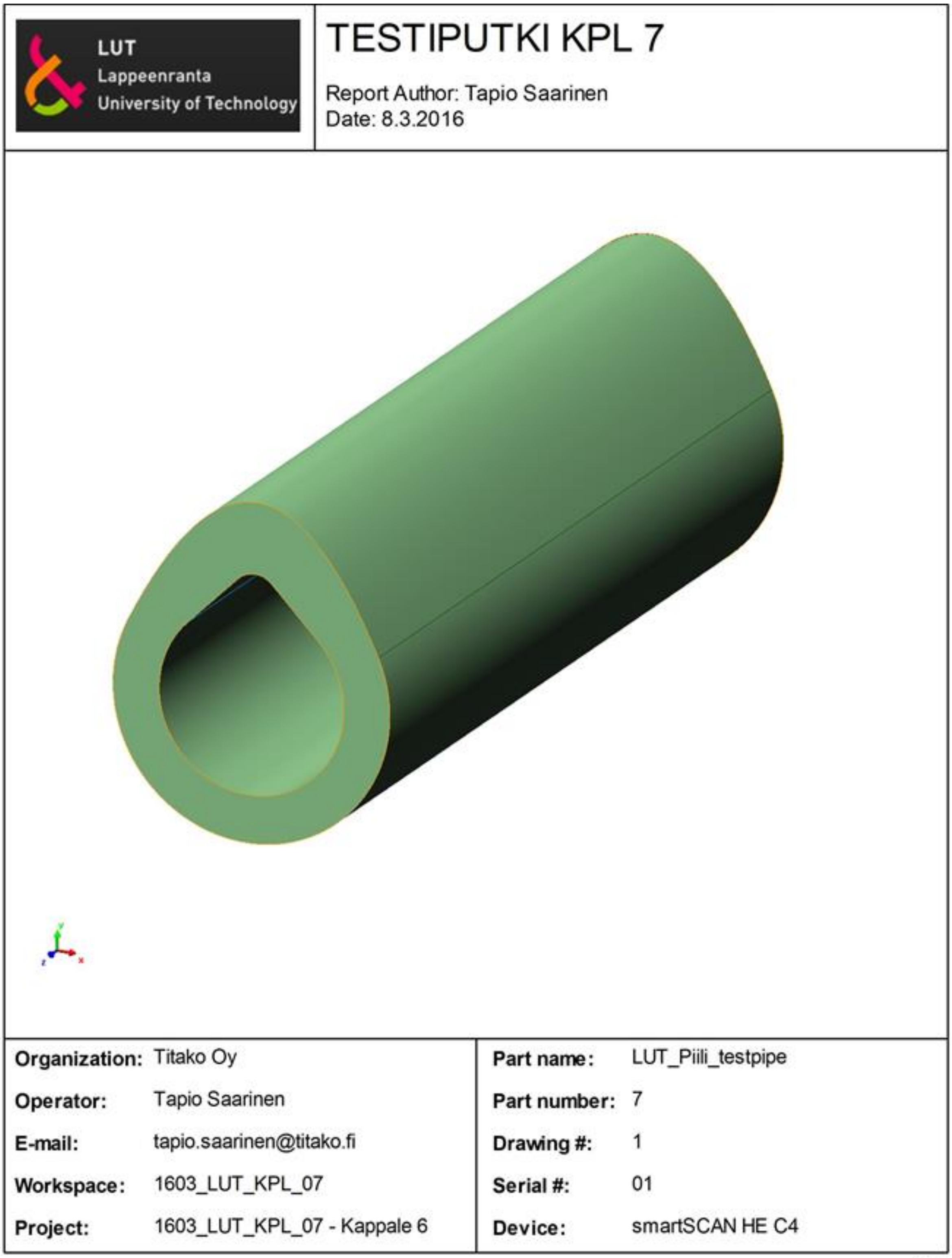

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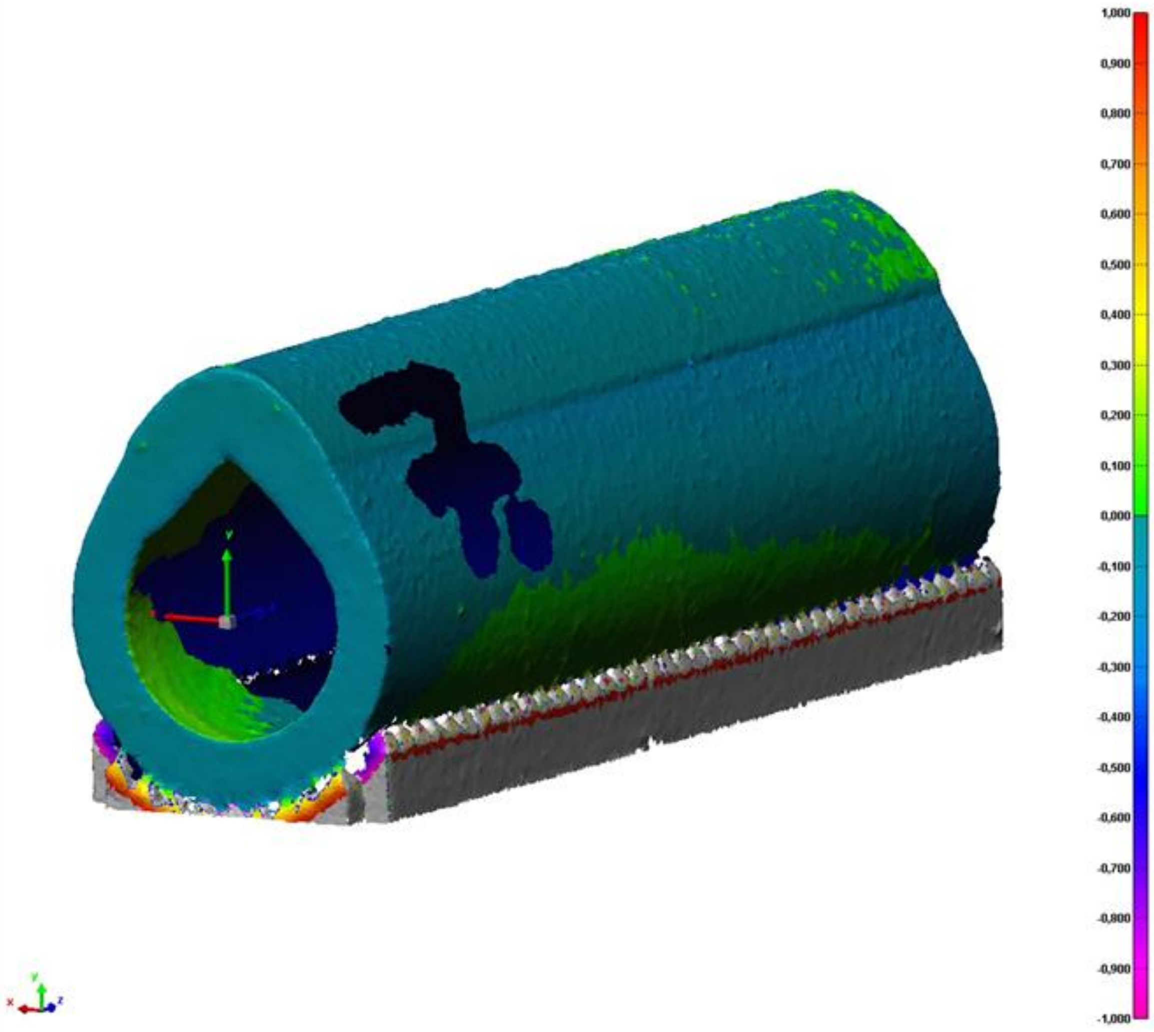
TESTIPUTKI KPL 7

Report Author: Tapio Saarinen
Date: 8.3.2016

Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	7
E-mail:	tapio.saarinen@titako.fi	**Drawing #:**	1
Workspace:	1603_LUT_KPL_07	**Serial #:**	01
Project:	1603_LUT_KPL_07 - Kappale 6	**Device:**	smartSCAN HE C4



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	7
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6

8.3.2016

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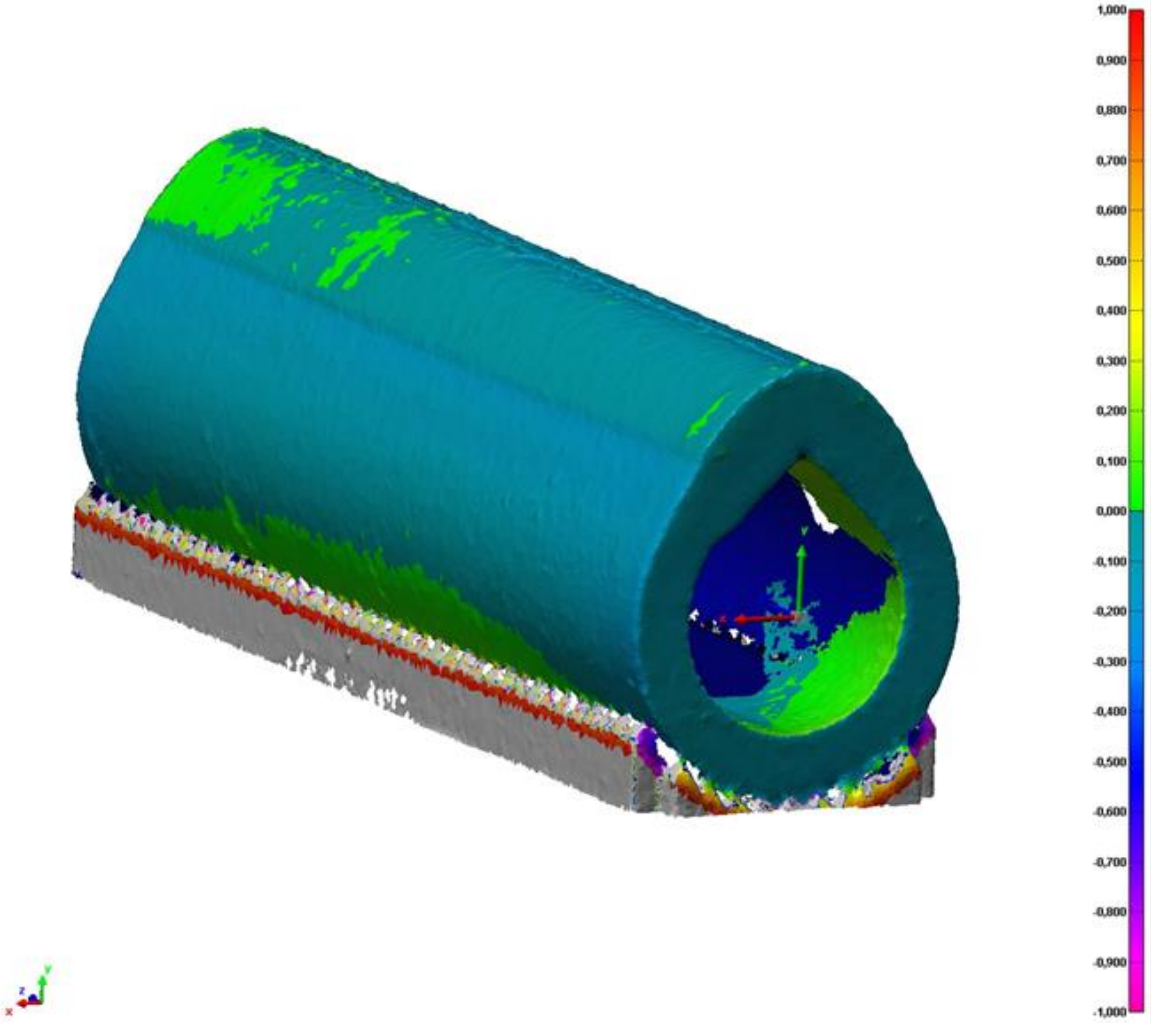
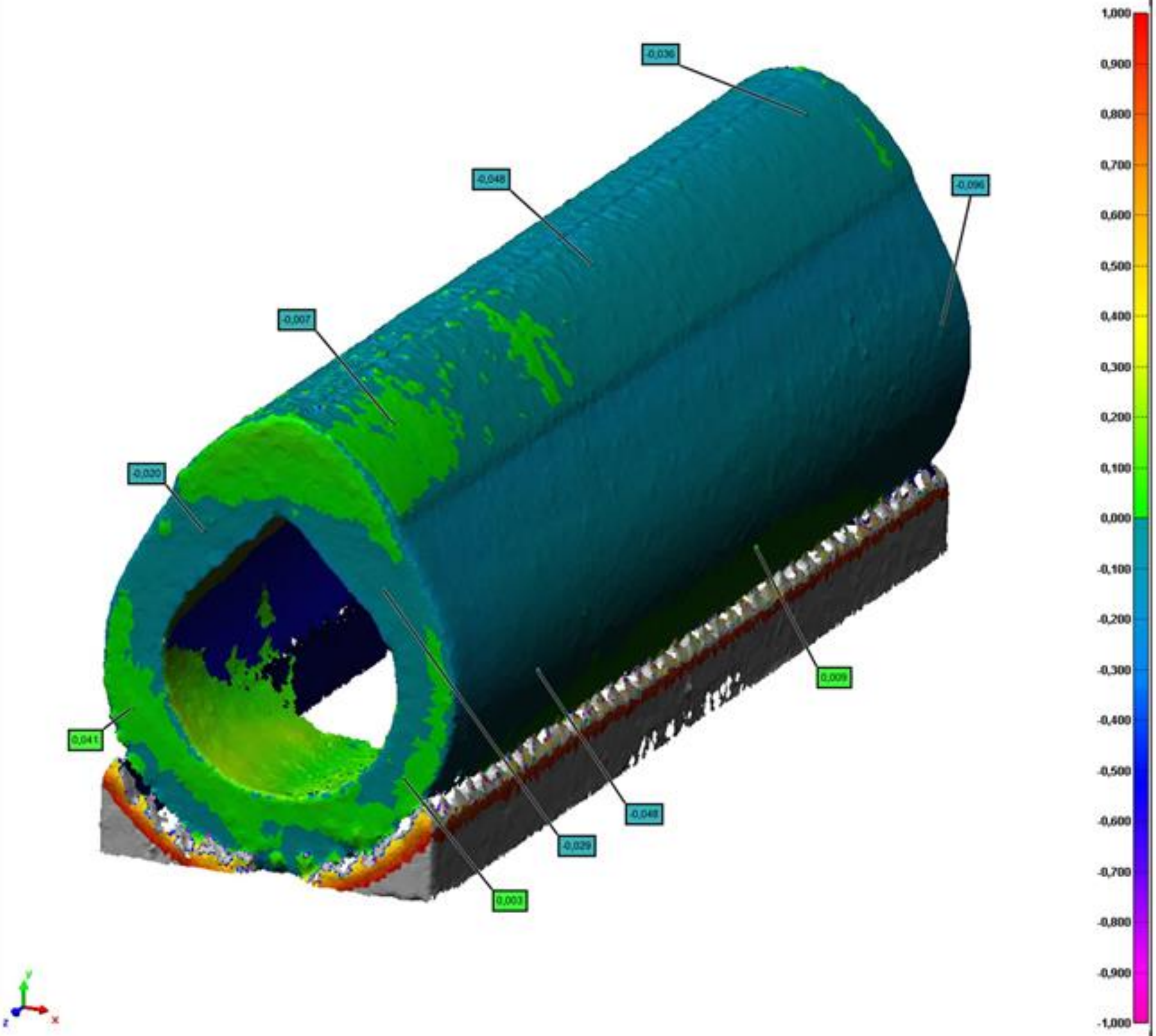


Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	7
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	7
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 6

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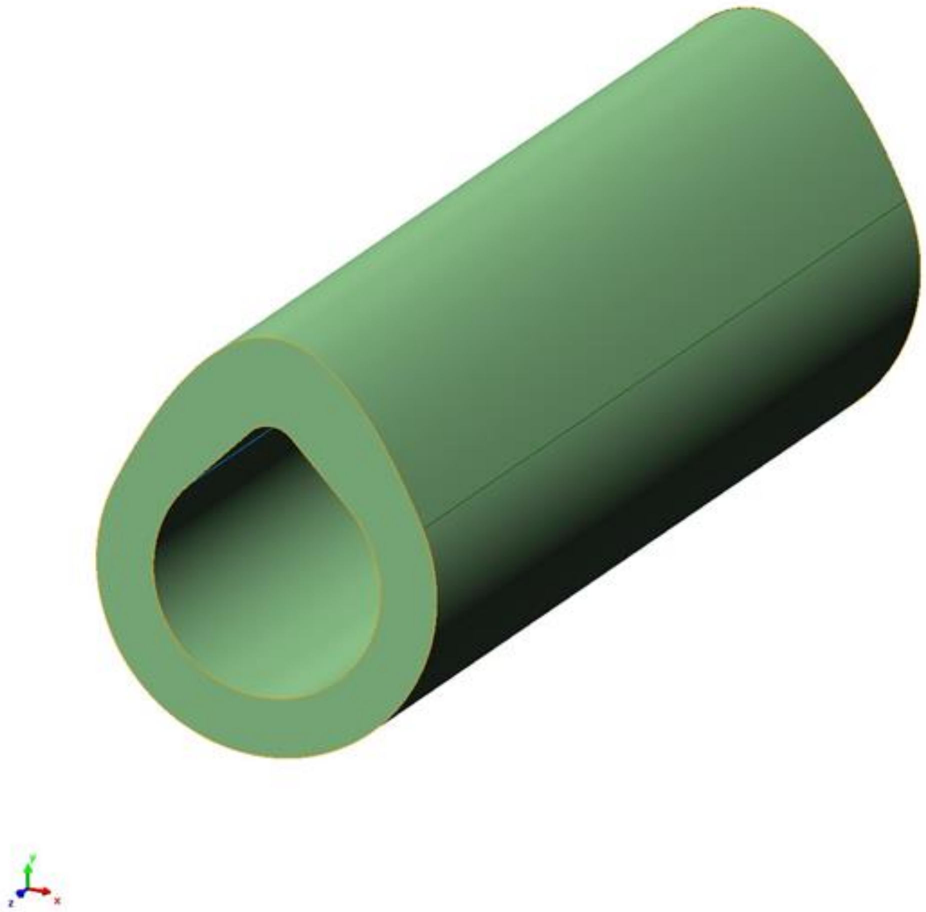
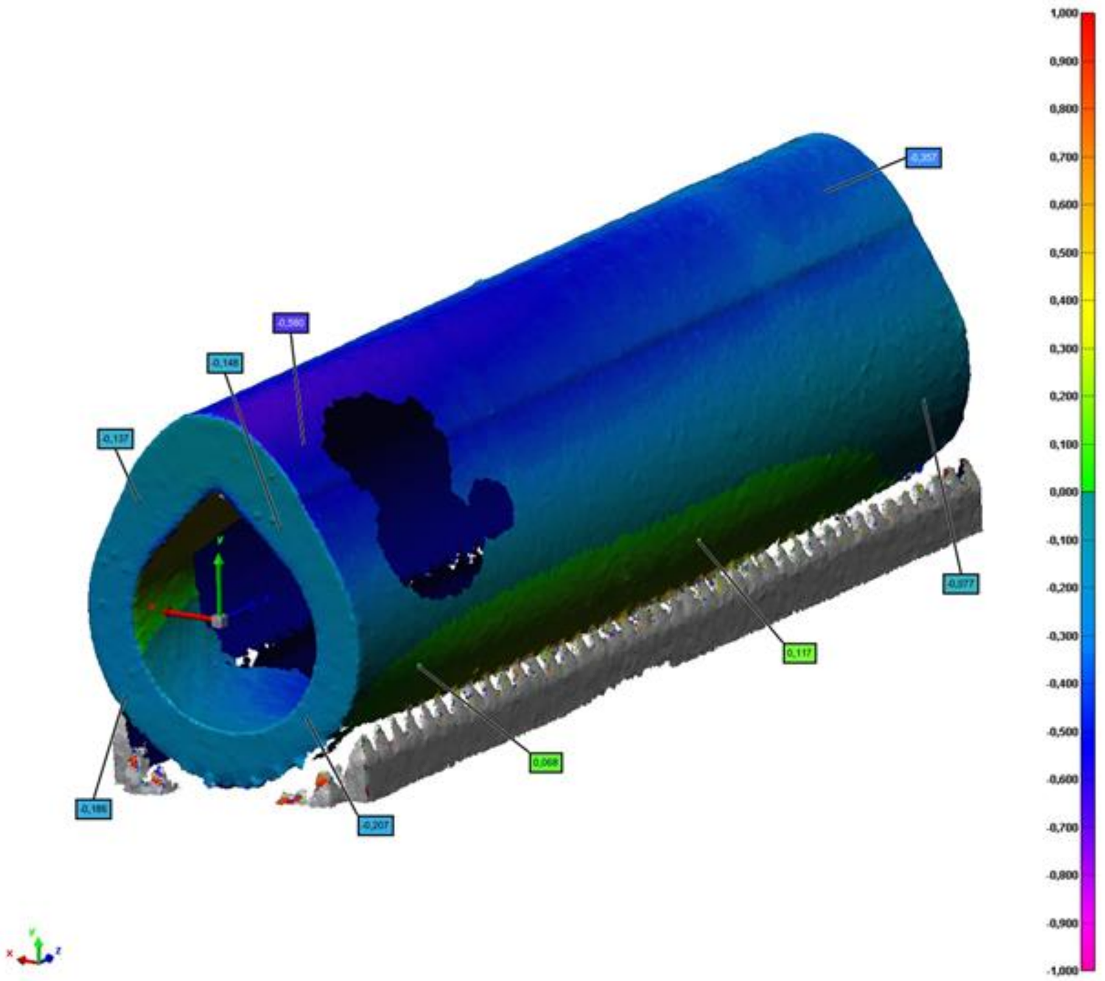
TESTIPUTKI KPL 8

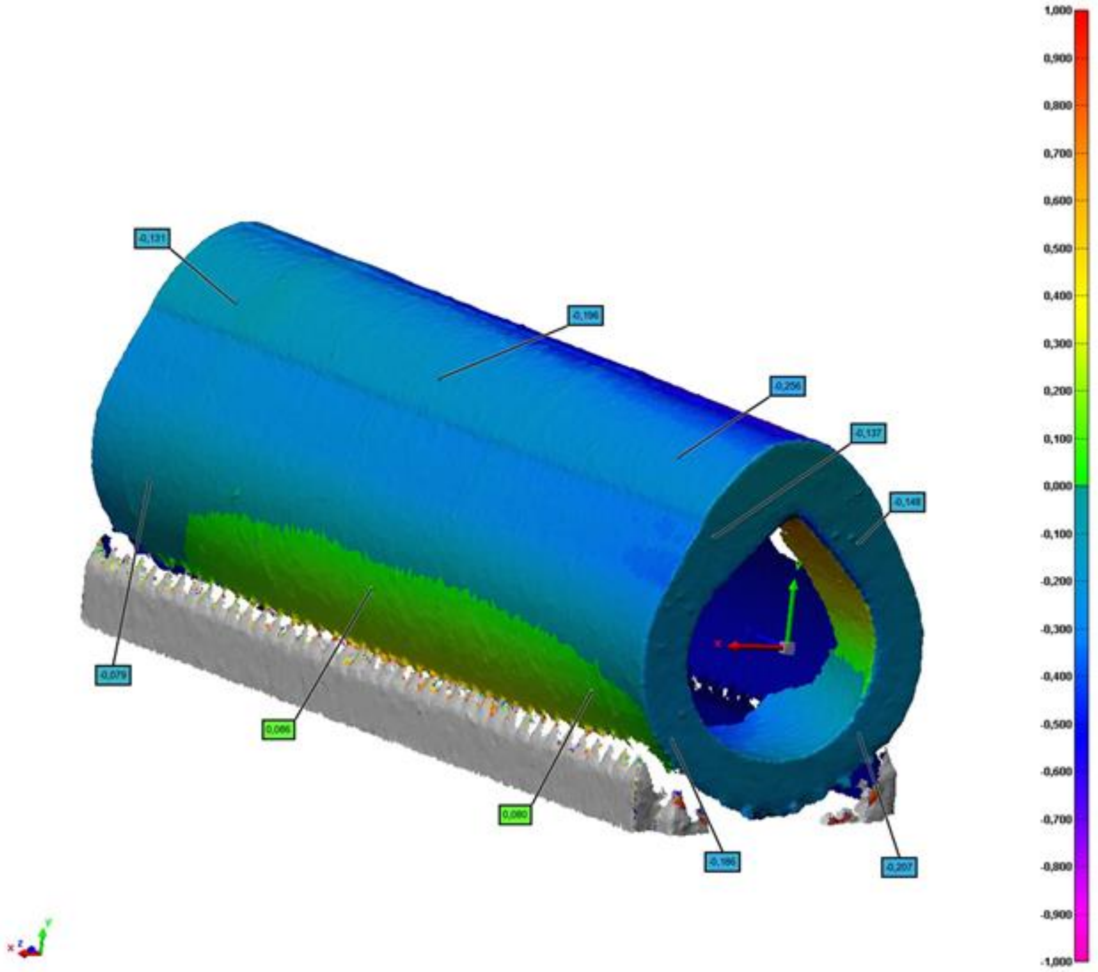
Report Author: Tapio Saarinen
Date: 8.3.2016



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	8
E-mail:	tapio.saarinen@titako.fi	**Drawing #:**	1
Workspace:	1603_LUT_KPL_08	**Serial #:**	01
Project:	1603_LUT_KPL_08 - Kappale 8	**Device:**	smartSCAN HE C4



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	8
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 8



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	8
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 8

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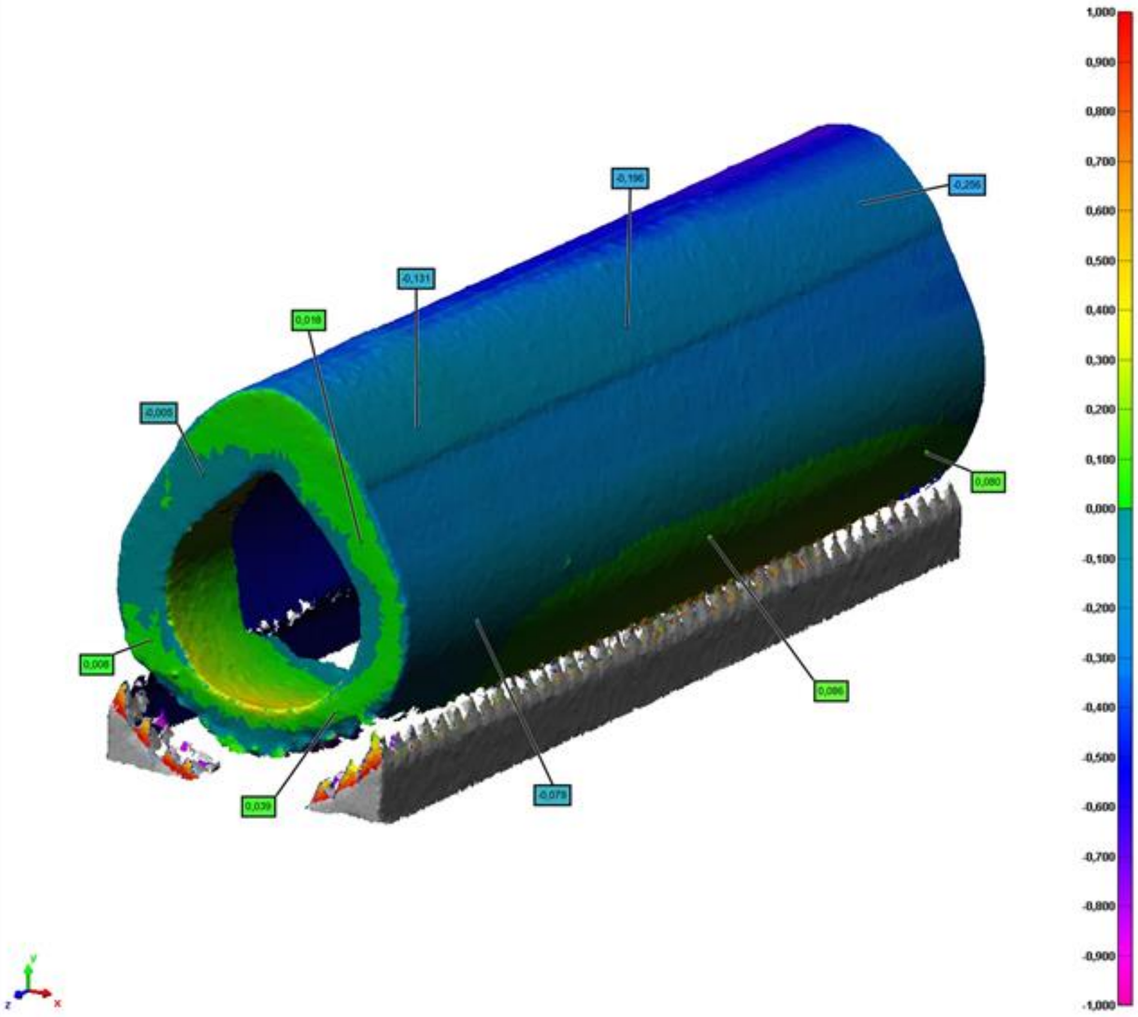
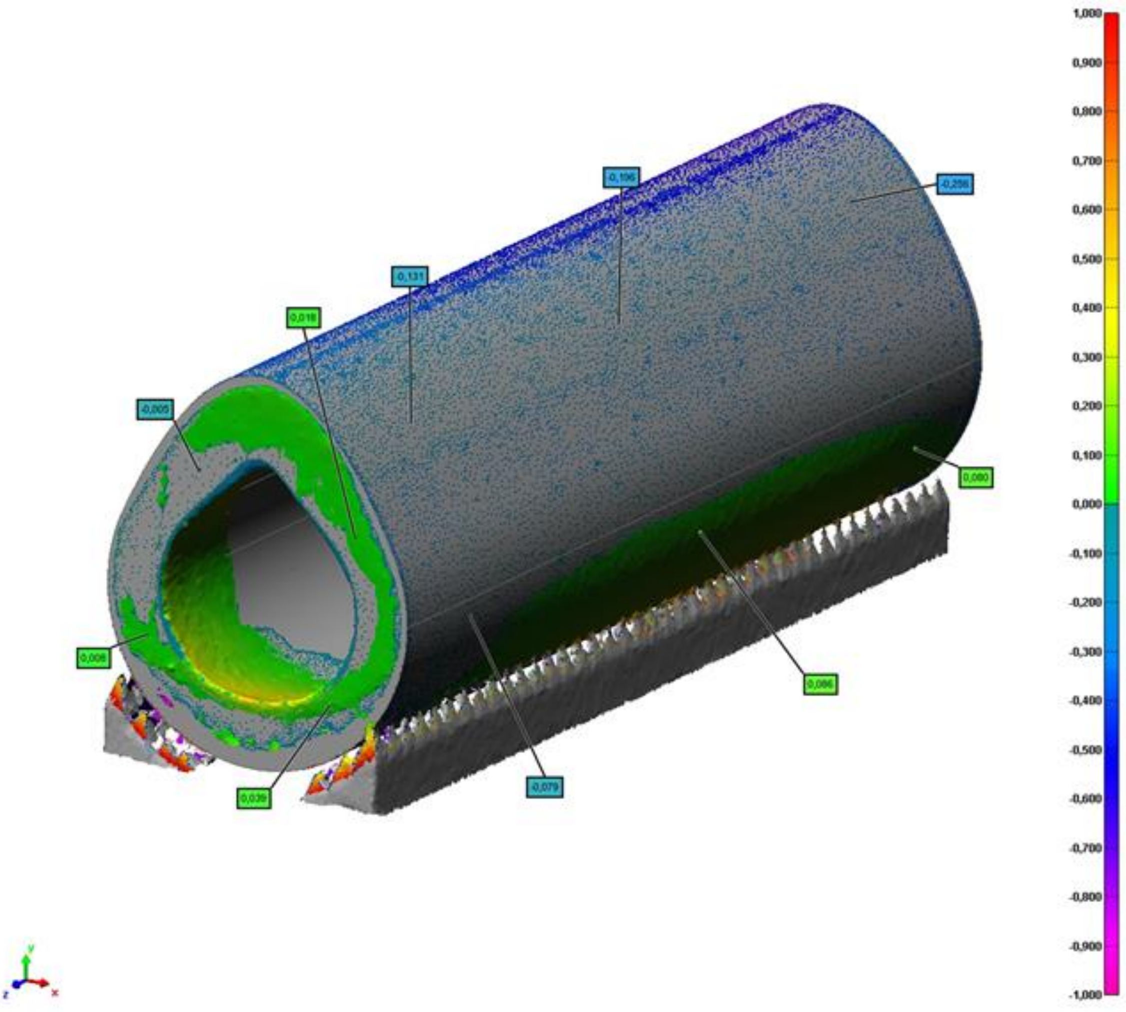


Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	8
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 8

8.3.2016



Organization:	Titako Oy	**Part name:**	LUT_Piili_testpipe
Operator:	Tapio Saarinen	**Part number:**	8
E-mail:	tapio.saarinen@titako.fi	**Piece:**	Kappale 8