Standardization in additive manufacturing

Recommended parameters and fixture solutions for hybrid printing

Standardisering inom additiv tillverkning

Rekommenderade parametrar och fixturlösningar för hybrid printing

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Abstract

This study analyses and examines the hybrid printing process at Uddeholms AB in Hagfors. The objective of this study is to present recommended parameters to achieve optimal printing results in a newly developed steel as well as a steel powder material designed for additive manufacturing.

The study showed that the best results occurred when printing on metal in a delivery state, with a thin layer thickness and double exposure. This resulted in full density in the fusion zone and a gradient hardness change compared to a linear hardness change which was achieved when using single exposure. This leads to a lower chance of crack initiation due to internal stresses in the material.

Additionally, a fixture system is presented that can fixate a variety of geometries simultaneously. The use of this fixture system leads to a reduction in lead time by up to approximately 85% comparing to the fixture solution in use today. Another benefit is the increased economic sustainability since the operator does not need bespoke fixturing solutions for specific jobs.

To achieve optimal properties of the printed detail, the parameters presented in this study should be used in conjunction with the fixture system.

Sammanfattning

Denna studie analyserar och undersöker hybrid printing processen hos Uddeholms AB i Hagfors. Syftet med detta arbete är att presentera rekommenderade parametrar för att uppnå optimala printresultat i ett nytt stål, vilket inkluderar ett metallpulver för additiv tillverkning.

Studien visade att de bästa resultaten uppnåddes när materialet var i leveranstillstånd, med en tunn lagerhöjd och dubbel exponering användes. Detta resulterade i full densitet i bindzonen och en gradient hårdhetsförändring jämfört med en linjär hårdhetsförändring som uppnåddes vid användning av enkel exponering. Detta leder till en lägre risk för sprickinitiering på grund av restspänningar i materialet.

Dessutom presenteras ett fixtursystem som kan fixera en mängd olika geometrier samtidigt. Användningen av detta fixtursystem leder till minskad ledtid med upp till cirka 85% jämfört med fixeringslösningen som används idag. En annan fördel är den ökade ekonomiska hållbarheten eftersom operatören inte behöver specialanpassade fixturlösningar för specifika jobb.

För att uppnå optimala egenskaper hos den utskrivna detaljen bör de parametrar som presenteras i denna studie användas i kombination med fixtursystemet.

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1. Introduction

In this chapter the project will be described. This includes the description of the background to the project, what purpose this work serves and what the goals for this project are. The project was carried out in conjunction with Uddeholms AB at their additive manufacturing department in Hagfors and is a bachelor thesis work.

The boundaries and priorities will also be described in this chapter.

On top of this, the chapter also describes how the results will be delivered and presented.

1.1 Project background

Creating parts using additive manufacturing is an expensive process both in cost and time. That is why it has become more interesting to look for alternative solutions in the form of hybrid printing, where you print the complex part on top of a machined base (milling or lathing).

To be able to do hybrid printing, one would need to have a stable way of mounting the hybrid base in the printer so that it would not deform during the process due to the residual stresses that forms. This puts a high demand on the precision of the fixturing solution and requires knowledge of the transition zone between the printed part and the hybrid base.

This was the background description given by Uddeholms AB and is the premiss of this bachelor thesis work.

1.2 Problem description

The main question this thesis work revolves around is: How can one internally standardize an additive manufacturing process?

This main question can then be separated into two major sub questions:

1. How can one create a universal fixturing system that can handle a variety of geometries, sizes, and a varying amount of the hybrid bases?
2. How will the different parameters used when printing affect the final product?

This first sub question is mainly related to the fixturing of the hybrid base inside the additive manufacturing machine whilst the second question is related to the parameter set used when printing, which will be explained in greater detail in section 1.5 Technical background. Together these two questions will form the base for this thesis work.

Furthermore, a problem description was provided by Uddeholms AB. This can be seen in the list below and lay the foundation for the main question and in extension the two sub questions presented previously.

- Today Uddeholms AB don't have an internal standard for hybrid printing.
- Increase the knowledge regarding the residual stresses and how they affect the hybrid bases and the final tool.
- Study how the exposure strategy influences the transition zone between the printed part and the hybrid bases in terms of porosity and microstructure.
- Analyse potential cost savings in hybrid printing, and if it is more desirable to have near net-shape hybrid bases or not.

In other words, the problems that exists are that there is not an internally standardized way for fixturing of the hybrid bases during printing at Uddeholms AB. At this moment customized build plates are used for every different geometry and are single use.

The reason for why there is no standard in place today is that the additive manufacturing is a new process relative to more conventional manufacturing processes. Therefore, many parts and variables included in the additive manufacturing process have not yet been studied and optimized.

1.3 Purpose and goals

1.3.1 Purpose

The purpose of this project is to investigate the possibilities of hybrid fixturing and how this process can be standardized. Another purpose of the project is to investigate how the characteristics of the final part are affected by the residual stresses and how the exposure strategy/first layers influence the transition zone between the printed part and the hybrid base.

1.3.2 Goals

The goal of this project is to help standardizing the hybrid printing process at Uddeholms AB, part of this is to deliver a fixturing solution and to be able to give recommendations regarding the parameters used in the printing process.

1.3.3 Delivery

The results from this work will be presented at Uddeholms AB 2023-06-15. The physical delivery of the solution to Uddeholms AB will be in the shape of drawings and CAD-files. To accompany the drawings and CAD-files, a scale model will be presented.

On top of this there will be a 15-minute oral presentation at Karlstads University 2023-05-24, a digital exhibition and a physical exhibition 2023-05-26.

There will also be a final report that will be presented and given to Uddeholms AB. This report will be examined and graded by the examinator of this course.

1.4 Project boundaries & priorities

The focus for this project will be the internal standardization of the hybrid printing process at Uddeholms AB, therefore this will be the prioritized topic.

Also, the exposure strategy will be analysed. This will occur in the form of an analysis of the porosity and hardness of the final part depending on changes to different parameters.

The topic with the lowest priority is the knowledge regarding the residual stresses and how they affect the hybrid bases and the final part. Therefore, this topic will be outside of the boundaries for the project and will not be analysed. This has been confirmed and agreed by Uddeholms AB (2023-01-27).

The reason for this is because that there will not be enough time to analyse and study this topic thoroughly. This is also a very complex topic and will as stated previously not be the focus for this project.

The Near net shape analysis will not be analysed either, this is due to longer than expected delivery times for the materials used for prototyping and testing. Therefore, due to the tight timeline of the project, this topic will be regarded as future work. This has been agreed by Uddeholms AB (2023-04-13).

1.5 Technical background

In this chapter, a description of the technical background for the project will be presented. This includes an overview of the additive manufacturing as a process, *Powder Bed Fusion – Laser Beam (PBF-LB)*. Then some of the main parameters used in PBF-LB and what effect they have on the final product will be briefly presented. Lastly regarding the additive manufacturing process, the term *Double exposure* will be introduced.

Furthermore, a description of *Flexible Manufacturing Systems (FMS)* and *Flexible Fixture Systems (FFS)* will be provided in this chapter.

1.5.1 Powder Bed Fusion – Laser Beam (PBF-LB)

PBF-LB is an additive manufacturing technique that selectively fuses regions of a powder bed using a high-powered laser source to produce parts layer by layer, a schematic of this is presented in Figure 1. In other words, PBF-LB uses the energy from a laser to locally melt and solidify a bed of metallic powder (Pauzon et al. 2020). Firstly, a part is created using computer aided design (CAD) that provides a 3D representation of the intended part. Secondly this CAD file is converted to a STL file which segments the part into a collection of 2D representations. Lastly, this STL file is prepared for printing using a specialized software. When this is complete, the printing process can be started. (Hearn 2023)

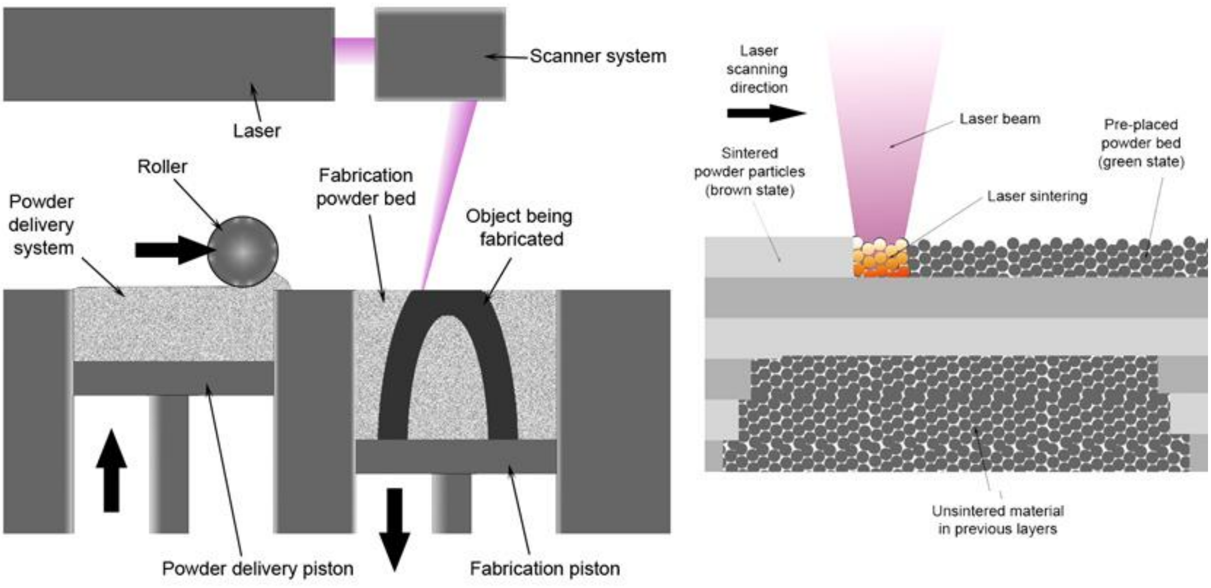


Figure 1: Schematic of a general PBF-LB process, on the left is the general overview of the printer and on the right is a close-up on the material, by Materialgeeza, 2008, https://commons.wikimedia.org/wiki/File:Selective_laser_melting_system_schematic.jpg

Parameters, structures and properties

When working with PBF-LB there are some crucial parameters, structures and properties to take into account. Even though PBF-LB seems simple in principle, it involves a highly complex multiphysics phenomenon occurring in the powder bed, in the resulting melt pool and in the solidifying phase of the parts (Ahmed et al. 2022). Ahmed et al. (2022) also states that a clear understanding of influence of the various 3D printing parameters on the outcome of the process is essential to build a good quality part.

Figure 2 illustrates some of the different common parameters available in the PBF-LB process that are known to influence the material's structure, and the structure in turn influences the final properties of built part. (Ahmed et al. 2022).

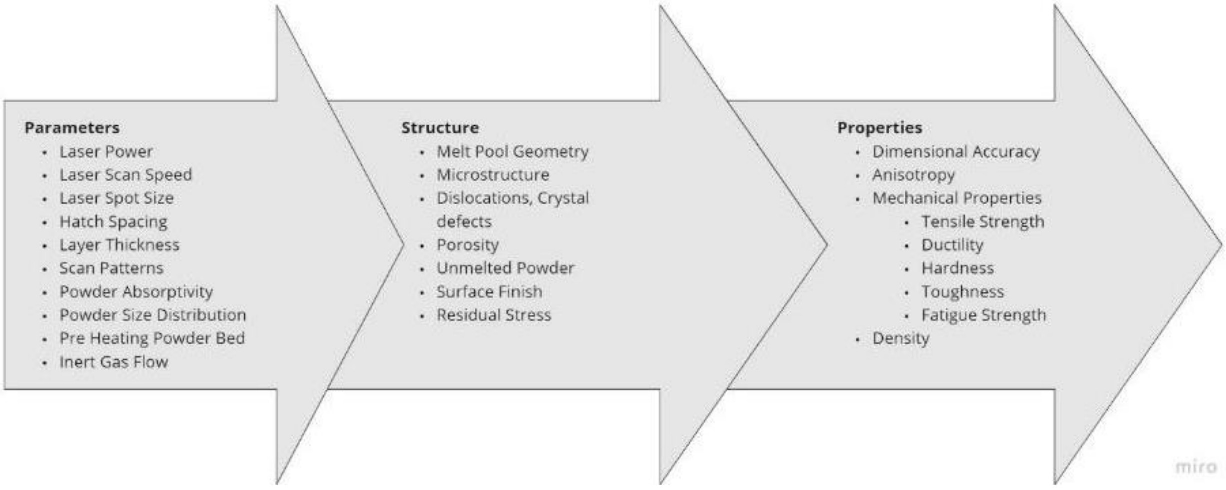


Figure 2: Relationship between common parameters, structure and properties.

The effect of process parameters

The majority of the studies previously done on PBF-LB parameter utilizes the influence of laser energy density on part densification. This results in Equation 1 which describes that the energy density (R) is related to the primary process parameters such as laser power (P), scanning speed (v), hatch spacing (h) and layer thickness (t). (Ahmed et al. 2022)

$$R = \frac{P}{v \times h \times t} \tag{1}$$

Double exposure

Liu et al. (2019) states that during remelting or double exposure, an already scanned layer is exposed with laser once more, therefore the actual layer is completely re-melted. This should in theory ensure that there is no un-melted powder left in that powder layer that can create pores in the fusion zone.

1.5.2 Flexible Manufacturing Systems (FMS) & Flexible Fixture Systems (FFS)

The needs for a flexible manufacturing system have become increasingly desirable due to a higher demand for a greater product variety and innovation, shorter product life-cycle, lower unit cost, higher product quality and shorter lead-times according to (Bi & Zhang 2001).

Bi & Zhang (2001) also states that both “market pull” and “technological push” are forcing firms towards greater flexibility when manufacturing. It’s also to note that an FMS is economically advantageous when having a low to medium volume range in production due to the varying geometries of the produced details.

Bi & Zhang (2001) believes that the flexibility of a whole FMS is restricted by the flexibility of any of its components, including fixture systems. Bi & Zhang (2001) continues and states that the cost of designing and fabricating the fixtures in an FMS can amount to 10-20% of the total system cost.

A comprehensive flexible fixture system consists of locating elements, supporting elements, and fastening elements. The flexible fixture can be divided into two categories: traditional flexible fixtures and modern flexible fixtures. (Li et al. 2021)

Li et al. (2021) states that the modern flexible fixtures with high adaptive performance, reconstruction, and high machining precision has become the mainstream in today’s industry and production.

The main purpose of an FFS is to be competent of fixturing a large variety of geometries and have become a prospective way of reducing the unit cost of a product, especially in low to medium volume production. Carr Lane (n.d.) describes it as a work holding system that uses a series of standardized components for building specialized work holders. The components can then be assembled in different combinations to create an unlimited amount of fixturing solutions.

2. Method

In this chapter the methods used will be presented. This includes the different methods involved in the general project planning and process, development of the fixture system and lastly methods used in the material analysis.

2.1 Double diamond

This thesis work follows the process model double diamond, this is visualised in Figure 3.

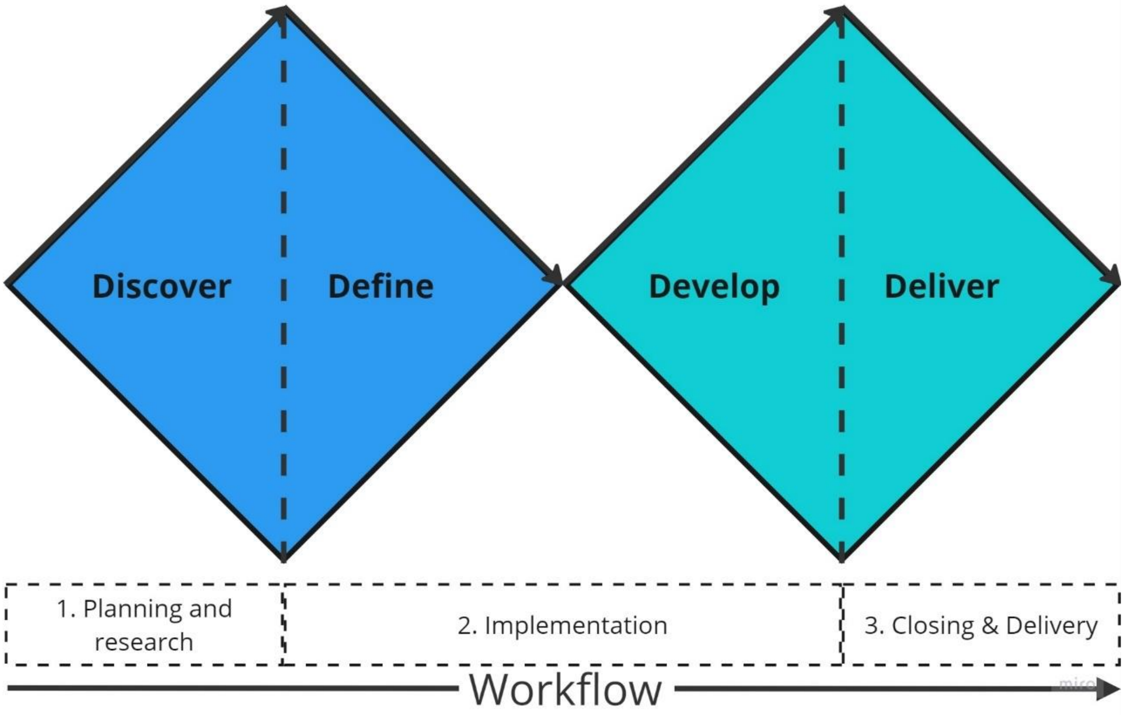


Figure 3: Double diamond

The Double Diamond design model has four stages: Discover, Define, Develop and Deliver. Together, these stages work as a map for designers and engineers to organize their thoughts in order to improve the creative process. (Costa 2018).

The double diamond can also be separated into 3 major phases: Phase 1. – Planning and research, Phase 2. – Implementation and Phase 3. - Closing & Delivery. A more in-depth description of the three phases can be found in Appendix A: Project plan.

The activities in this project will be presented in chronological order down below:

Discover

1. Project plan
2. Work Breakdown Structure (WBS)
3. Gantt Chart
4. Risk analysis
5. Litterature Studies

Define

1. Litterature Studies
2. Requirement Specification
3. Function analysis
4. Design of Experiments (DoE)

Develop

1. Brainstorming
2. Scamper
3. Pugh Matrix
4. Occham's razor
5. Computer Aided Design (CAD)

Delivery

1. Experiments and test analysis
2. Recomended parameters
3. CAD files
4. Drawings
5. Exhibits
6. Presentations
7. Final report

2.2 Project plan

This thesis revolves around a project plan that has been made to break the work down into smaller tasks. This is to keep track of time and resources available. The project plan is a living document that may change during the course of the project and it is not definitive (Lilliesköld & Eriksson 2005). Although, Lilliesköld & Eriksson (2005) states that the project plan provides a great foundation for discussions regarding the project and potential changes.

> *"If you fail to plan, you plan to fail" (Lilliesköld & Eriksson 2005)*

For the full project plan, see Appendix A: Project Plan.

2.3 Work Breakdown Structure (WBS)

A WBS is a project planning method where the project is broken down into smaller parts. According to Lilliesköld & Eriksson (2005) the WBS follows 7 steps:

1. Break to project down into manageable parts and tasks
2. Identify task assignments
3. Identify dependencies
4. Do a time estimation
5. Identify the critical path
6. Allocate resources
7. Enter into Gantt chart, resource diagram and time plan.

Lilliesköld & Eriksson (2005) also explains that there needs to be a project specification and that the project needs to have a measurable goal in order for the WBS to work.

For the full WBS, see Appendix A: Project Plan.

2.4 Gantt chart

A Gantt chart is used to show how the different tasks and activities tie in with each other (Lilliesköld & Eriksson 2005). The Gantt chart gives a graphical picture of the project. For smaller projects a Gantt chart might not be necessary (Lilliesköld & Eriksson 2005).

For the full Gantt chart, see Appendix A: Project Plan.

2.5 Risk analysis

To identify the most threatening risks in a project a risk analysis can be made. To calculate the risk factor the following variables can been used:

- P = Probability of the risk occurring
- C = The consequences of the risk
- R = Risk factor

$$R = P \times C \tag{2}$$

The variables showed in Equation 2 are scored 1-4, where 1 is the lowest and 4 is the highest. Therefore, a low value of R is to be preferred. This risk analysis method is presented more in detail by Lilliesköld & Eriksson (2005) in their book. The risk factor R is calculated using Equation 2.

For the full risk analysis, see Appendix A: Project Plan.

2.6 Literature studies

Bohgard et al. (2015) explains that literature studies are often used to gather and collect background information for a study or work. The literature study can have two different purposes, either to describe the current knowledge of a specific topic or to gather domain knowledge in a specific field.

For the full literature study, see Appendix C: Literature studies.

2.7 Requirement specification

Bohgard et al. (2015) states that the requirement specification determines what the product should achieve and includes ergonomic requirements, economic requirements, functional requirements, quality requirements, aesthetic requirements, etc. A requirement specification should not contain any formulations about how to solve the problem.

In this thesis the requirement specification focuses mainly on functional requirements and quality requirements. The requirement specification is also a good way to control that the solution fulfils the desired tasks and goals.

For the requirements, see Table 1 and for the full requirement specification, see Appendix B: Requirement specification.

2.8 Function analysis

Function Analysis is a technique used to identify and understand the needs of the project, product or service, in other words: what does it do, what must it do. (Value Analysis Canada 2023). Bohgard et al. (2015) states that the starting point of function analysis is what is to be achieved, not how it is to be achieved. Cross (2000) means that a function analysis consists of four steps:

1. Express the overall function as the transformation of input to output.
2. Break down the overall function into central sub-functions.
3. Draw a block diagram that shows the interactions between the sub-functions.
4. Allocation of sub-functions to components.

2.9 Design of Experiments (DoE)

To be able to base decisions on facts and carry out quality improvements, it is necessary to systematically collect and process data. In order to increase knowledge about the product or process, and thus the conditions for improvements, one must also plan and conduct experiments. Well-planned experiments provide knowledge about which parameters affect products and processes and which values should be chosen for these parameters to obtain the best possible products or processes at the lowest possible cost. (Bergman & Klefsjö 2020)

Teo et al. (2021) states that under normal circumstances, the number of experiments required increases on a factorial scale with the number of parameters under consideration. In addition, when dealing with a large dataset, with large numbers of possible combinations between parameters, important correlations among them may be missed. Here, the use a design of experiments (DoE) approach to tailor preparation process for improved performance is beneficial.

Teo et al. (2021) continues, DoE is a well-established method for optimizing experimental sets with the goal of maximizing statistical power and/or minimizing the number of trials. The exploitation of DoE reduces the number of experiments without compromising information quality (statistical power) due to the relatively cost- and labour-intensive preparation process.

In this thesis, planned experiments were executed. This is because planned are more efficient than single factor experiments in regards to time. Bergman & Klefsjö (2020) states that by using reduced factor experiments a lower number of tests are required, which leads to a reduction in cost. But the risk of faulty conclusions increases due to overlays that occur.

2.10 Brainstorming

When first starting to generate concepts a session of brainstorming is useful, this is for two reasons; the first reason is to start thinking as well as summarizing the information from the previous research and brainstorming is a great tool for this.

The second reason for why a brainstorming session is useful is that brainstorming generates a lot of ideas where the focus is on quantity over quality, this is also mentioned by Wikberg Nilsson et al. (2021) which is needed in an early stage of the concept generation.

2.11 Scamper

A scamper session is executed through 6 steps, Wikberg Nilsson et al. (2021) describes the 6 steps in their book:

1. Generate ideas, solutions and concepts through brainstorming or 19pprox.19wing
2. For each of the solutions ask the following questions: Replace? Combine? Adapt? Modify? Use in a different way? Eliminate? Think the opposite?
3. Let the participants speculate freely about each question and note the ideas.
4. Go through each question for every idea/concept to really make sure that all possible solutions have been thought of.
5. Document
6. Categorize the new solutions and concepts and evaluate for further work.

Wikberg Nilsson et al. (2021) states that the Scamper session uses the material from a previous brainstorming session and the aim is to further develop the material as previously mentioned.

2.12 Pugh Matrix

A Pugh Matrix is a decision matrix where alternatives or solutions are listed on one axis, and evaluation criteria are listed on the other axis. The objective is to evaluate and prioritize the alternatives or solutions. The team first establishes and weights the evaluation criteria and then evaluates each option against those criteria. (Carlson 2012)

Ulrich et al. (2020) mentions that "The purposes of this stage are to narrow the number of concepts quickly and to improve the concepts.". On top of this it is a good way to connect the requirements specification and elimination of concepts.

Also, as Wikberg Nilsson et al. (2021) states when talking about concept matrices on page 237, that the aim is to discuss the concepts based on fulfilment of criteria rather than personal opinion regarding the different concepts, this part is very important. The matrix Wikberg Nilsson et al. (2021) discusses is not a Pugh Matrix but the idea is the same for both of the matrices and they share great similarities.

2.13 Occham's razor

Occham's razor is a design principle that focuses on simplicity. Wikberg Nilsson et al. (2021) states that a simple design is a goal that should be desired to reached and that simplicity is preferred over complexity.

Wikberg Nilsson et al. (2021) continues and states that unnecessary elements reduce the effectivity of a design because the users' needs to question how a product is supposed to be used instead of intuitively understand.

2.14 Computer Aided Design (CAD)

The software used for CAD work will be PTC Creo. PTC Creo lets the user effectively combine the power and control of parametric modelling with the ease of use and flexibility of direct modelling. As well as running simulations on parts to see how they will perform under real-world conditions. (PTC 2023)

The main use of the CAD software for this thesis work will be for the modelling of the fixture system.

2.15 Experiments and test analysis

As stated in section 2.6, the planning of tests and experiments will be carried out using Design of Experiments (DoE), and the results from this will then be inserted into MODDE12 Pro. This software will later be used to compile the data for further analysis.

The test specimens will be printed during one print session. These test specimens will then be taken into the laboratory for a metal structure analysis with the help of a Light Optical Microscope (LOM) and hardness testing.

The light optical microscope will be used to count and study the number of pores which have originated in the fusion zone, then the hardness test will be used to study the hardness of the test specimens.

The results from the tests will be entered into MODDE12 Pro to generate results in the form of graphs and tables.

2.15.1 Light Optical Microscope (LOM)

Light microscopy is used to make small structures and samples visible by providing a magnified image of how they interact with visible light, e.g., their absorption, reflection and scattering. (Schädler 2022)

Schädler (2022) continues, fundamentally a microscope comprises two subsystems: an illumination system to illuminate the sample and an imaging system that produces a magnified image of the light that has interacted with the sample, which can then be viewed by eye or using a camera system.

2.15.2 Hardness testing

A hardness test is typically performed by pressing a specifically dimensioned and loaded object (indenter) into the surface of the material. The hardness is determined by measuring the depth of indenter penetration or by measuring the size of the impression left by an indenter. (Struers 2023).

2.16 Material comparison

When comparing the materials for eventual use for the fixturing system, Granta EduPack 2022 will be used. Granta EduPack 2022 provides support to enhance undergraduate materials education. EduPack includes a database of materials and process information, materials selection tools and a range of supporting resources. (ANSYS, Inc n.d)

3. Results

In this chapter, all the results from the project will be presented.

3.1 Requirement specification

In Table 1 the full list of all the requirements and wishes is presented. The priorities are ranked 1-5, where 1 is the lowest and 5 is the highest. The *R* and *W* describes if it's a requirement or wish.

Table 1: Requirements and wishes

#	Category	Requirements	Priority (1-5)	R/W
1	Use	Being able to fixture hybrid bases of different size and geometry	5	R
2	Material	Withstand pre-heating up to 200℃	5	R
3	Use	Fit AM-machine: EOS M290	5	R
4	Reference system	The fixture solution must have an accurate reference point system with a minimum of two reference points	5	R
5	Manufacturing	Top face of the fixture solution should be parallel with the bottom face of the hybrid base	5	R
6	Use of AM-machine	Being able to simultaneously fixture more than one hybrid base at a time	5	W
7	Material	Made of in-house materials	4	W
8	Cost	No changes should be made to the AM-machine	4	W
9	Manufacturing	Being able to manufacture the fixture system with tools available at Uddeholms AB	4	W
10	Use	No changes needed to the hybrid bases	4	W
11	Use	Fit AM-machines: EOS M270, EOS M280 and EOS M400	3	W
12	Reference system	Positioning accuracy better than 0,1 mm	3	W
13	Assembly/Use	Weight of build plate < 25kg	2	W

For a more in-depth description of a specific requirement or wish, see Appendix B: Requirement specification.

When verifying and screening, each of the concepts will be given a score of:

- *True*: if the concept meets the given requirement
- *False*: if the concept does not meet the given requirement

The reason for this step is to quickly eliminate the concepts that meet the least amount of the requirements, to pass this stage every requirement needs to be scored as *True*. The concepts that manage this will pass through to the second stage of screening where a score of 1-5 will be given on how well the concept meets the various requirements and wishes.

The concept with the highest total score after the second stage of screening and verification will be the one that will be finalized and delivered to Uddeholms AB.

3.2 Fixture solution

3.2.1 Concept generation and selection

The concept generation resulted in 5 separate concepts (Figure 5-9) and were based on the requirements and wishes which are presented in Table 1.

In order to create the concepts, brainstorming and scamper where the main methods used. Occham's razor was taken into consideration when designing and screening the concepts.

After brainstorming, a scamper session was performed. Here the previous concepts from the brainstorming were combined and more rendered sketches of the concepts where made. It was in this stage that the requirements and wishes from the requirement specification (Table 1), as well as the function analysis (Figure 4) started to play a bigger role in the concepts.

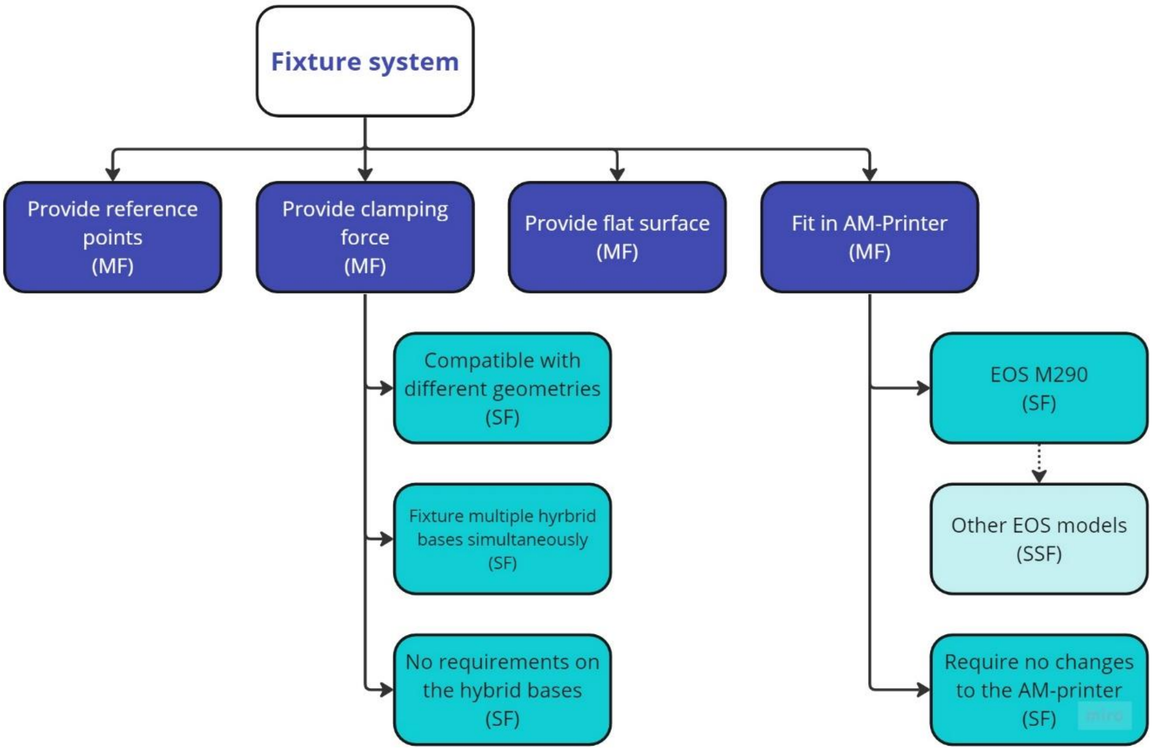


Figure 4: Function analysis

From this session the previous 8 concepts were combined, eliminated, and reworked into 5 concepts; these can be seen in Table 2.

Table 2: Combination, elimination, and reworking of concepts.

Original Concepts	**Changes / Combinations**	**Resulting Concept**
Concept A + Concept B	The pin-idea from concept A was combined with the reference system from concept B	Concept 1 – Pins
Concept B + Concept C	Parts of the reference system from concept B was combined with the groves from concept C	Concept 2 – Groves
Concept D	The spring idea from concept D remained the same	Concept 3 – Springs
Concept E + Concept F	Here the conventional magnets of concept E were eliminated in favour for the electromagnets of concept F	Concept 4 – Electromagnets
Concept G + Concept H	The clamps idea from concept H was eliminated in favour for the vise from concept G for usability	Concept 5 – Vise

For a full description of the different concepts and a complete, in-depth explanation of the concept generation and selection process, see Appendix D: Concept Selection.

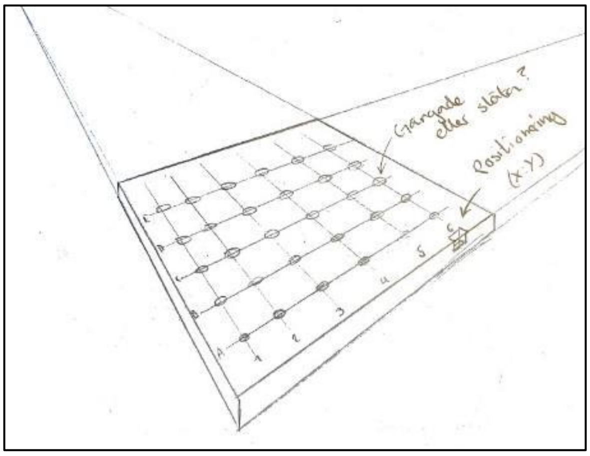


Figure 5: Concept 1 – Dowel holes

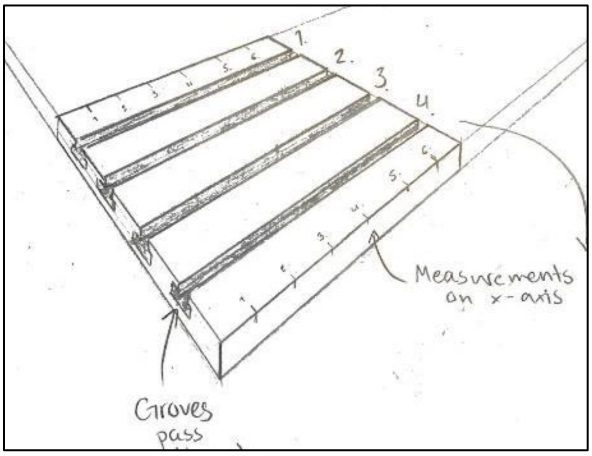


Figure 6: Concept 2 – T-slots

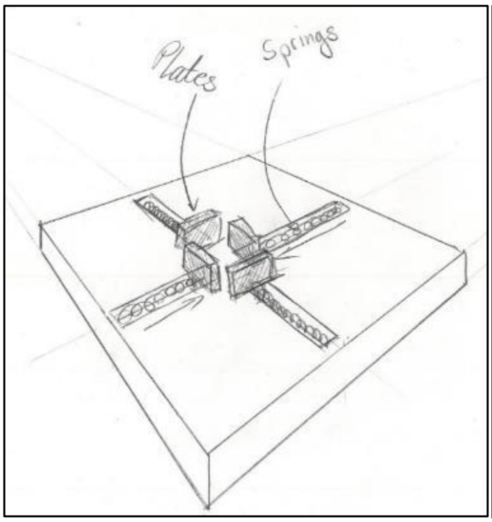


Figure 7: Concept 3: Springs

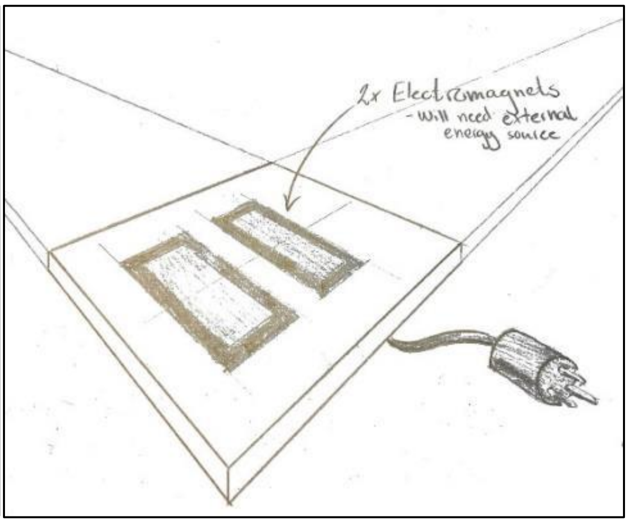


Figure 8: Concept 4 – Electromagnets

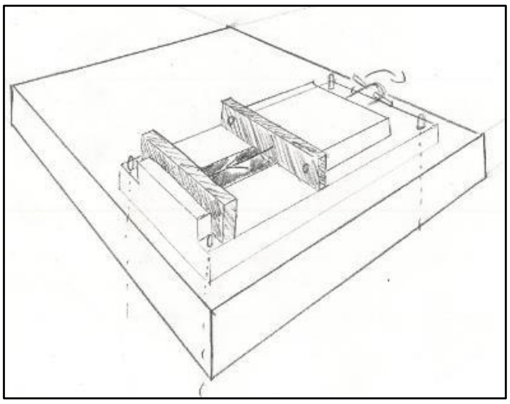


Figure 9: Concept 5 – Vise

When the concepts had been generated, a Pugh Matrix was used to evaluate the results from the concept generation. The Pugh Matrix can be seen in Figure 10.

Pugh Matrix - Fixture solution

Project: Internal standardization - Uddeholms AB

	Criteria	Baseline	Concept 1 - Dowel holes	Concept 2 - T-slots	Concept 3 - Springs	Concept 4 - Electromagnets	Concept 5 - Vise	Totals	Rank
1	Fixture hybrid bases	0	+	+	+	+	+	5	1
2	Withstand pre-heating	0	0	0	–	–	0	-2	13
3	Fit given AM-machine: EOS M290	0	0	0	0	0	0	0	
4	Reference point system	0	+	+	–	–	0	0	9
5	Build plate must be parallel with the hybrid base	0	0	0	–	0	0	-1	10
6	Fixture multiple hybrid bases	0	+	–	0	+	–	0	7
7	Made of in house materials	0	0	0	0	0	0	0	
8	No changes needed to the AM machine	0	0	0	0	–	0	-1	11
9	Ease of manufacturing	0	+	+	–	–	+	1	5
10	No changes needed to the hybrid bases	0	+	–	0	0	0	0	8
11	Fit alternative AM-machines	0	+	+	+	+	+	5	1
12	Positioning accuracy better than 0,1 mm	0	+	+	0	+	+	4	3
13	Weight of build plate < 25kg	0	+	+	+	+	+	5	1
		Totals	6	4	0	1	4		
		Rank	1	3	5	4	2		

Symbols	Relationship	Value
+	Better than baseline	1
0	About the same	0
–	Worse than baseline	-1

Figure 10: Pugh Matrix, current base plate in use at Uddeholms AB is used as baseline.

The results from the Pugh Matrix are listed in Table 3 and shows that concept 1 is the superior concept since it meets the requirements and wishes the best.

Table 3: Pugh matrix scores

Concept	Score	Rank
Concept 1 – Dowel holes	6	1
Concept 2 – T-slots	4	3
Concept 3 – Springs	0	5
Concept 4 – Electromagnets	1	4
Concept 5 – Vise	4	2

3.2.2 Final fixture solution

The selected concept, Concept 1 – Dowel holes (Figure 5) implements the use of a grid-based fixed positioning system (Figure 11) in the base plate. To read the position of the hybrid base, the operator uses the coordinate system (A, 1) to get an exact (X, Y)-position of the part.

The holes have a diameter of 8 mm and the spacing is 21 mm in both directions (x- axis and y-axis). The top and bottom row of holes are also threaded with M8x1.25. This feature was a request form Uddeholms AB, this is in order to fixture large geometries with the help of screws.

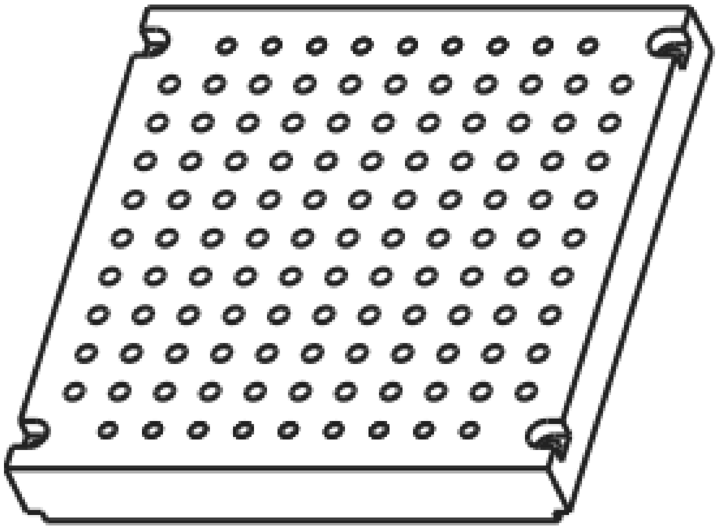


Figure 11: Hole pattern, taken from drawing. See Appendix F for full drawing.

This concept can be used in combination with different standard components and standardized screws and pins. Moreover, custom made fixture points (Figure 12) and fixture rails (Figure 13) that are mounted on the dowel pins can be manufactured in different sizes to suit the customers' needs.

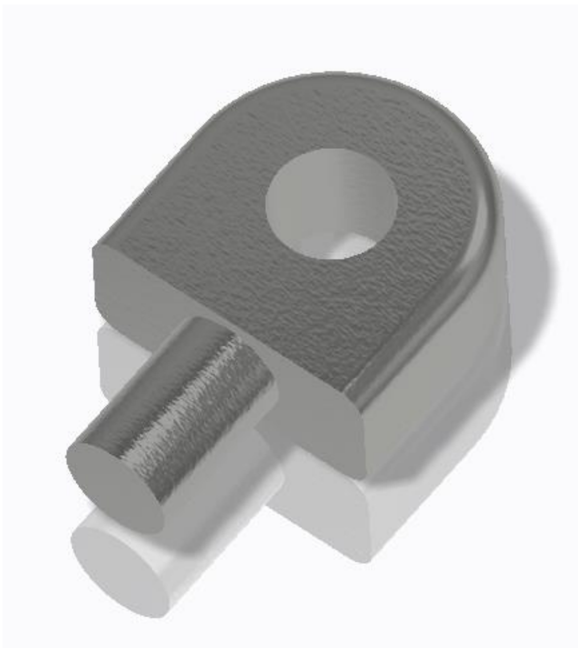


Figure 12: Fixture point feature

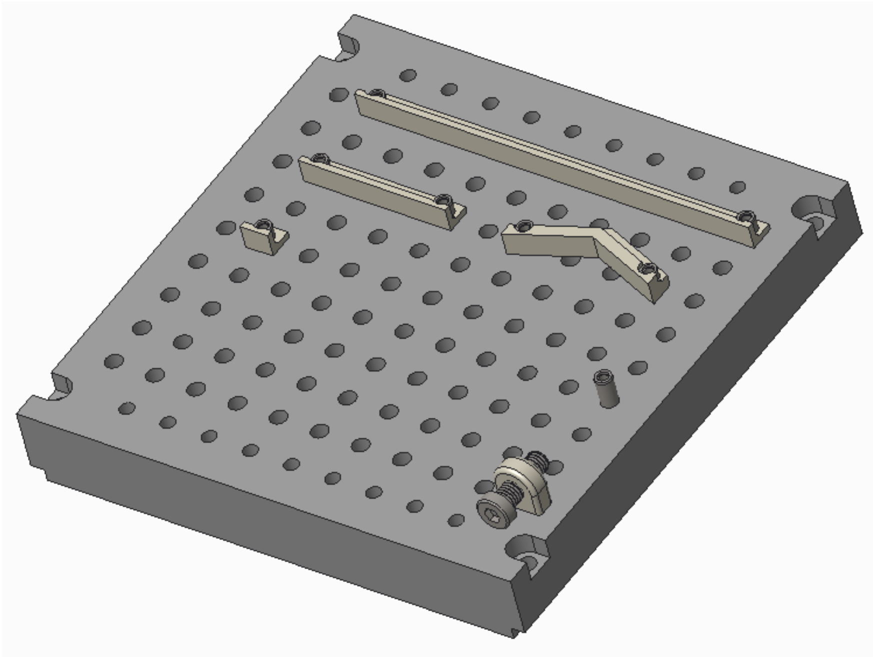


Figure 13: Full fixture system, with all available features

These fixture points and fixture rails (Figure 12 & Figure 13) opens the possibility for the operator to quickly create a bespoke base plate for every print job in a standardized way. Although, for some print jobs the dowel-pins will be sufficient to fixture the hybrid base and the use of a custom fixture point will not be necessary. The dowel-pins intended for this application are the Wiberger CPIG 8x24, these are also the same dowel pins that secure the fixture rails. This concept can fixture a variety of different geometries without major, permanent changes to the base plate and can fixture multiple hybrid bases at the same time.

The fixture rails are available in four configurations, the main difference is the shape. One option is a straight rail with three different sizes. One that is just one hole in length (14 mm), one that is three holes in length (75 mm) and one that is nine holes in length (201 mm). The other option is a wedge shape with the purpose of fixturing circular geometries.

The purpose of these fixture rails is to quicky be able to fixture multiple hybrid bases simultaneously and to simplify the referencing in these cases.

Another positive aspect of this concept is the reference system. Since the reference system is directly implemented into the base plate it provides an accurate and true reading of the positioning of the hybrid base.

There will not be a problem to change the size of this fixture solution to suit other printers in the Voestalpine group.

See Figure 14 for an example of how the concept is intended to be used.

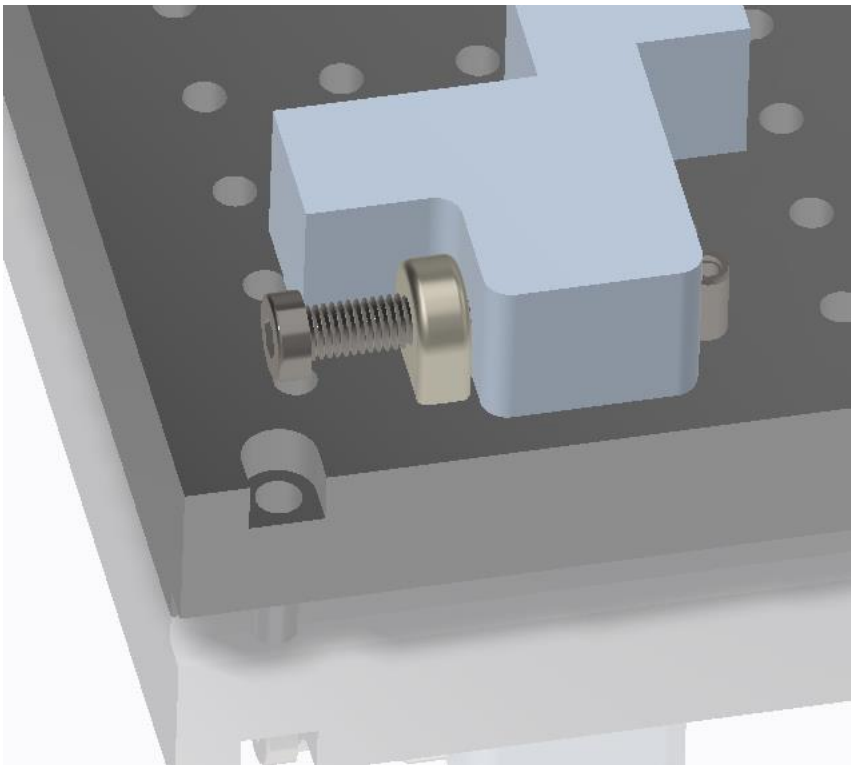


Figure 14: Fixturing example

Down below is a brief summary of the arguments to why this is the best solution are, in relation to the requirement specification:

- Ease of use, no custom made base plates are needed (*Requirement 1, 5, 6, 10*)
- Ease of manufacturing (*Requirement 7, 9*)
- Easy to change dimensions to be compatible with multiple AM-printers (*Requirement 3, 11, 8*)
- Compatible with different standard components, such as vises etc. (*Extra*)
- Great possibility for the use of custom components if needed (*Extra*)
    - A possibility for potential up-sales with different types of standardized mounting points
- A simple but effective reference system (*Requirement 4, 12*)
- Possibility to mount multiple hybrid bases simultaneously (*Requirement 1, 5, 6, 10*)

This plus the results from the Pugh Matrix (Figure 10) gave enough data to be able to make the decision to select this concept as the one to go forward with.

Moreover, the selected concept complies the best with the function analysis (Figure 4).

The drawings for the flexible fixture system can be found in Appendix E: Drawings, and the scale model of the fixture system can be seen in Figure 15.

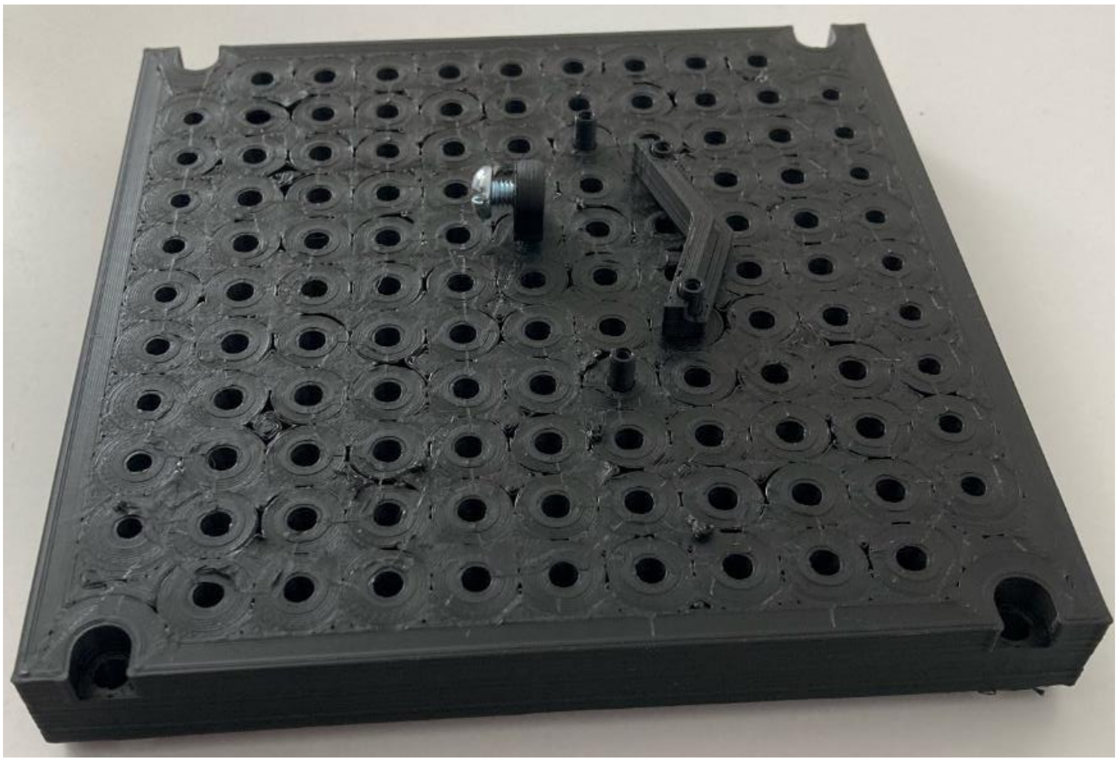


Figure 15: Scale model of the fixture system, scale 1:2

3.2.3 Material selection

The material that will be used for the entire fixture system is a low-carbon steel produced at Uddeholms AB in Hagfors which available in their product catalogue. The material can be supplied in as-hot-rolled or fine-machined condition.

The composition of the material can be seen in Table 4.

Table 4: Material composition for the fixture system

Typical analysis %	C 0,18	Si 0,3	Mn 1,4
Standard specification	(W.-Nr. 10050, SS 2172)		
Delivery condition	Hot rolled. Hardness 30 approx. 170 HB		
Colour code	Black		

3.3 Material analysis

3.3.1 Results from the tests

The first step in the planning of the tests was to determine which parameters that were going to be analysed. At the beginning of the material analysis process there were six parameters that were intended to be studied, see Table 5.

Some of these parameters are present in Figure 2, State of hybrid base and Surface preparation are not present since these are parameters related to the hybrid base and not directly to the printing process.

Table 5: Original parameters

Parameter	**Index**
Hatch spacing	*Hat*
Layer thickness	*Lay*
Scanning speed	*Sca*
Exposure strategy	*Exp*
State of hybrid base	*Sta*
Surface preparation	*Sur*

Although when discussed with the supervisors at Uddeholms AB and Karlstads University, it was determined that the number of parameters that were to be studied needed to be reduced. This was mainly due to the time constraints of the project.

On top of the time constraints, the first two parameters: Hatch spacing, and scanning speed are the most standardized parameters to date at Uddeholms AB.

Secondly, surface roughness was determined to not be studied. The reason for this was that it is hard to create a controlled test environment due to the difficult and somewhat uncontrolled difference between the fine and rough surface of the bases due to the different states of the material. Therefore, a change in layer thickness was determined to be used instead. This is because in theory this would show the same (if not better) results regarding the change in porosity, due to un-melted powder for example, and would create a more controlled test environment.

After the reduction of parameters, three parameters were left to be studied, these are listed in Table 6.

Table 6: Final test parameters

Parameter	Index
Layer thickness	*Lay*
State of hybrid base	*Sta*
Exposure strategy	*Exp*

The aim for the tests is to analyse if the parameters listed in Table 6 affect the porosity and hardness in the fusion zone of the final product. The test where then constructed in MODDE12 Pro and the result of this can be seen in Table 7.

Table 7: Test matrix

	1	2	3	4	5	6	7	8	9
	Exp No	Exp Name	Run Order	Incl/Excl	State of base	Exposure	Layer Thickness	Porosity	Hardness
1	1	1-1s	1	Incl	Hardened + Annealed	Single	0,05	8	444,13
2	2	1-1d	2	Incl	Hardened + Annealed	Double	0,05	5	520,09
3	3	1-3s	3	Incl	Hardened + Annealed	Single	0,15	8	433,44
4	4	1-3d	4	Incl	Hardened + Annealed	Double	0,15	11	356,92
5	5	2-1s	5	Incl	Hardened	Single	0,05	1	567,22
6	6	2-1d	6	Incl	Hardened	Double	0,05	1	606,85
7	7	2-3s	7	Incl	Hardened	Single	0,15	2	596,26
8	8	2-3d	8	Incl	Hardened	Double	0,15	0	634,79
9	9	3-1s	9	Incl	Delivery State	Single	0,05	9	417,16
10	10	3-1d	10	Incl	Delivery State	Double	0,05	1	366,69
11	11	3-3s	11	Incl	Delivery State	Single	0,15	4	462,08
12	12	3-3d	12	Incl	Delivery State	Double	0,15	0	441,91

When performing the tests, three different bases are used where each one of the bases have a unique state; Delivery state, Hardened and Hardened + Annealed. These are then pre-heated in the printer to 40°C before printing.

The hardening and the annealing curves for the hybrid bases can be found in Appendix F: Hardening curves.

On each base, two different thicknesses will be used, *Thick* and *Thin*. The thinner part of the hybrid base will have a thicker first layer of powder and vice versa.

Then, half of the printed tests will experience double exposure. See Figure 16 for a visual explanation. The test specimens will be printed during one print session. All of the different test specimens are presented in Table 8.

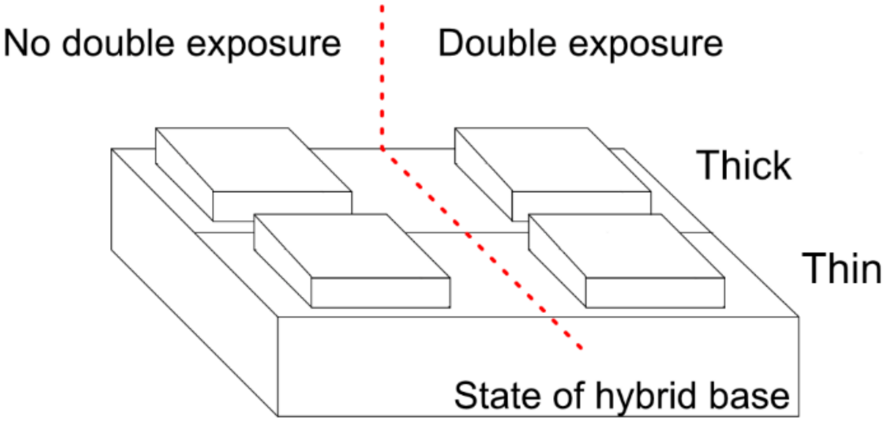


Figure 16: Description of the test specimen

Table 8: All test specimens, variation of Table 7

Test number	Exposure strategy	Layer thickness	State of hybrid base
1-1s	Single exposure	Thin	Hardened + annealed
1-1d	Double exposure	Thin	Hardened + annealed
1-3s	Single exposure	Thick	Hardened + annealed
1-3d	Double exposure	Thick	Hardened + annealed
2-1s	Single exposure	Thin	Hardened
2-1d	Double exposure	Thin	Hardened
2-3s	Single exposure	Thick	Hardened
2-3d	Double exposure	Thick	Hardened
3-1s	Single exposure	Thin	Delivery state
3-1d	Double exposure	Thin	Delivery state
3-3s	Single exposure	Thick	Delivery state
3-3d	Double exposure	Thick	Delivery state

After the tests are printed, they will be cut to size using an Electrical Discharge Machine (EDM) and then polished according to internal standards at Uddehoms AB to create a prepped surface for the hardness tests and microscope analysis. The final test specimens are showed in Figure 17.

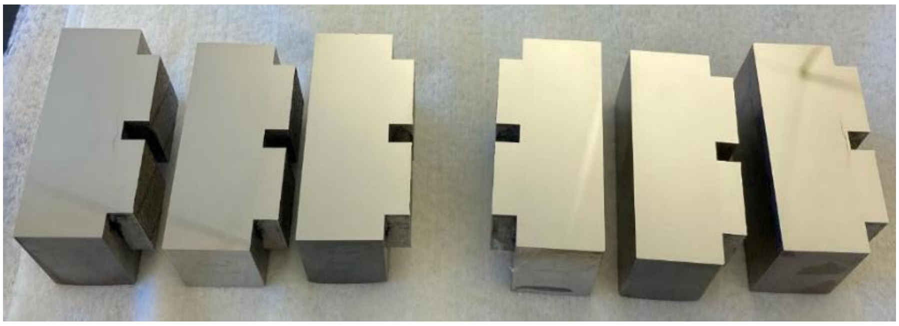


Figure 17: Final test specimens

The thickness, layer thickness and hardness of the test specimens is presented in Table 9.

Table 9: Thickness of the hybrid bases, layer thickness and hardness of the hybrid bases

State	Base thickness, Thick [*mm*]	Base thickness, Thin [*mm*]	ΔT [*mm*]	Layer thickness, Thick [*μm*]	Layer thickness, Thin [*μm*]	Hardness [*HRC*]
Delivery state	16,05	15,98	0.07	15	5	20
Hardened	16,06	15,98	0.08	15	5	54,5
Hardened + annealed	16,06	15,99	0.07	15	5	16

3.3.2 Materials used for the tests

The material used for the hybrid base in the tests was a new stainless steel produced by Uddeholms AB in Hagfors. For the printed parts of the test, the same newly developed steel in powder form, which is also produced by Uddeholms AB in Hagfors was used.

Unfortunately, since this is a newly developed material, no further information regarding the materials can be presented.

3.3.3 Test results

The result parameters that were studied are Porosity and Hardness as previously stated, they are found in Table 10.

Table 10: Result parameters

Parameter	Unit
Porosity	Frequency [*x*]
Hardness	Vickers [*HV0,1*]

The porosity is measured in the number of pores that exists in the fusion zone. The reason for why these pores exists and what effects they have on the fusion zone are discussed in section 5.

The hardness is measured in Vickers (*HV0,1*) and gives an indication of the homogeneity of the hardness throughout the fusion zone (*FZ*) in the final detail. If a higher value for the hardness in the fusion zone is desirable will be discussed in chapter 6.

The porosity-parameter is of higher importance in this thesis, since it is known that a lower number of pores will lead to a higher quality of the final part, whereas it is not as clear if a high value for the hardness is desired.

Figure 18 shows how the different parameters affect the results, here it can be seen that the porosity increases on the hardened + annealed test as well as with single exposure. On the other hand, porosity decreased on the hardened test as well as with double exposure.

Figure 18 also shows that the hardness is completely dependent on the hardness of the hybrid base.

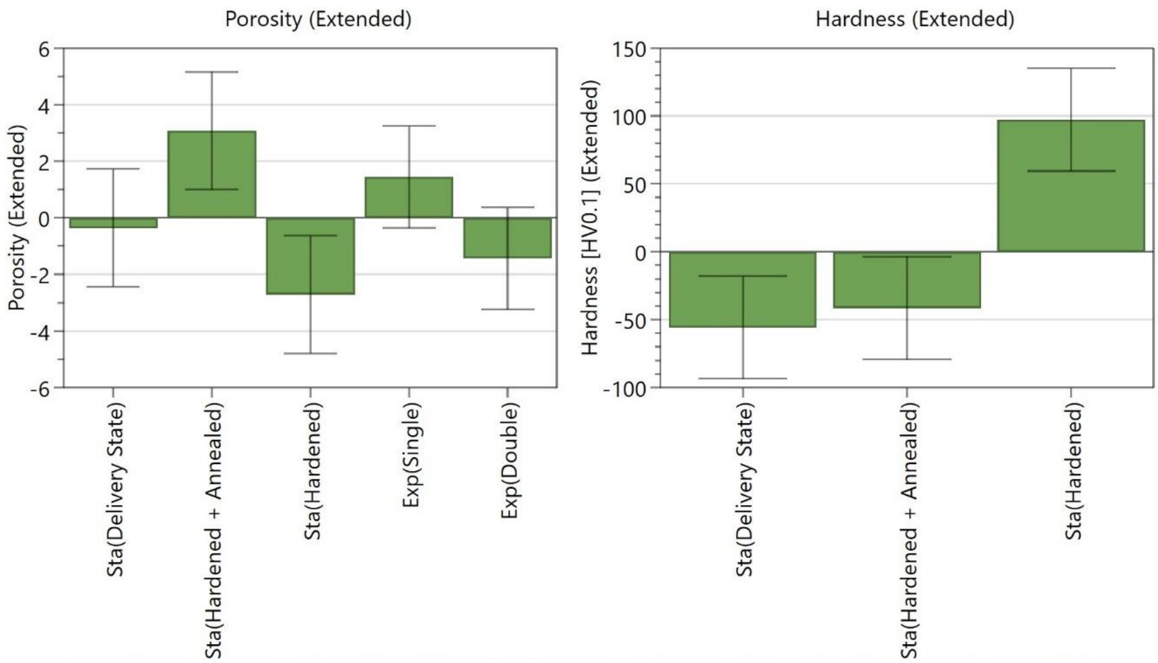


Figure 18: Coefficient results from MODDE

The prediction plot is shown in Figure 19. Hardened and double exposure was used as constant for the prediction plot. They were also used as constant for the coefficient results in Figure 18.

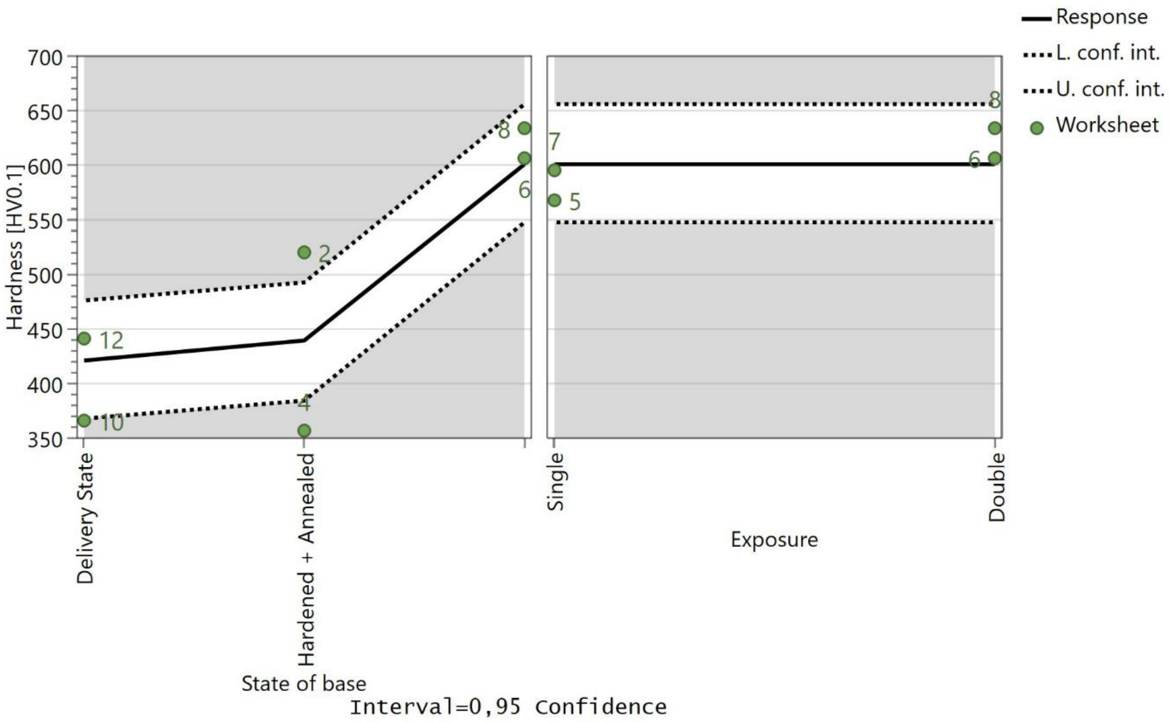


Figure 19: Prediction plot from MODDE

The results from the tests can are presented in Table 11.

Table 11: Test results

#	Test, exposure	Hardness, mean [HV0,1]	Hardness, FZ [HV0,1]	Pores, [x]
1	1-1s	447.70	444.13	8
2	1-1d	436.89	520.09	5
3	1-3s	428.09	433.44	8
4	1-3d	413.24	356.92	11
5	2-1s	640.52	567.22	1
6	2-1d	627.52	606.85	1
7	2-3s	662.35	596.26	2
8	2-3d	668.55	634.79	0
9	3-1s	419.22	417.16	9
10	3-1d	412.42	366.69	1
11	3-3s	412.06	462.08	4
12	3-3d	416.08	441.91	0

Visual inspection

On visual inspection of the test specimens, the only critical thing noticed is that the Hardened test had symmetrical cracks on all sixteen corners of the printed parts, see Figure 20. Otherwise, no visual changes could be seen when comparing the test specimens visually by eye.

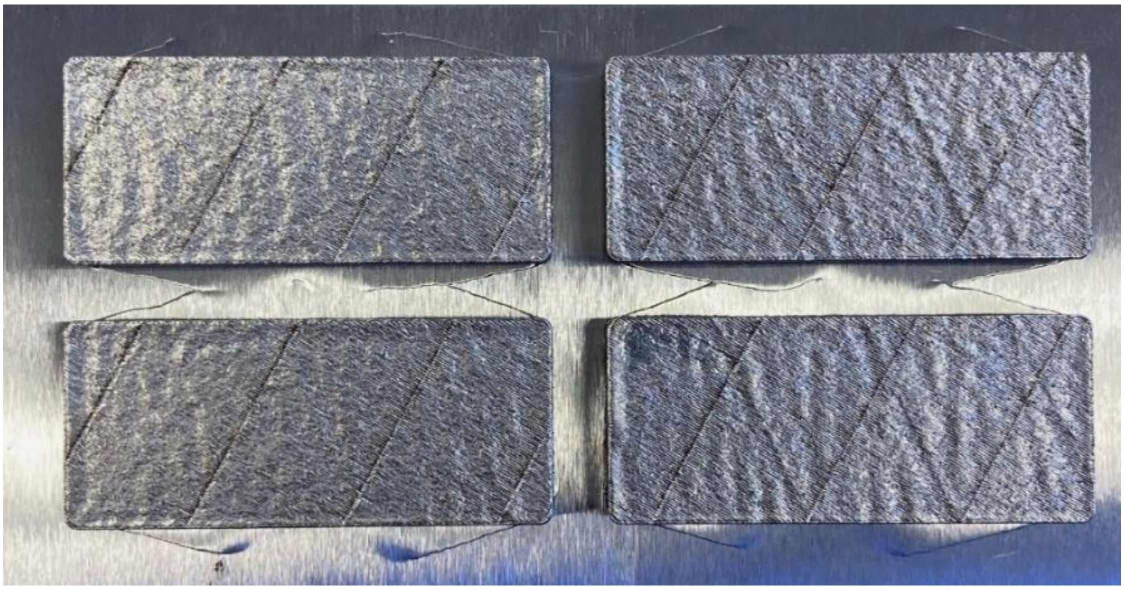


Figure 20: Crack formation on the Hardened test

3.3.4 Hardness profiles

The hardness profiles had the test pattern showed in Figure 21 and were placed roughly in the middle of the printed portion of the test specimen over the fusion zone. 9 spots were tested in the material where one indent (Point number 5) was directly in the fusion zone, see Figure 22.

Figure 21: Test pattern: 0,075 mm spacing between indents, 0,6 mm total length. Point 1 is on the hybrid base and point 9 is on the printed part

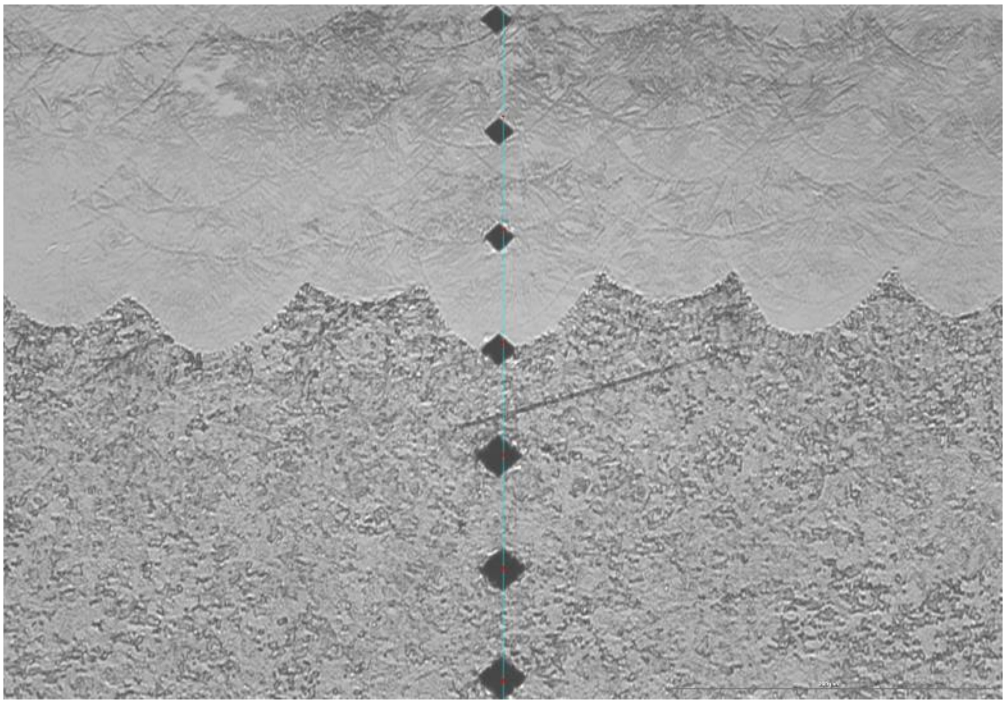


Figure 22: Test pattern placed on one of the test specimens, point 1 and 9 are outside of the picture

The hardness profiles showed that the hardness value across the fusion zone can be approximated as linear for the hardened + annealed and the delivery state tests. The tests that were not affected by double exposure could be regarded as completely linear. This is proved by the graphs in Figure 23 and Figure 24 respectively.

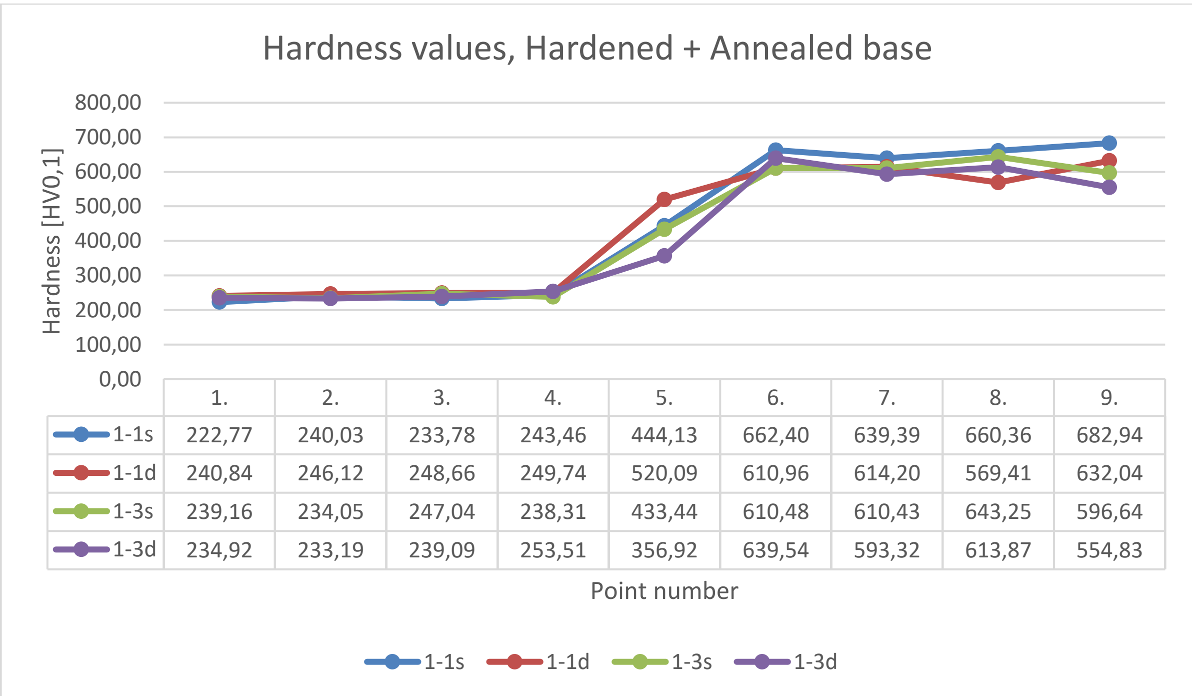
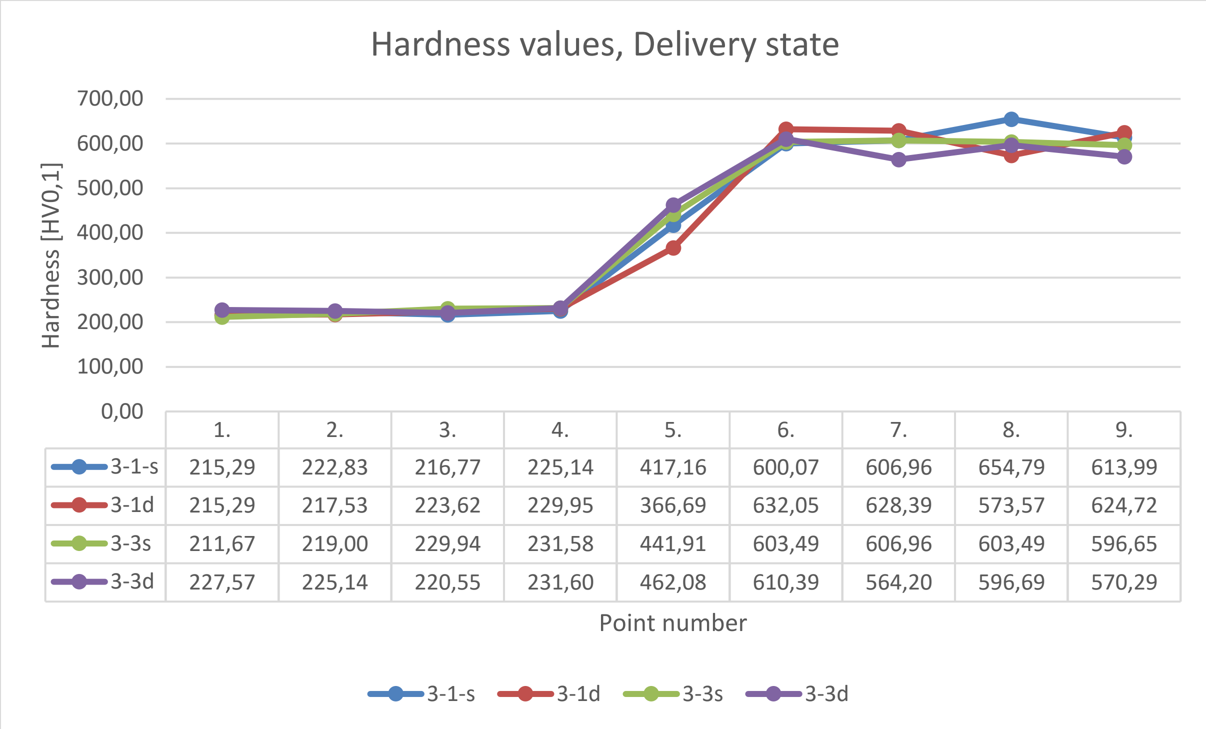


Figure 23: Hardened + annealed hardness profiles



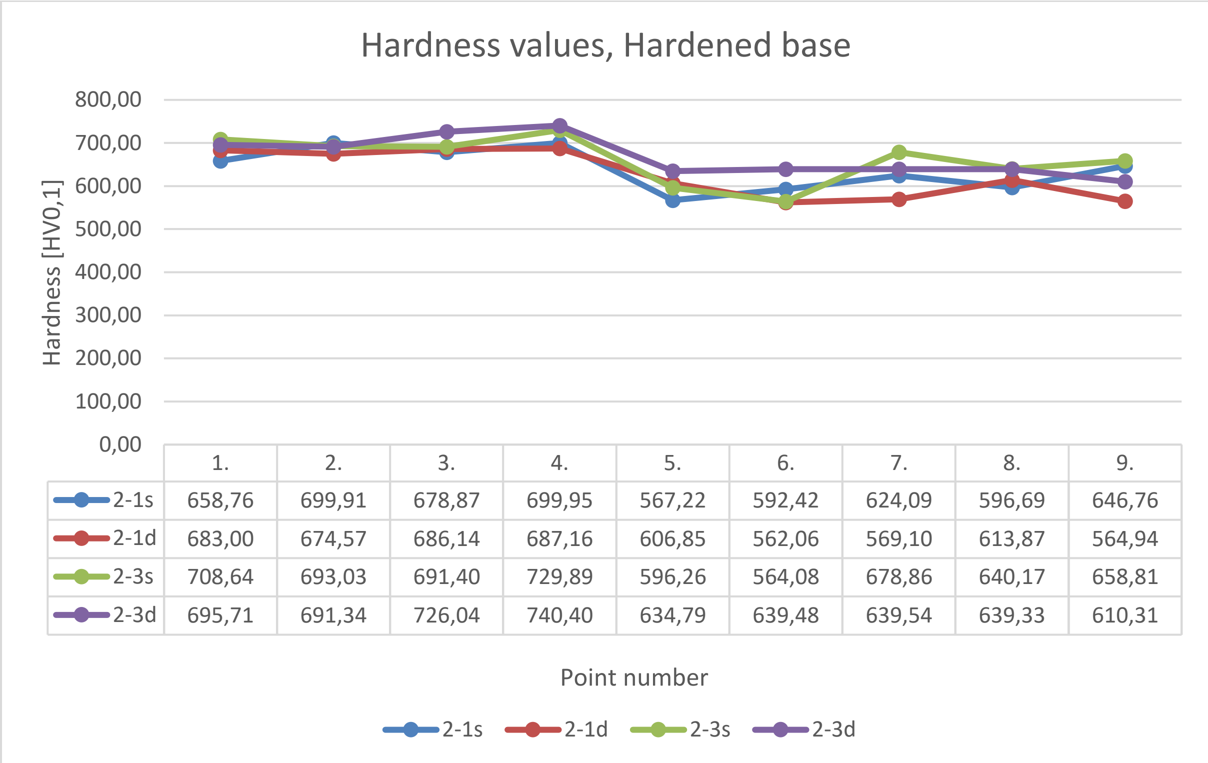
	1.	2.	3.	4.	5.	6.	7.	8.	9.
3-1-s	215,29	222,83	216,77	225,14	417,16	600,07	606,96	654,79	613,99
3-1d	215,29	217,53	223,62	229,95	366,69	632,05	628,39	573,57	624,72
3-3s	211,67	219,00	229,94	231,58	441,91	603,49	606,96	603,49	596,65
3-3d	227,57	225,14	220,55	231,60	462,08	610,39	564,20	596,69	570,29

Figure 24: Delivery state hardness profiles

The best homogeneity regarding hardness throughout the detail was achieved when printing on the hardened test, which is shown in Figure 25.

Furthermore, Figure 26 shows all the hardness profiles layered on top of each other. This further proves that be best hardness homogeneity throughout the final detail is achieved when printing on the hardened base.

It is also noticeable that all the tests that only have a single exposure have a more linear hardness change through the fusion zone whereas the tests that experienced double exposure have a more gradient change of hardness.



	1.	2.	3.	4.	5.	6.	7.	8.	9.
2-1s	658,76	699,91	678,87	699,95	567,22	592,42	624,09	596,69	646,76
2-1d	683,00	674,57	686,14	687,16	606,85	562,06	569,10	613,87	564,94
2-3s	708,64	693,03	691,40	729,89	596,26	564,08	678,86	640,17	658,81
2-3d	695,71	691,34	726,04	740,40	634,79	639,48	639,54	639,33	610,31

Figure 25: Hardened hardness profiles

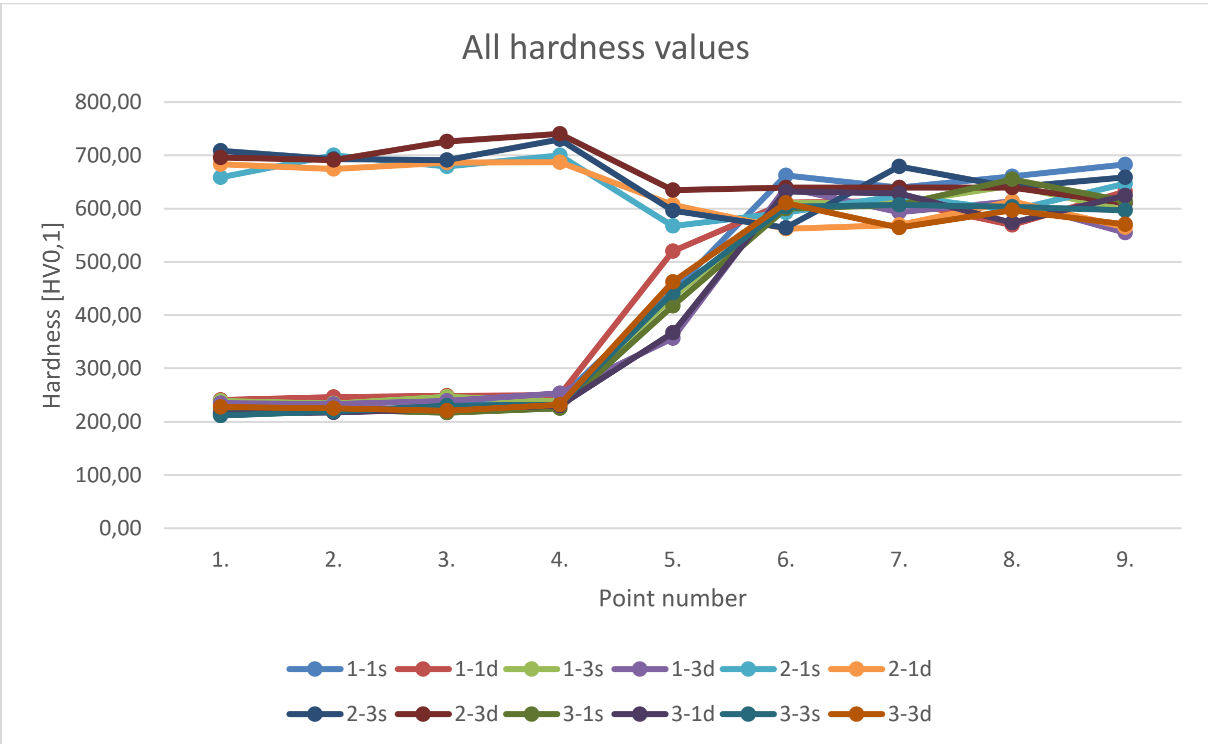


Figure 26: All hardness profiles

3.3.5 Microscope analysis

Test 1-1s

Figure 27 shows the layer depth (122,3 µm) and the general fusion zone of the test.

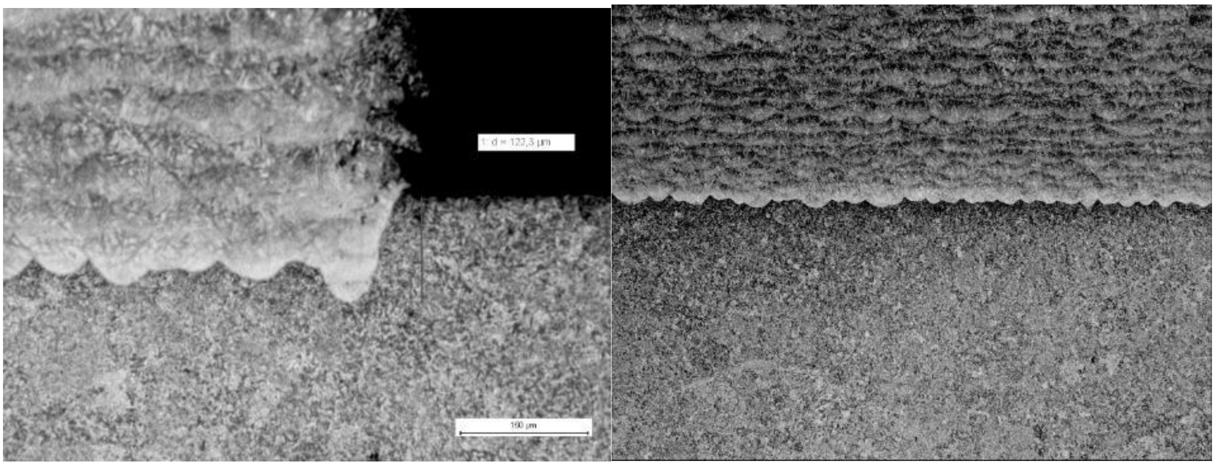


Figure 27: To the left is the layer depth and to the right is the general fusion zone, test 1-1s

Test 1-1d

Figure 28 shows the layer depth (125,8 µm) and the general fusion zone of the test.

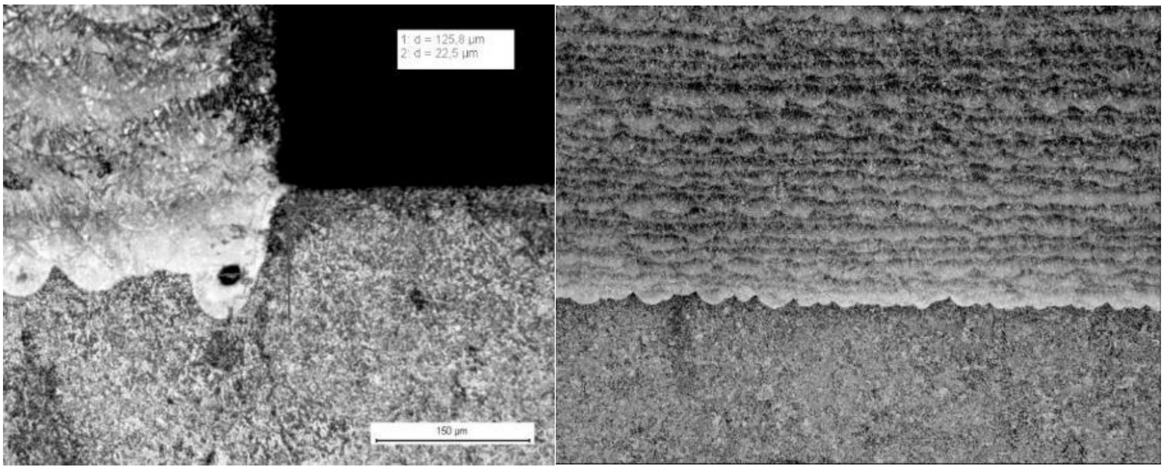


Figure 28: To the left is the layer depth and to the right is the general fusion zone, test 1-1d

Test 1-3s

Figure 29 shows the layer depth (108,9 µm) and the general fusion zone of the test.

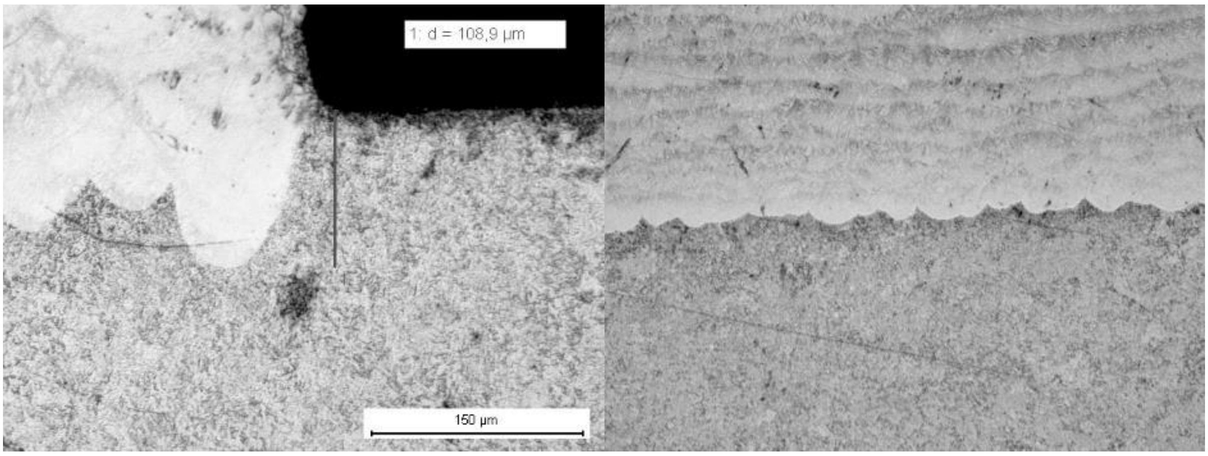


Figure 29: To the left is the layer depth and to the right is the general fusion zone, test 1-3s

Test 1-3d

Figure 30 shows the layer depth (77,3 µm) and the general fusion zone of the test.

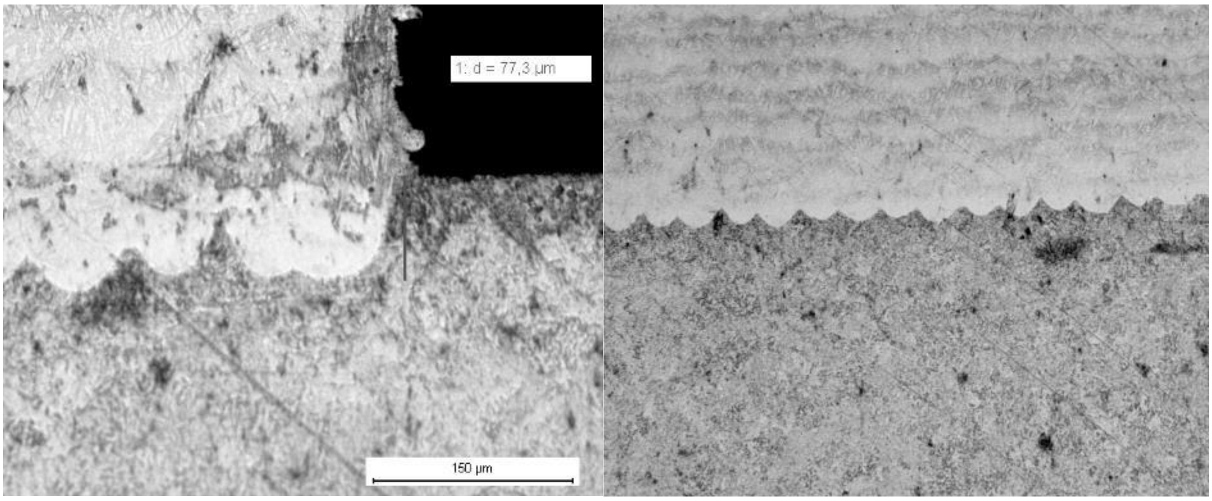


Figure 30: To the left is the layer depth and to the right is the general fusion zone, test 1-3d

Test 2-1s

Figure 31 shows the layer depth (173,6 µm) and the general fusion zone of the test.

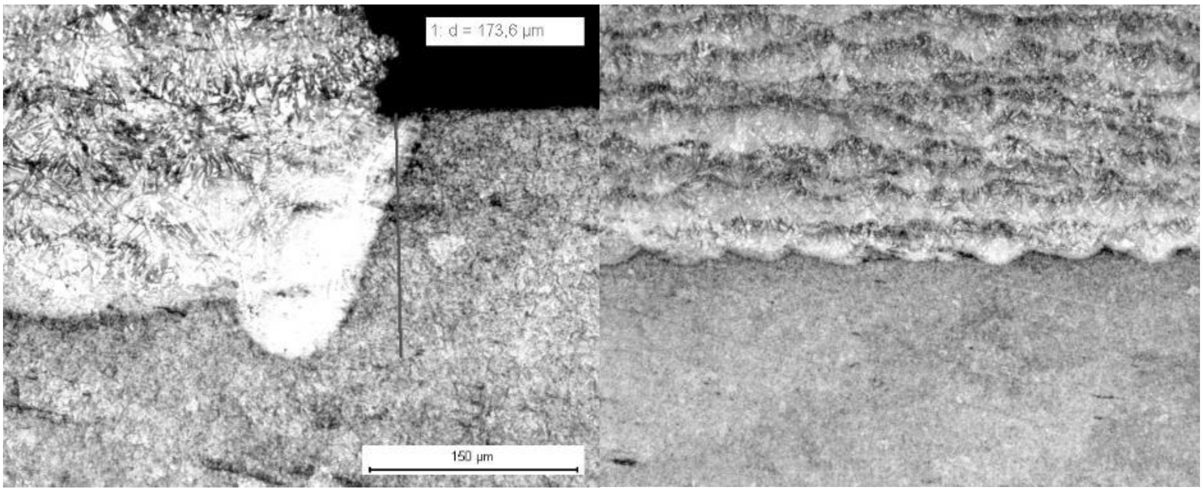


Figure 31: To the left is the layer depth and to the right is the general fusion zone, test 2-1s

Test 2-1d

Figure 32 shows the layer depth (133,5 µm) and the general fusion zone of the test.

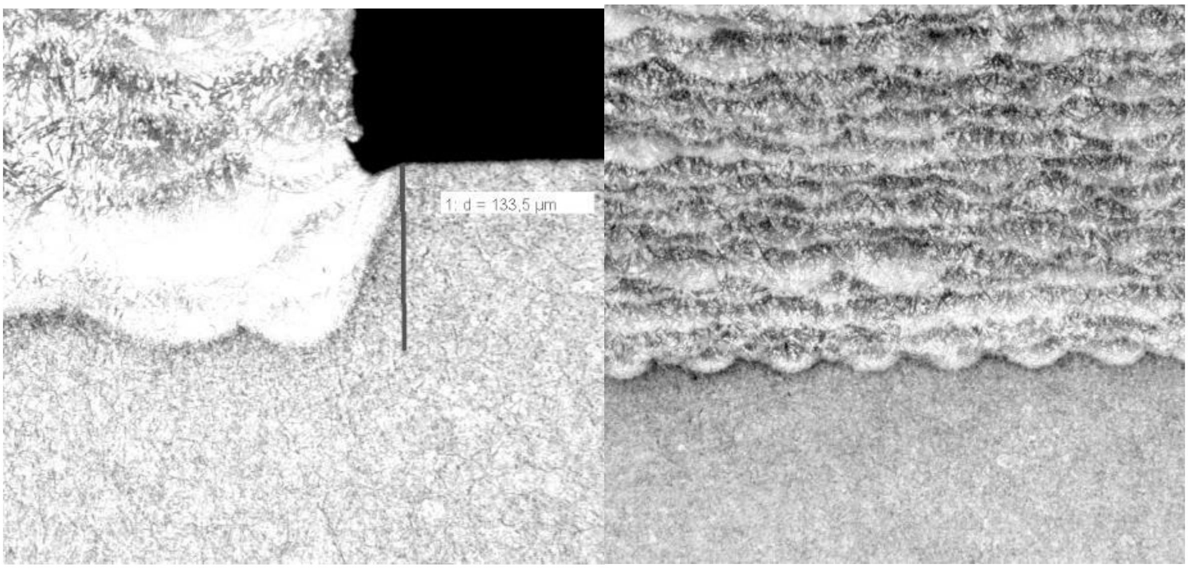


Figure 32: To the left is the layer depth and to the right is the general fusion zone, test 2-1d

Test 2-3s

Figure 33 shows the layer depth (110,3 µm) and the general fusion zone of the test.

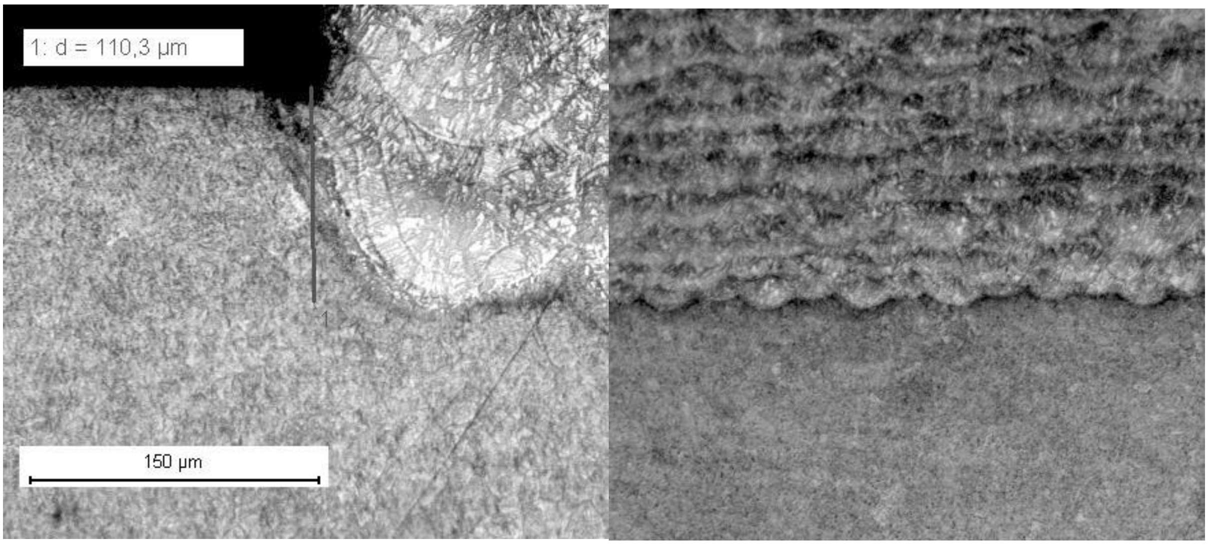


Figure 33: To the left is the layer depth and to the right is the general fusion zone, test 2-3s

Test 2-3d

Figure 34 shows the layer depth (106,3 µm) and the general fusion zone of the test.

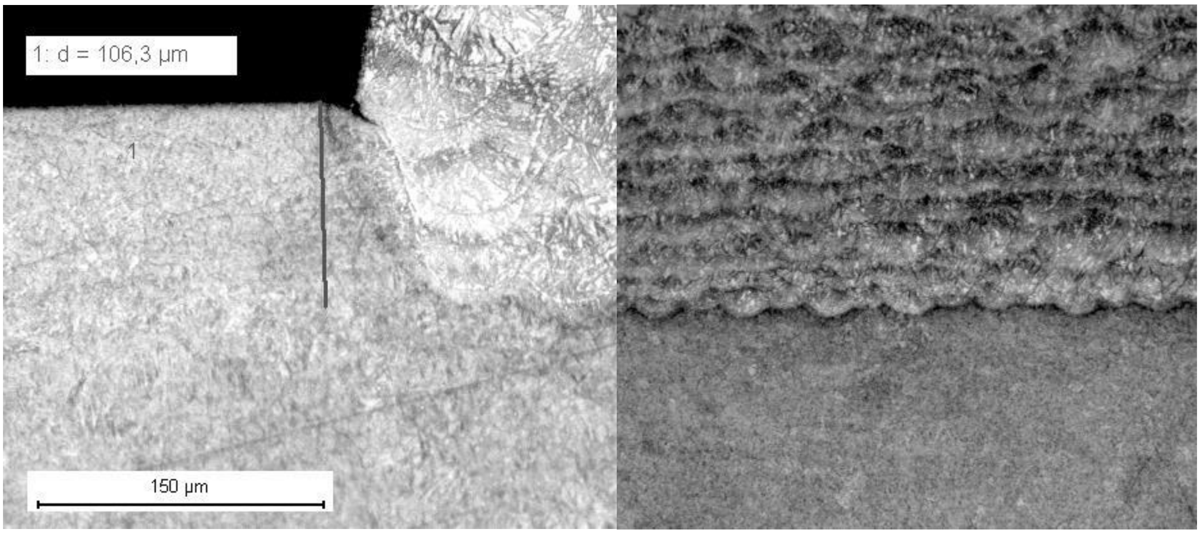


Figure 34: To the left is the layer depth and to the right is the general fusion zone, test 2-3d

Test 3-1s

Figure 35 shows the layer depth (186,3 µm) and the general fusion zone of the test.

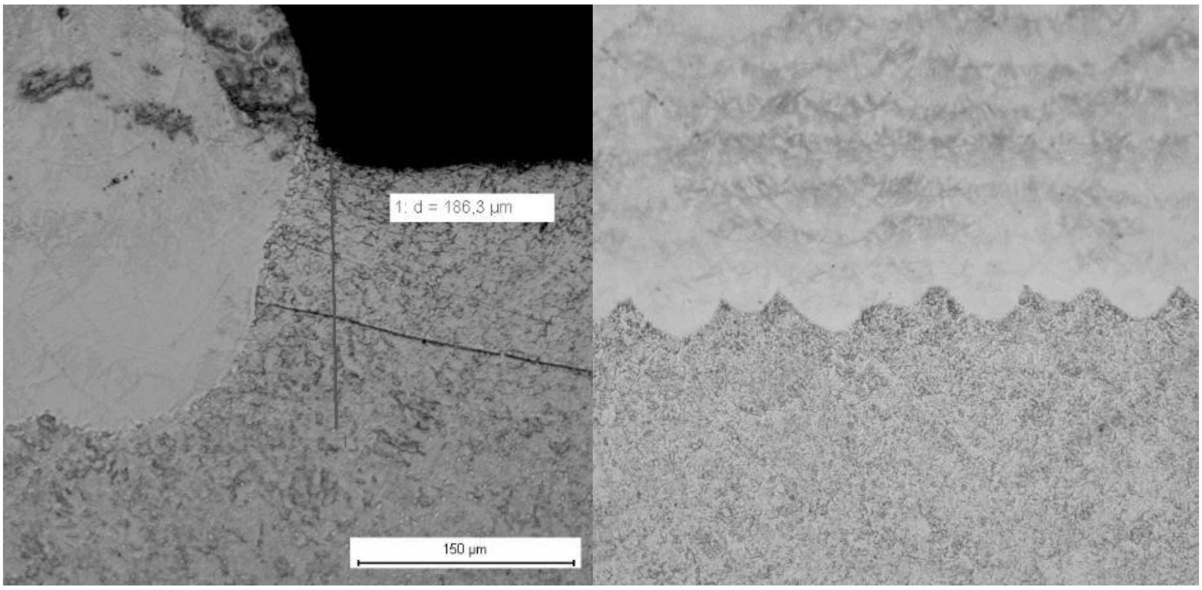


Figure 35: To the left is the layer depth and to the right is the general fusion zone, test 3-1s

Test 3-1d

Figure 36 shows the layer depth (129,3 µm) and the general fusion zone of the test.

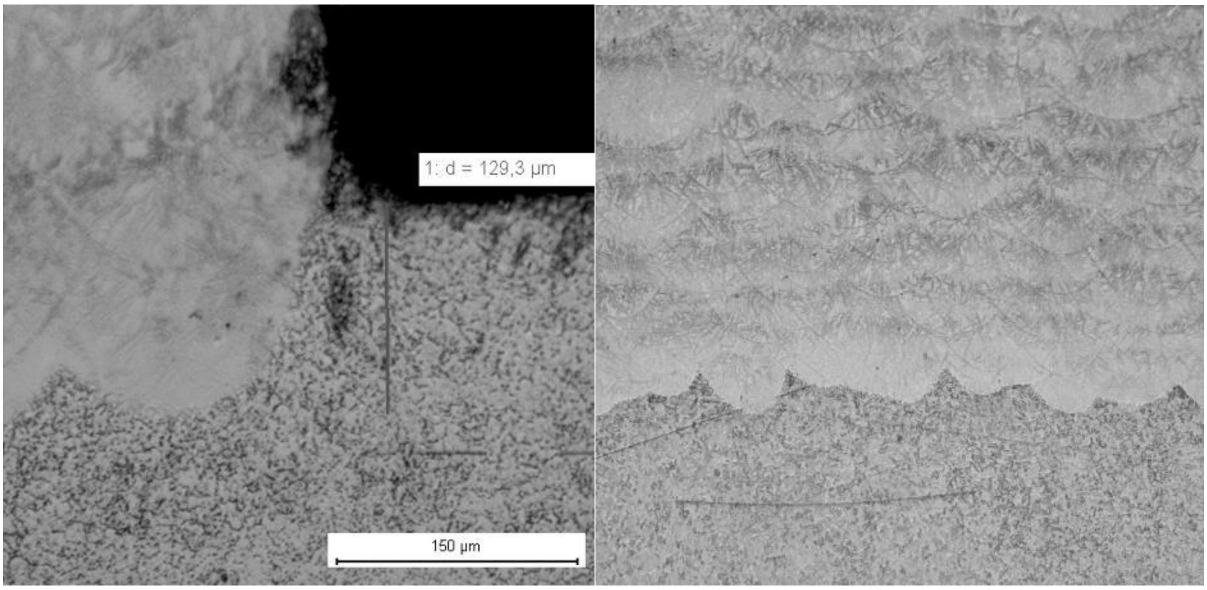


Figure 36: To the left is the layer depth and to the right is the general fusion zone, test 3-1d

Test 3-3s

Figure 37 shows the layer depth (131,4 µm) and the general fusion zone of the test.

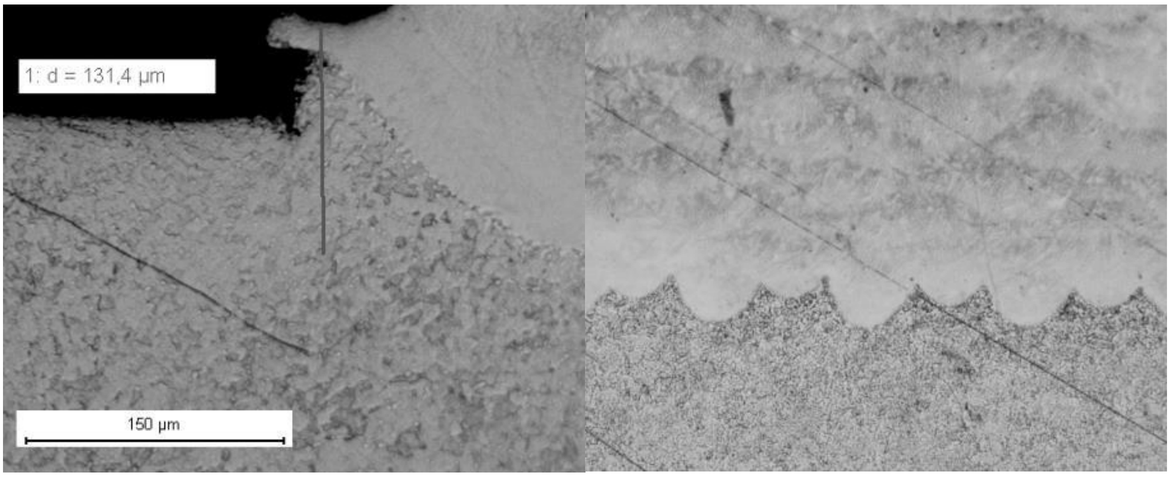


Figure 37: To the left is the layer depth and to the right is the general fusion zone, test 3-3s

Test 3-3d

Figure 38 shows the layer depth (168,7 µm) and the general fusion zone of the test.

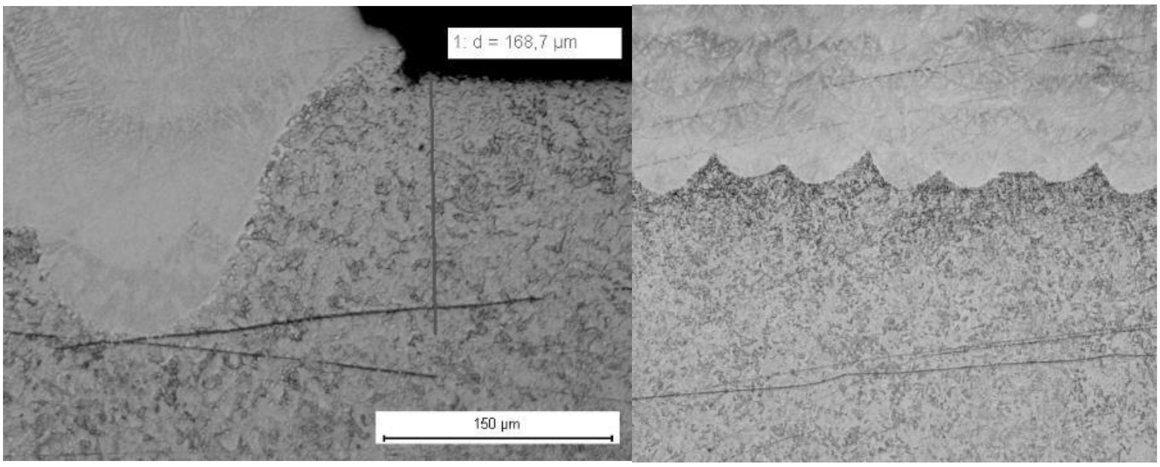


Figure 38: To the left is the layer depth and to the right is the general fusion zone, test 3-3d

Fusion depth

Table 12 shows the total fusion depth for all of the different tests. This is not one of the studied parameters, although one could take the fusion depth into account when presenting an optimal parameter set.

Table 12: Fusion depth

Test name	Fusion depth [μm]
3-1s	186,3
2-1s	173,6
3-3d	168,7
2-1d	133,5
3-3s	131,4
3-1d	129,3
1-1d	125,8
1-1s	122,3
2-3s	110,3
1-3s	108,9
2-3d	106,3
1-3d	77,3

Here it can be seen that test 3-1s hade the deepest penetration into the hybrid base material and therefor the largest fusion depth of 186,3 μm. Test 1-3d hade the lowest fusion depth with only 77,3 μm.

3.3.6 Recommended parameters

The recommended print parameters that are presented in this thesis is showed in Table 13 and in Figure 39.

Table 13: Recommended parameters

State of base	Exposure strategy	Layer thickness
Delivery state	Double exposure	Thin

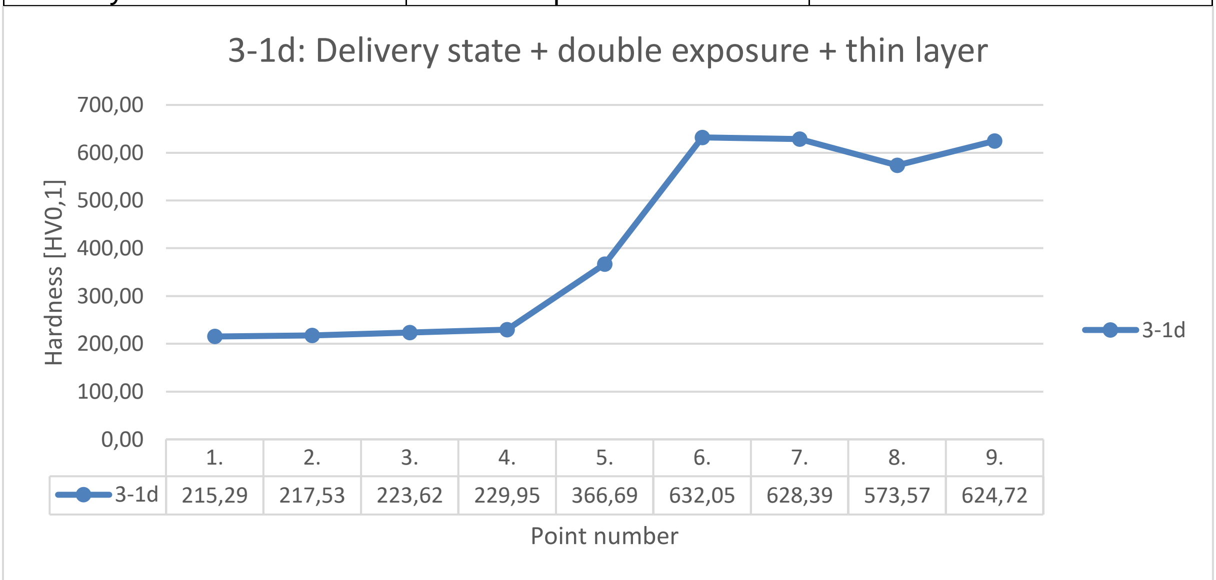


Figure 39: Hardness curve of the recommended parameters

The reason for why these parameters is presented is that they provide the best hardness homogeneity with the lowest number of pores and with no other complications. If the hardened test had not cracked, test 2-3d would have been presented as the best parameter set.

4. Analysis

4.1 Analysis of the fixture system

Bi & Zhang (2001) means that an adaptation of FFSs can greatly reduce manufacturing costs in low-to-medium volume products, and the design and set-up automation of FFSs can reduce the lead-time of the product. This is well in line with how the market for additive manufactured parts is at the Voestalpine concern today and therefore this fixture system solution can be declared as valid.

Another discussable topic is the lead-time that Bi & Zhang (2001) mentions, where a reduction in lead-time is desirable, which this fixturing system provides. Although, there are no concrete measurements yet. These measurements can prove to be hard to collect due to the vast majority of different geometries, each with a different lead-time.

With the use of the existing fixture system the operator needs to create bespoke fixturing solutions for the different print jobs, where the time from starting to create the baseplate to print-ready could take as long as one working day (8 hours) depending on the geometry.

With the use of the fixturing system presented in this thesis, a geometry could theoretically be rigged up and ready to go in under an hour, providing a decrease in lead-time up to around 85%. However, it is very difficult to provide an exact number of the decrease in lead-time. This is due to several different factors.

One of the major factors regarding lead-time is the pre-heating and cooling procedure of the fixture system. Unfortunately, there is only a few things that can be done to reduce the time it takes to complete this procedure which are strictly related to the fixture system. One example of a solution that might be relevant is the introduction of cooling channels in the fixture system.

Another major factor regarding lead-time is the variety of geometries, some geometries are naturally easier to secure than others, therefore the decrease in lead-time for that specific geometry is not that substantial. One would also have to take into account the possibility to secure multiple geometries simultaneously with the presented fixture system which greatly decreases lead-time.

Another crucial factor for decreasing the lead-time is the integrated reference system, here no tests need to be run to assure the correct position for the hybrid base which results in a shorter lead-time.

It is quite interesting to see that Li et al. (2021) and Yu et al. (2018) does not speak about the potential decrease in lead-time in their studies, Bi & Zhang (2001) does mention the potential for a decrease in the lead-time but no concrete numbers or readings are presented.

On top of the decreased lead time, Yu et al. (2018) means that the fixture design and manufacturing cost often are very high, usually accounting for 10%–20% of the total manufacturing system cost. With this fixture system, a decrease in cost will be achieved since the fixture system will be reusable and interchangeable which eliminates the need to create bespoke building plates for each print job.

One flaw with this fixture system is the lack of adjustability in the vertical axis (z-axis). But since the hybrid bases often have quite small dimensions in the vertical axis this should not be a problem. Although if it shows down the line that this becomes an issue, designing a new fixture point with a longer pin will not be expensive nor time consuming.

The problem with a higher fixture point is the potential interference with the powder spreader arm in the machine, as the fixture point must not be taller than the hybrid base itself, therefore the decision was made to make the fixture point be as close to the top surface of the fixture plate as possible to avoid this problem.

Yu et al. (2018) describes their fixture system for automotive body parts as a flexible fixture system which is composed of a base part, some locating units, and a control system, which can finish locating adjustments of end locating blocks or pins in three coordinate axle directions. The case is the same for the fixture system presented in this thesis, although one axle direction is fixed as previously stated. Adjustments are only available in the x-axis and the y-axis.

Another interesting topic is the life span of the fixture system. Since the aim for the thesis was to develop a new fixturing solution, the time frame for the project did not provide enough time for a complete, in-depth life cycle analysis. This is because the focus was to develop and design.

4.2 Analysis of the test results

One major factor to keep in mind is that the results from the tests in this thesis are unique for the specific material studied, the newly developed steel material created by Uddeholms AB.

Therefore, if one were to change the material the same results might not be achieved. This is due to the varying characteristics of the different materials. Many previous studies use AM 316L SS as the material for their tests. This material is used by Vukkum & Gupta (2022), Roirand et al. (2022), Liang et al. (2022) and Ahmed et al. (2022) for example and therefore the results from their studies are somewhat complicated to compare to this study since the difference in material have a fundamental impact on the results. Although, the authors mentioned does not study the same parameters as in this thesis which should be kept in mind.

Hearn (2023) on the other hand studies an 8620 low-alloy steel which is a completely different material and will with almost certainly not produce the same results.

When Liang et al. (2022) studied the effects of rescanning on an AM 316L SS, the results showed that rescanning with different parameters locally refined cell size from 0.84 µm to 0.35 µm and increased local density by 0.21– 0.42% from an initial value of 99.55 %. This study also showed that rescanning or double exposure as it is also called, increased the density of the final product.

None of Vukkum & Gupta (2022), Roirand et al. (2022) or Ahmed et al. (2022) discuss the effects of rescanning. The reason for this might be that the material properties studied in their papers is not directly affected by rescanning.

It is also hard to compare the results in this study to other studies done on the subject. This is because the majority of all previous studies is done on fully additive manufactured parts, not hybrid prints. The results presented by the authors mentioned above might be correct and true when studying a whole detail, although their discoveries might not apply to the fusion zone of a hybrid print which is the focus of this thesis.

5. Discussion

5.1 Fixture solution

As time goes on, there is a possibility is that an increased number of geometries appears more commonly and therefore a revision of the fixture system might be relevant. A solution for this might be to create a larger offering of standardized fixture points to cope with the more commonly used geometries. Bi & Zhang (2001) states that passive elements in a fixture system can be replaced by active elements in order to achieve more flexibility and automation and vice versa to cope with this situation.

At this point in time though, there are no such geometries and therefore the aim was to create a universal fixture system that can be customized for each geometry. This is because the production of additive manufactured parts is one-piece production exclusively for the most part.

Also, with a pre-determined vertical position the principle of Occham's razor comes into play. As Wikberg Nilsson et al. (2021) mentions, unnecessary elements reduce the effectivity of a design because the users' needs to question how a product is supposed to be used instead of intuitively understand. Although it might not be regarded as unnecessary to have the possibility to adjust the vertical position of the fixture point, it presents a situation where human error might occur.

Therefore, the lack of adjustability probably increases the user friendliness of the fixture system and decreases the risk of incorrectly fixturing a hybrid base.

The fixture system in use today at Uddeholms AB are made of a low-carbon steel produced in-house at Uddeholms AB in Hagfors for the most part. Considering that the fixture system presented in this thesis will be made of the same material and must withstand the same type of stresses under the same circumstances as the original, the argument can be made that the life span of the new fixturing baseplate should in theory be the same, if not longer than the original solely due to material properties.

The reason for the material choice for the fixture plate is that this is the material used today for the original baseplates and have proven to work, therefore the decision was made to continuing to use this material. Here there is a possibility to do a further material analysis regarding the material for the baseplate and this analysis might prove that there are more suitable materials. None of the papers from Yu et al. (2018), Li et al. (2021) or Bi & Zhang

(2001) discusses the material used in their fixture systems, but one can assume that some type of tool steel is used, similar to the material used at Uddeholms AB today.

When comparing the low-carbon steel from Uddeholms AB to similar low-carbon steels regarding price versus Young's modulus it can be seen that they are very similar to each other, this is illustrated in Figure 42.

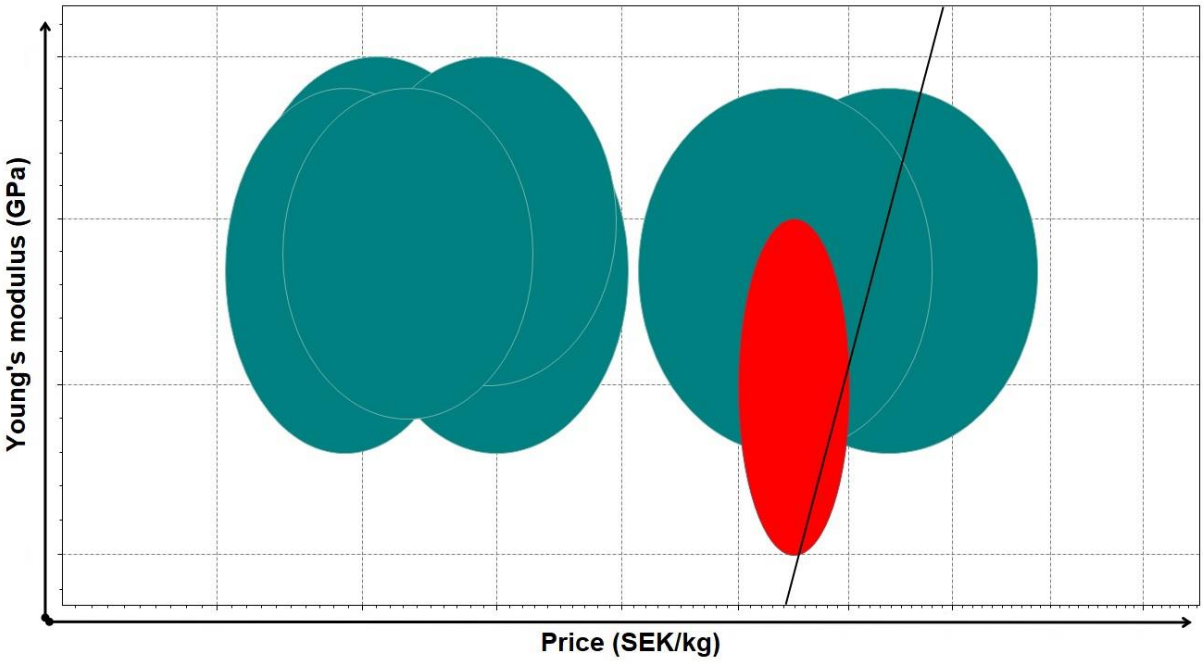


Figure 42: Material comparison, created in Granta EduPack 2022

The material from Uddeholms AB is represented by the red oval in Figure 42, while the blue ovals represent similar low-carbon steels. The exact values of the price and Young's modulus cannot be displayed for various reasons, although the graph gives a visual indication of the comparison. In this case, Granta EduPack 2022 shows the most optimal material to use for the fixture system in Figure 42 in regard to the parameters selected on the axes. This means that the material with the highest Young's modulus and the lowest cost is presented high up and to the left in the graph provided by Granta EduPack 2022.

There are some low-carbon steels that are cheaper and with a higher Young's modulus, but one has to take into account that these are materials that needs to be purchased and shipped to Uddeholms AB's facilities while the low-carbon steel produced by Uddeholms AB is available on demand at site, therefore making it the better choice.

The main question is how long the fixturing points can maintain the required precision. Here, measuring will be required to ensure that the fixturing points meats the precision requirements. Although, new fixturing points can easily be made and revisions are easy to make.

The fixture points will be conventionally manufactured. The reasoning behind this is that the fixture points will be easy to revise, and changes can be made if needed. The cost of this operation is also lower than if the fixture points where to be made using additive manufacturing, therefore there is no economic gain at this point in time to use additive manufacturing for these parts.

5.2 Material analysis

5.2.1 Results from the hardness tests

In Table 10 it can be seen that the hardness of the printed detail has both increased and decreased compared to the baseline test (3-1s). The reason for this comes from the state of the hybrid base and it is hard to prove and provide a general conclusion, since a noticeable, regularly occurring change in the fusion zone cannot be seen. However, the question can then be asked, is a change in hardness a desirable phenomenon?

In the majority of cases, an increase or decrease of hardness in the fusion zone is not desirable since this will create an area which is more susceptible to cracking due to changes in the internal stresses in the material. Tucho et al. (2018) states that specimens with low hardness is associated with a high number of pores and defects which increases the risk of crack initiation. Although it should be noted that Tucho et al. (2018) discusses a fully additive manufactured detail, not a hybrid print. But, since the fusion zone generally have a high hardness and a low amount of pores the result is in line with the statements from Tucho et al. (2018).

On the other hand, Hearn (2023) states that when lowering the specimen hardness, the material is less susceptible to cold cracking when discussing 8620 low-alloy steels. The probable reason for the differing results is due to the different materials.

This phenomenon might be used to one’s advantage though since it might be a successful way to integrate a designated “cracking-zone” into the final part. Although, if this is a desirable feature will ultimately be decided by the final use of the printed detail. However, this thesis will not study this in greater detail, since an optimization of the parameters will be needed before certain recommendations for a use of this nature can be presented.

Ahmed et al. (2022) described Equation 1 for the Laser Energy Density as one of the major factors for achieving full density in printed details. Therefore, one can ask the question, why are the parameters included in the equation not studied in this thesis work?

The reason for this is that Uddeholms AB has already optimized these parameters and can achieve full density (>99,995%) in their printed details for a layer thickness of 30 µm as well as 60 µm.

Ahmed et al. (2022) also states that it can be observed that energy density for achieving higher densification is spread over wide range of values (53 J/mm^3 –238 J/mm^3) indicating that the optimized process parameters set is specific to the individual machines and depends on the flexibility the machine offers in terms of modifying the parameters, and hence the values cannot be entirely generalized.

Ahmed et al. (2022) continues and explains that the optimum range of energy density values are scattered in the range between 50 J/mm^3 to 150 J/mm^3 . According to data from the studies done by Liang et al. (2022), the highest densification values occurred at Laser Energy Density values around 229 J/mm^3 to 250 J/mm^3, further proving the point that these values are difficult to generally optimize, which was confirmed by Ahmed et al. (2022).

Uddeholms AB's Laser Energy Density are within the ranges of 55 J/mm^3 to 90 J/mm^3, which are in the optimal range described by Ahmed et al. (2022) but outside the optimal range described by Liang et al. (2022). This is in line with the conclusions from Ahmed et al. (2022), that the Laser Energy Density cannot be generalized.

5.2.2 Varying results due to printer model

It should also be noted that the result from this study might vary depending on what model of printer is used. The one used in this thesis is an EOS M290 and produced the results presented in Table 11 and the recommended parameters in Table 13. However, when discussing with personnel at Karlstads University who are using a Reinshaw printer, problems related to the gas flow and powder spreading were brought into discussion.

These problems are not present at Uddeholms AB, but it is still a discussable topic. Generally, the results should be of similar nature if run on another model of 3D-printer. But since the aim for this thesis work is an internal standardization, it means that the results from the study should not differ based on which type of EOS printer is used, with the exception of the EOS M400 which have a different gas flow compared to the other EOS models. This is because the internal gas flow and powder spreading is identical in all the other EOS printers used in the

Voestalpine concern, the only thing that differs is the dimensions of the build plate carrier. However, this cannot be confirmed with 100% certainty that this is the case.

Another point to make is that the parameters which are analysed are directly related to the hybrid base, not the printer. Therefore, a swich in printer might produce different results but not due to the parameters studied in this thesis.

One of the plausible reasons for why different printer might produce slightly different results are due to the Laser Energy Density described and discussed in the previous section. Here one will need to do a separate analysis for the specific printer used to achieve optimal results. General target values for the Laser Energy Density can be presented, but one needs to consider that these are not optimal for every printer.

5.2.3 Crack formation

One of the probable reasons for why the cracks initiated is due to the pre-heating temperature of 40°C. Usually, a pre-heating temperature of 200°C is used. The reason for why 40°C was used is because of printer limitation, since there were some issues with the printer at the time the tests were constructed. Although, previous tests in this material have shown that it is possible to get similar results using 40°C as compared to 200°C.

Ahmed et al. (2022) describes that a preheating temperature range of 150–200 ◦C resulted in a densification of 99.4% - 99.7% and a homogenous structure. Therefore, it would have been optimal to print the tests with a 200°C pre-heating temperature.

The reason for pre-heating is that it improves the heat absorptivity of the powder and improves the wettability properties of substrate resulting in complete melting of powder. (Campanelli et al. 2010)

One explanation for why the cracks only occur on the hardened test is probably due to the high hardness of the hybrid base at 54,5 HRC. This results in a brittle hybrid base, which creates an optimal environment for crack initiating in combination with the residual stresses in the printed material. This is also the reason for why it would have been interesting to print on the hardened hybrid base with a pre-heating of 200°C, to investigate if crack formation is relative to the pre-heating temperature for the hardened material.

Another interesting phenomenon is that on the test that did not experience double exposure, illustrated in Figure 43, the cracks went along the melt pool into the base material while on the test with double exposure the cracks were shifted downwards into the material, illustrated in Figure 44, on the test with a thick layer.

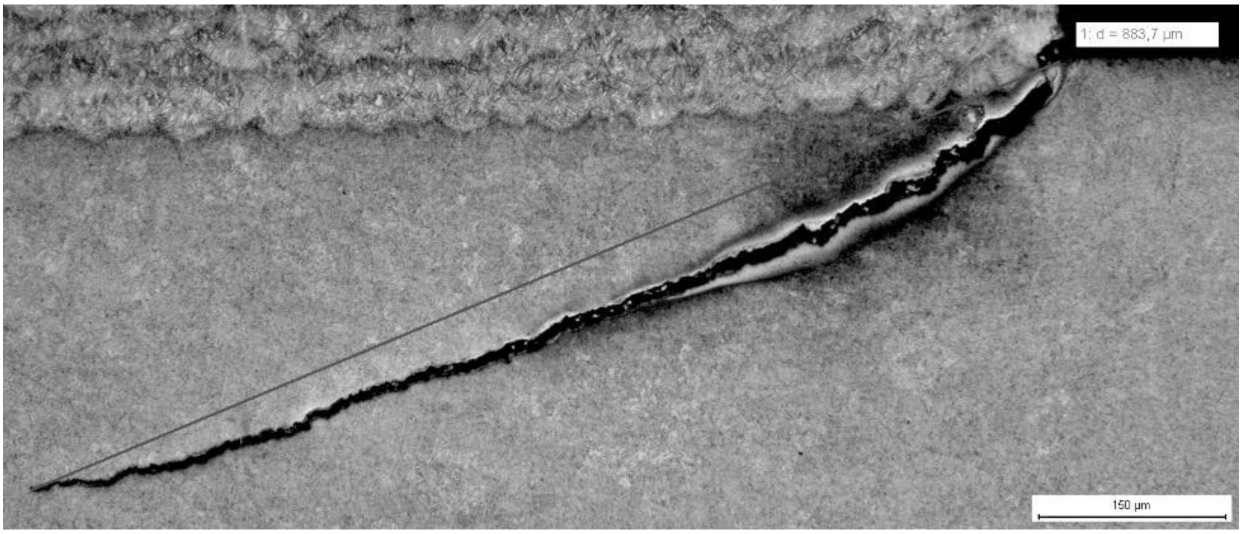


Figure 43: Crack formation in the fusion zone, no double exposure, thick layer

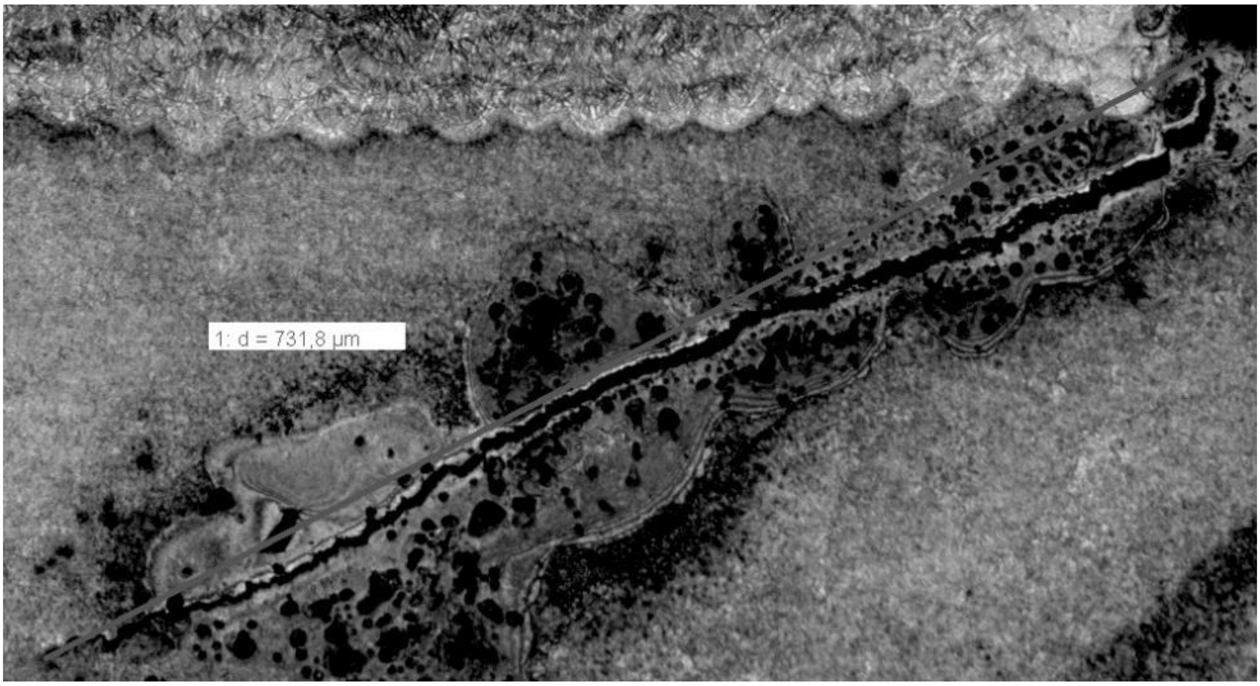


Figure 44: Crack formation in the fusion zone, double exposure, thick layer

The cause for this is unknown, although one has reason to believe that the double exposure is the main reason for this.

If one can recreate the porosity results and hardness profile for the hardened base without the cracking, this might well be the best parameter set to use for hybrid printing due to the few pores and a good homogeneity in the hardness of the detail.

5.3 Increased sustainability

The work in this thesis increases sustainability in the additive manufacturing department at Uddeholms AB in Hagfors in several ways. Since the fixturing solution will be reusable, there will be savings in both material and energy usage. One of the reasons to why the material selected (Figure 42) for the fixture solution is that it does not need to be shipped to Uddeholms AB in Hagfors and this reduces the carbon footprint of the fixture system due to less shipping, this was lightly discussed previously.

Also, when having a fixed and standardized reference system the energy usage is further decreased since the process of ensuring that the print is occurring on the right location is eliminated. This leads to a reduction in the amount of Argon used and energy in the shape of electricity.

Furthermore, there is an economical advantage of using the fixture system presented in this thesis. A reusable system naturally leads to less material used and less energy consumed producing it. This also means a lower general cost of the system. On top of the decreased production cost, Uddeholms AB also has the possibility to commercialise this product and create revenue from it, further decreasing the total cost and creating a more sustainable internal economy.

The operators also get a more sustainable work environment, since the standardization of the fixturing system creates a familiar tool that provides a sense of familiarity and therefore may decrease the stress of the worker. This fixture system also provides the possibility to decrease lead-times which gives the worker more time for other tasks.

6. Conclusion

The conclusion of this thesis is that the optimal printing results will occur when using the fixture system presented in this thesis in combination with the recommended parameters shown in Table 13.

The fixture solution also provides a greatly decreased lead-time, leading to a more effective printing process, both in regard to lead-time as well as economically.

It can be seen that printing on the material in delivery state and a thin layer thickness in combination with double exposure created the least number of pores and the most homogeneous hardness. This leads to the best results regarding the final density of the printed product. The recommended parameters also provide the best mechanical properties of the printed detail in general.

As previously stated, the best results would have been to print on a hardened base with a thick layer thickness and double exposure. However, as shown in Figure 43 and 44 the test cracked and could therefore not be declared as valid.

7. Future work

Common geometries

For future work it might be interesting to analyse and collect data of the different geometries for the hybrid bases. Here there might arise an opportunity to see patterns or possibly group different geometries together and from there create specialized fixture points for each geometry group.

Deeper parameter study

For the parameters studied in this thesis there might be more to analyse. For example, one could study how the temperature of the hardening and hardening + annealing process affects the final product as well as how the pre-heating temperature influences the final product.

As time goes on more and more additive materials will be available. In this thesis only one type of steel powder is analysed and the results and recommended parameters for this material will with a high likelihood not be the same for other materials. Here a parameter study is required for the individual materials to be able to give recommendations for a greater variety of materials.

Further work on the fixture system

The basic working principle of the fixture system is presented and discussed in this thesis. However, a deeper material study for the fixture system is required for an optimization of the fixture system. The hole pattern is also not yet fully optimized and a topology optimization is possible to execute for potential cooling channels in the fixture system.

Most of the parameters required for a complete optimization of the fixture system can be acquired and analysed through the usage of the fixture system and while gathering this data, a complete life cycle analysis of the fixture system can be performed. This then leads to more standardization parameters that can be recommended, for example the expected lifespan of the fixture system and how often it is recommended to change the fixture points due to wear etc.

Also, a cost analysis for the fixture system is preferably performed.

Finally, a manual should be created for the fixture system and printing parameters. This is to further streamline the process. The goal would be to have a manual with the recommended print parameters, a walkthrough of the usage of the fixture system. This creates the opportunity for Uddeholms AB to commercially sell a complete additive manufacturing solution (excluding printer) if wanted. This additive manufacturing solution will then include all the materials needed for companies to produce their own products.

The materials included in this additive manufacturing solution would be:

- Raw material (powder)
- Fixture system
- Guidelines on how to perform the print process (manual)

Residual stresses

Research and analysis of the residual stresses occurring when printing is an interesting topic and there are a lot of valuable information to be gained from this study. Therefore, for future work, a method for analysing the residual stress would be needed for research. Unfortunately, this is a very complicated topic, but the possibility that it is achievable is there.

Near net shape

An analysis regarding the desirability regarding near net shape production in additive manufacturing can be regarded as future work. Depending on the results from this study, changes to the fixturing system might be in question. If the study shows that near net shape is not economically advantageous, the common geometries discussed previous in this section will be very interesting. This mainly for the topic of standardized fixture points.

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Acknowledgements

Finally, thank you to all the people who have been involved in the creation of this thesis work. A special thank you is aimed towards JanErik Odhe from Karlstads University and to Carl Högman and the Research and Development department at Uddeholms AB in Hagfors for supervising and giving me advise throughout the project.

Also, thank you to the Voestapline concern and Uddeholms AB in Hagfors for giving me the opportunity to work with you and giving me access to your facilities to carry out this thesis work.

Best regards and thank you,

Appendix A: Project Plan

Project Plan

Project Plan for Bachelor Thesis at Uddeholms AB

Projektplan

Projektplan för examensarbete hos Uddeholms AB

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JanErik Odhe
Leo De Vin
2023-01-26
1

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1. Background

1.1 Project Background

Creating parts using additive manufacturing is an expensive process both in cost and time. That is why it has become more interesting to look for alternative solutions in the form of hybrid printing, where you print the complex part on top of the machined based (milling or lathing).

To be able to do hybrid printing, one would need to have a stable way of mounting the hybrid base in the printer so that it would not deform during the process due to the residual stresses that forms. This puts a high demand on the precision of the fixturing solution and also requires knowledge of the transition zone between the printed part and the hybrid base.

This was the background description given by Uddeholms AB.

1.2 Problem Description

- Today Uddeholms AB don't have an internal standard for hybrid printing.
- Knowledge regarding the residual stresses and how they affect the hybrid bases and the final tool.
- How the exposure strategy influences the transition zone between the printed part and the hybrid bases in terms of porosity and microstructure.
- Cost saving in hybrid printing, and if it is more desirable to have near net-shape hybrid bases or not.

This was the problem description given by Uddeholms AB.

In other words, the problems that exists are that there is not an internally standardized way for fixturing of the hybrid bases during printing at Uddeholms AB. At this moment customized build plates are used for every different geometry and are single use.

1.3 Project Boundaries & Priorities

The focus for this project will be the internal standardization of the hybrid printing process at Uddeholms AB, therefore this will be the prioritized topic.

Also, the exposure strategy will be analysed. This will occur in conjunction with the analysis of the porosity and microstructure of the final part. However, most of the time available will be focused on the standardization.

The topic with the lowest priority is the knowledge regarding the residual stresses and how they affect the hybrid bases and the final part and therefore this topic will be outside of the boundaries for the project and will not be analysed. This has been agreed by Uddeholms AB (2023-01-27). The reason for this is because that there will not be enough time to analyse and study this topic thoroughly. This is also a very complex topic and will as stated previously not be the focus for this project.

The Near net shape analysis will not be analysed either, this is due to longer than expected delivery times for the materials used for prototyping and testing. Therefore, due to the tight timeline of the project, this topic will be regarded as future work. This has been agreed by Uddeholms AB (2023-04-13).

The boundaries regarding to time in this project is 600 hours over 22 weeks, from week 3 to week 24, for the student according to the course and the goal is to finish the thesis in this time. This project will be at 50% pace during the first phase (week 3-12) due to parallel courses. Then from week 13-24 the project will go on at 100% pace.

2. Purpose and Goals

2.1 Purpose

The purpose of this project is to investigate the possibilities of hybrid fixturing and how this process can be standardized. Another purpose of the project is to investigate how the characteristics of the final part are affected by the residual stresses and how the exposure strategy/first layers influences the transition zone between the printed part and the hybrid base.

2.2 Goals

The goal of this project is to help standardizing the hybrid printing process at Uddeholms AB, part of this is to deliver a fixturing solution and to be able to give recommendations regarding the parameters used in the printing process.

2.3 Delivery

The results from this work will be presented at Uddeholms AB. 2023-06-15 is the preliminary date for this presentation. The physical delivery of the solution to Uddeholms AB will be in the shape of drawings and CAD-files. To accompany the CAD-files, a scale model will be presented.

On top of this there will be a 15-minute oral presentation at Karlstads University 2023-05-24, a digital exhibition and a physical exhibition 2023-05-26.

There will also be a final report that will be presented and given to Uddeholms AB. This report will be examined and graded by the examinator of this course.

3. Censoring

During this project the student will sign a non-disclosure agreement.

To avoid conflicts regarding this topic, some sensitive details will be censored and anonymized in the final report. This is a solution that is recommended by Paulsson (2020) and have been agreed with both the student and the company. This should not result in a hindrance for the final examination.

What details and subjects that will need to be censored will be continuously discussed with the supervisor at Uddeholms AB. The supervisor at Uddeholms AB will also do a final read through of the final report before submitting it for examination.

4. Organization

4.1 Project members

The members in this project will consist of a student from Karlstads University and a steering group from Uddeholms AB consisting of three persons where one of them will be the main contact person. There will also be a supervisor from Karlstads University at hand. (See Table 1: Project members)

Table 1: Project members

Name	Organization	Role
Patrik Andersson	KARLSTADS UNIVERSITET	Student
JanErik Odhe	KARLSTADS UNIVERSITET	Supervisor
Leo De Vin	KARLSTADS UNIVERSITET	Examinator
Carl Högman	UDDEHOLM	Main contact / Supervisor
Henrik Andersson	UDDEHOLM	
Panagiotis Katsanos	UDDEHOLM	

4.2 Role description

Student: Student at Karlstads University

Supervisor: A teacher from Karlstads Universitet whose role is to help and lead the student throughout the project.

Main contact: This is the main contact person from Uddeholm AB. This person will be answering questions from the student and provide information from the company when needed.

4.3 Communication channels

The main contact between the student and the supervisor will be via phone and mail, there will also be physical meetings for feedback and supervision.

The main contact between the student and the main contact at Uddeholms AB will be via mail, phone and also physical meetings at Uddeholms AB´s facilities in Hagfors.

4.4 Available Tools

During this project there will be some available tools provided to the student by Uddeholms AB. The tools are of in physical form and computer software.

The physical tools are:

- Uddeholms AB's 3D-printer, EOS M290, including powder
- Uddeholms AB's machining workshop

Provided software:

- MODDE12 Pro for design of experiments, DoE

The physical tools are located in Hagfors at Uddeholms AB's facilities.

5. Project model

The project started at week 3 and ends by week 22, the project model is divided into 3 phases.

The three phases are:

1. Planning & Research phase: week 3-10
2. Implementation phase: week 11-19
3. Closing & Delivery phase: week 20-24

The project model will likely be modified along the course of the project when more information and knowledge have been gathered.

5.1 Phase 1: Planning & Research

The first phase in the project will be the planning and research phase. The planning phase includes the project plan, a WBS (see Appendix A: WBS) and a Gantt chart (see Appendix C: Gantt chart). This is to create a holistic view of the project and to divide the available resources accordingly.

The student is expected to put 600 hours into this project over the course of 22 weeks.

The research phase is about gathering as much knowledge as possible regarding the relevant topics. This will occur mainly via literature studies, interviews, and discussions.

Important dates and activities:

- Project plan (2023-02-03)
- Requirements specification (2023-03-12)

5.2 Phase 2: Implementation

In the implementation phase the ideas and the solutions are going to be generated. The generated concepts and solution need to meet the requirements specification which have been verified and approved by Uddeholms AB. The concept selection then needs to be approved by Uddeholms AB before pursuing further.

When the concept and solution have been given the green light from Uddeholms AB further development can occur in the form of detail engineering, material choice, testing, prototyping etc.

After this stage the CAD models and drawings will be finalized.

Important dates and activities:

- Concept selection (2023-04-16)
- CAD model and drawings (2023-05-14)
- Prototyping (2023-05-14)
- Testing (will occur continuously during Phase 2)

5.3 Phase 3: Closing & Delivery

The closing phase is the final phase of the project. This includes the final presentations of the work, opposition and finalizing the report.

In the closing phase the final examination will take place.

Important dates and activities:

- Final presentation at Karlstads University (2023-05-24)
- Final presentation at Uddeholms AB (2023-06-15)
- Opposition on the Final report (2023-05-19)
- Final report submission (2023-06-16)

6. Risk analysis

To identify the most threatening risks to the project a risk analysis has been made. The risk analysis is shown in Table 2.

To calculate the risk factor the following variables have been used:

- **P** = Probability of the risk occurring
- **C** = The consequences of the risk
- **R** = Risk factor

$R = P \times C$ *Eq. 1*

The risk factor is calculated using *Eq. 1*.

The variables are scored 1-4, where 1 is the lowest and 4 is the highest. Therefore, a low value of **R** is to be preferred. This risk analysis method is presented more in detail by Lilliesköld & Eriksson (2005) on page 44 in their book.

From the risk analysis the most crucial risks in the project can be identified as:

Table 2: Risk Analysis – Crucial risks

Risk	**P**	**C**	**R**	**Proposed action**
Important data cannot be acquired	3	4	**12**	Look at other possibilities to acquire the data or rework the problem to avoid the usage of the data
Results cannot be presented in the final report due to the non-disclosure agreement	4	3	**12**	Look at the possibility to censor the sensitive data and results

For the full risk analysis, see Appendix B: Risk analysis

7. Document and version management

The documents will be saved on Google Drive and the students local device in the first place as standard.

Documents will be named after the following structure: (Name of the document)_(X.Y)_(Student name), for example: Project Plan_1.0_PatrikAndersson.

The X will be changed when a big audit of the document has been made and the Y will be changed after smaller changes to the document has been made. This will likely occur when feedback from the supervisor have been received.

Reference list

Paulsson, Ulf (2020). Examensarbete: att skriva uppdragsbaserade uppsatser och rapporter. Upplaga 1 Lund: Studentlitteratur

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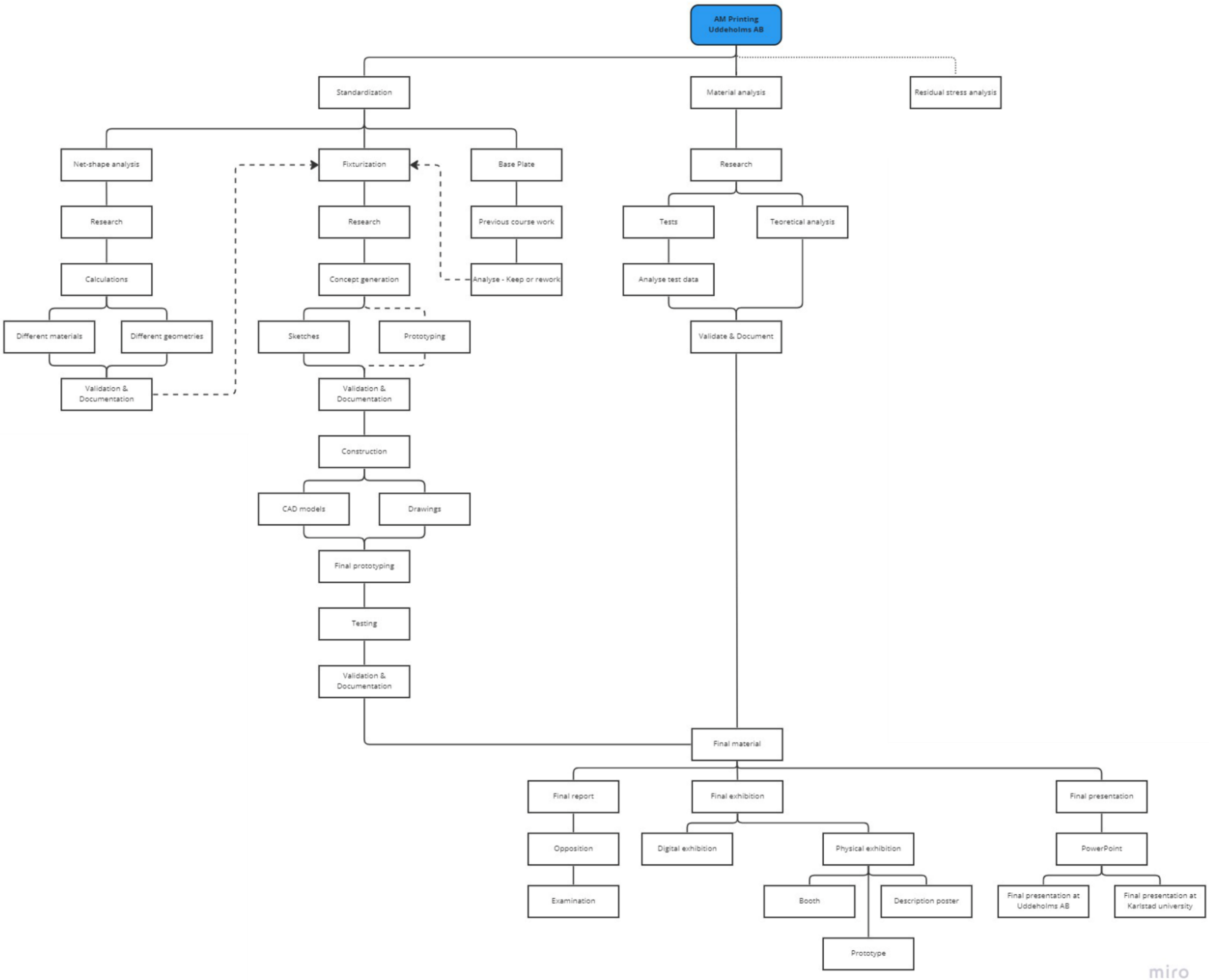
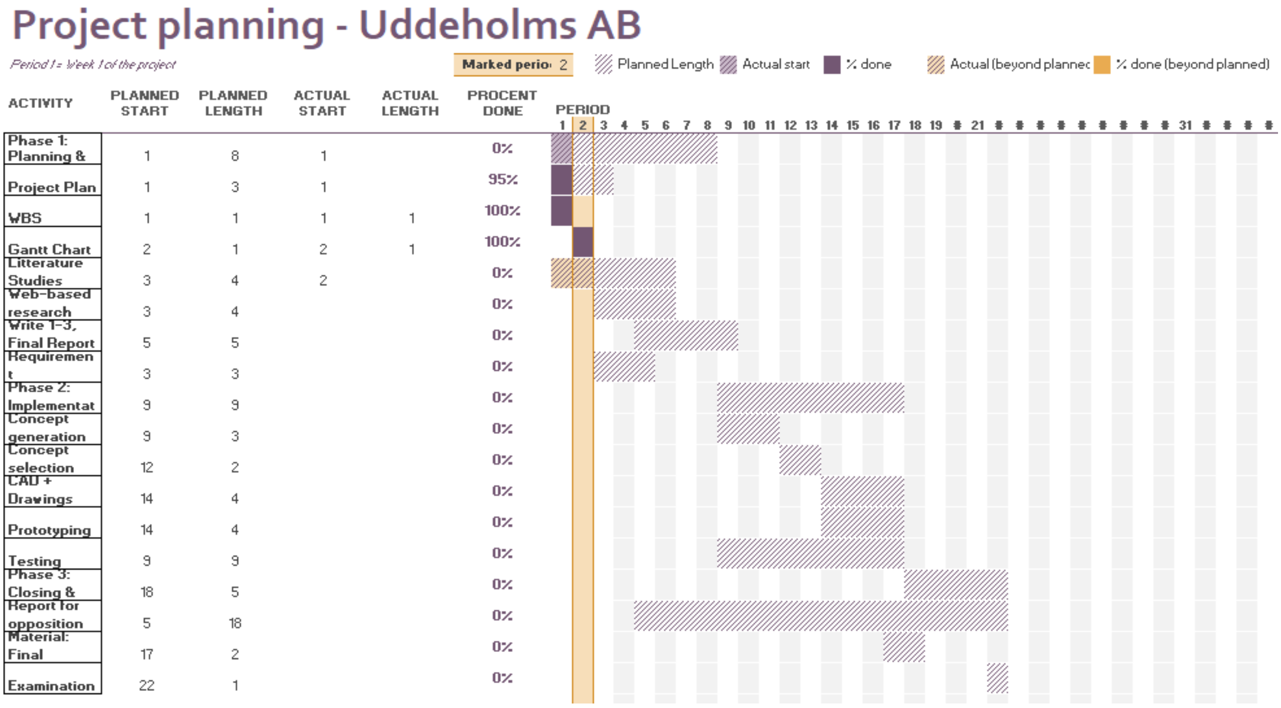
Appendix A: WBS



Appendix B: Risk analysis

Risk	P	C	R	Proposed action
The supervisor at Karlstads University quits	1	2	**2**	Discuss with Karlstads University about the possibility to be assigned a new supervisor
The main contact at Uddeholms AB quits	2	2	**4**	Discuss with Uddeholms AB about the possibility to be assigned a contact
The student gets sick during a long time	1	2	**2**	Plan the work according to this, try to work even if sick depending on the severity level of the sickness
Uddeholms AB loses interest in the project	1	4	**4**	Try to work out a project in another field or discuss the possibility to finish the project
Important data cannot be acquired	3	4	**12**	Look at other possibilities to acquire the data or rework the problem to avoid the usage of the data
Results cannot be presented in the final report due to the non-disclosure agreement	4	3	**12**	Look at the possibility to censor the sensitive data and results
The printer breaks down during the project for a long time	2	3	**6**	A theoretical solution will still be possible to produce, discuss with Uddeholms AB about the delivery and possibly rework the scope for the project
There is already a patent to the solution	1	2	**2**	Look at possibilities to rework the concept to avoid the patent and make sure there is substantial research on this topic
A new printer model is released with new dimensions	2	1	**2**	Design the solution parametrically to give the opportunity to easily change dimensions
A competitor releases a similar product	3	2	**6**	Make sure that the product exceeds the competitors
The ability to produce the powder used during printing can no longer be produced due to external factors	2	2	**4**	Discuss with supervisor at Uddeholms AB to shift all focus to the standardization topic of this project. Or use previous acquired data to do only a theoretical analysis

Appendix C: Gantt Chart



ACTIVITY	PLANNED START	PLANNED LENGTH	ACTUAL START	ACTUAL LENGTH	PROCENT DONE
Phase 1: Planning & Research	1	8	1		0%
Project Plan	1	3	1		95%
WBS	1	1	1	1	100%
Gantt Chart	2	1	2	1	100%
Litterature Studies	3	4	2		0%
Web-based research	3	4			0%
Write 1-3, Final Report	5	5			0%
Requirement Specification	3	3			0%
Phase 2: Implementation	9	9			0%
Concept generation	9	3			0%
Concept selection	12	2			0%
CAD + Drawings	14	4			0%
Prototyping	14	4			0%
Testing	9	9			0%
Phase 3: Closing & Delivery	18	5			0%
Report for opposition	5	18			0%
Material: Final exhibitions	17	2			0%
Examination	22	1			0%

Appendix B: Requirement specification

Requirement Specification

AM fixturing solution

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Leo De Vin

2023-02-16

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1. Requirements and wishes

In Table 1 the full list of all the requirements and wishes will be presented.

The priorities are ranked 1-5, where 1 is the lowest and 5 is the highest. The *R* and *W* describes if it's a requirement or wish.

Table 1: Requirements and wishes

#	**Category**	**Requirements**	**Priority (1-5)**	**R/W**
1	Use	Being able to fixture hybrid bases of different size and geometry	5	R
2	Material	Withstand pre-heating up to 200℃	5	R
3	Use	Fit AM-machine: EOS M290	5	R
4	Reference system	The fixture solution must have an accurate reference point system with a minimum of two reference points	5	R
5	Manufacturing	Top face of the fixture solution should be parallel with the bottom face of the hybrid base	5	R
6	Use of AM-machine	Being able to simultaneously fixture more than one hybrid base at a time	5	W
7	Material	Made of in-house materials	4	W
8	Cost	No changes should be made to the AM-machine	4	W
9	Manufacturing	Being able to manufacture the fixture system with tools available at Uddeholms AB	4	W
10	Use	No changes needed to the hybrid bases	4	W
11	Use	Fit AM-machines: EOS M270, EOS M280 and EOS M400	3	W
12	Reference system	Positioning accuracy better than 0,1 mm	3	W
13	Assembly/Use	Weight of build plate < 25kg	2	W

1.1 Absolute requirements

In this section the absolute requirements are described and presented in more detail.

1. Fixture hybrid bases

The main goal of the fixture solution is to be able to fixture hybrid bases of different kinds of geometries and sizes. This is crucial in order to save time that would otherwise be spent on constructing custom build plates for different hybrid bases. This will decrease the total lead time and cost of the printed products.

2. Withstand pre-heating

The fixture solution needs to be able to withstand preheating up to a temperature of 200°C. If the fixture solution were to deform in some way, the hybrid base may shift in position and the print will fail.

3. Fit given AM-machine

The fixture solution needs to be compatible with the AM-machine: EOS M290. Compatibility with the EOS M290 will be crucial since it´s the machine used at Uddeholms AB in Hagfors.

4. Reference point system

A reference point system needs to be included in the fixture solution. This is to ensure that the prints occur in the desired position on top of the hybrid base correctly every time the fixture solution is used.

5. Parallelism

The mating (top) surface of the fixture solution must be as flat as possible to create parallelism with the mating (bottom) face of the hybrid base. This is crucial for achieving the desired geometry when printing. Therefore, no added features can add angle to the hybrid base.

An accepted tolerance will be $< 0{,}05°$.

1.2 Wishes

In this section the wishes are described and presented in more detail.

6. Multiple hybrid bases

If possible, the fixture solution should be able to fixture multiple hybrid bases simultaneously in order to produce multiple print jobs at the same time. This will decrease lead times and to optimize the use of metal powder.

7. Made of in-house materials

The goal is to have the fixture solution constructed with materials found within Uddeholms AB's catalogue. The effect of this will be a reduction in cost and account for a smaller environmental impact.

8. No changes needed to the AM-machine

Uddeholms AB wishes to make no changes to their existing AM-machines in order to use the fixture solution.

9. Ease of manufacturing

In order to save manufacturing costs, the fixture solution should be easy to manufacture. This will be acquired by using the following manufacturing techniques: additive manufacturing, milling, drilling, tapping, sanding and reaming. To achieve the desired surface roughness of the build plate surfaces, sanding and reaming will be required.

The reason for why these specific manufacturing techniques have been chosen are because they are available at Uddeholms AB in Hagfors.

10. No changes needed to the hybrid bases

Since almost all of the print jobs are made to order, the fixture solution should preferably be able to handle all hybrid bases without demanding special mounting points that are required for the printing process.

11. Fit secondary AM-machines

The wish is for the fixture solution to fit the following machines: EOS M270, EOS M280 and EOS M400 since these are the AM-printers that are mainly used in the Voestalpine concern apart from the EOS M290 used in Hagfors.

12. Positioning accuracy

The build plate should be able to withstand the residual stresses that occur during printing whilst being able to maintain a positioning accuracy better than 0.1 mm.

13. Ease of use

The fixture solution should, if possible, be as light as possible. The goal is for the operator to be able to move and configurate the fixture solution without the help of external machines (for example: cranes, lifts etc.). If the total weight of the fixture solution is less than 25 kg, it will be approved to handle manually according to (Arbetsmiljöverket 2022).

2. Verification

The first step of the verification and screening process will be to give each of the concepts a score of:

- *True*: if the concept meets the given requirement
- *False*: if the concept does not meet the given requirement

The reason for this step is to quickly eliminate the concepts that meet the least amount of the requirements, to pass this stage every requirement needs to be scored as *True*. The concepts that manage this will pass through to the second stage of screening where a score of 1-5 will be given on how well the concept meets the various requirements and wishes.

The concept with the highest total score after the second stage of screening and verification will be the one that will be finalized and delivered to Uddeholms AB.

3. Market overview

The market overview showed that there are no direct competitors to the AM build plate for hybrid bases available on the market at the moment.

There are some build plates available on the market for additive manufacturing but none of the existing products can be used to fixture hybrid bases in a standardized way. Their main use is for conventional additive manufacturing where the whole detail is printed.

There are however some solutions for flexible fixturing but none of the existing solutions are specifically for additive manufacturing and therefore this solution will fill a market gap. This market gap will, with a high probability, increase over the following years since additive manufacturing is expanding with at rapid pace.

Reference list

Arbetsmiljöverket (2022). Manuell hantering - Arbetsmiljöverket. https://www.av.se/halsa-och-sakerhet/belastningsergonomi/manuell-hantering/ [2023-02-16].

Appendix C: Literature studies

Litterature Study

Bachelor Thesis

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2023-03-02

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Appendix A: Full search history
Appendix B: Literature list

1. Literature study

The literature study was executed primarily in OneSearch. When no information could be found on the topic the internet and websites provided the information. On top of this, previous course literature where used.

When searching for papers and reports in OneSearch, all the literature were selected to be peer-reviewed.

The technique of snowballing was used. Snowballing is tracking down references (or citations) in documents. The snowball method is a way of finding literature by using a key document on the selected subject as a starting point. Consult the bibliography in the key document (book or journal article) to find other relevant titles on the subject, then look in the bibliographies of these new publications to find yet more relevant titles.

The advantage of the snowball method is that one can find a lot of literature about a subject quickly and relatively easily. The disadvantage of this method is that the searching occurs retrospectively, so each source will be older than the previous one (especially in the case of books). (Hurkmans 2023)

2. Process and framing of questions

For this thesis work there are two main subject areas that the literature study was based on: Material and Fixture solutions, see Figure 1: Subjects. These subjects were later reworked into more concrete questions, see Table 1: Final questions.

These questions where the foundations for the search words used in OneSearch.

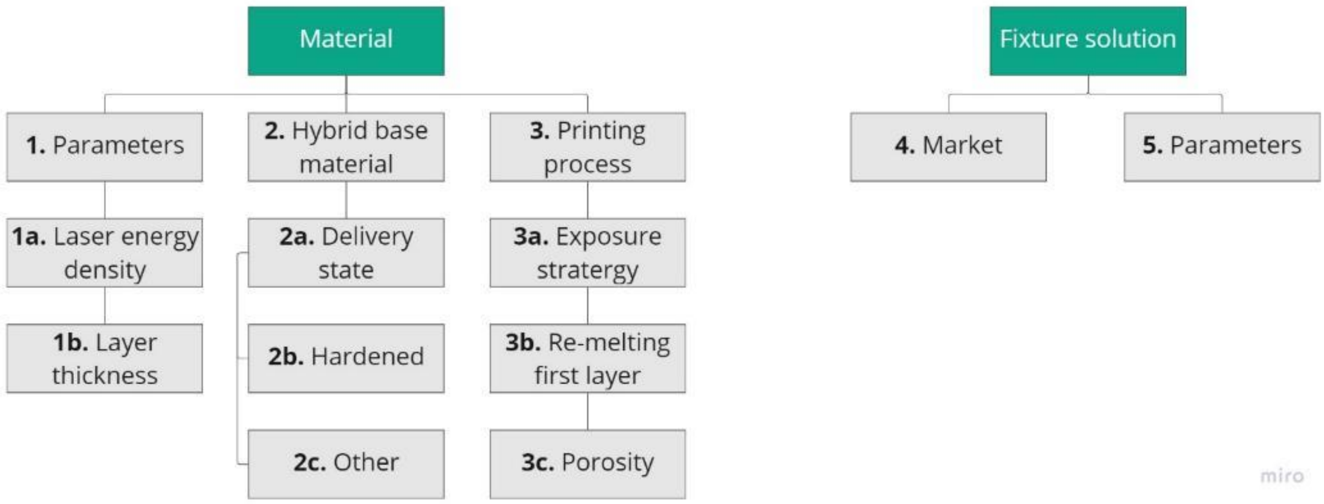

Figure 1: Subjects

Table 1: Final questions

#	Question
1.	What parameters are important when printing?
1a.	How does the Laser energy density affect the final product?
1b.	How does the layer thickness affect the final product?
2	How does the material in the hybrid base affect the final product?
2a.	Is a delivery state of the hybrid base material optimal?
2b.	Is a hardened state of the hybrid base material optimal?
2c.	Is any other state of the hybrid base material optimal?
3.	What parameters are important when printing the first layer?
3a.	How does the exposure strategy affect the final product?
3b.	Does remelting the first layer affect the final product?
3c.	How does porosity in the material affect the final product?
4.	What kinds of solutions are there on the market today?
5.	What parameters are important when designing a fixture system?

When the questions where finalized, search words were assigned to the questions for later use in the literature study in OneSearch. Table 2 illustrates an example of how to search results are presented.

Table 2: Search words

#	Search words	Limits	Results
Search date: 2023-01-23			
S7	(Metal* OR Steel*) AND (S2 AND S3 AND S6)	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	195
S6	Metal* OR Steel*	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	10,456,886
S5	(S2 AND S3 AND S4)	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	178
S4	Metal*	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	9,148,062

For the full literature search history and presentation, see Appendix A: Full search history.

3. Results from literature study

The literature study resulted in 30 viable journal articles, books and webpages for the following thesis work and report writing, these are presented in Appendix B: Literature list.

These texts where selected since they answered or provided information regarding the predetermined topics stated in Figure 1: Subjects. In Table 3: Literature presentation an example of how the results from the literature study are presented.

Table 3: Literature presentation

#	Author (year)	Title	Type
1	Lilliesköld & Eriksson (2005)	Handbok för mindre projekt	Book
2	Wu et al. (2022)	A segmented heat source for efficiently calculating the residual stresses in laser powder bed fusion process	Journal article
3	Li et al., (2021)	An approach for optimising the fixturing configuration in flexible machining fixtures	Journal article

References

Hurkmans, L. (2023). *LibGuides: Information Skills Toolbox: How to search for information?* https://buas.libguides.com/c.php?g=670074&p=4776470 [2023-03-2].

Appendix A: Full search history

#	Search words	Limits	Results
Search date: 2023-01-23			
S7	(Metal* OR Steel*) AND (S2 AND S3 AND S6)	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	195
S6	Metal* OR Steel*	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	10,456,886
S5	(S2 AND S3 AND S4)	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	178
S4	Metal*	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	9,148,062
S3	Fixture*	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	96,741
S2	"Additive manufactur*" OR AM OR "3D-printing" OR 3Dprinting	Avgränsare - Peer reviewed Sökinställningar - Hitta alla mina söktermer	6,072,546
S1	"Additive manufactur*" OR AM OR "3D-printing" OR 3Dprinting	Avgränsare - Peer reviewed; Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	3,791,704
Search date: 2023-02-08			
S3	"Flexible fixture system"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	5
S2	"Flexible fixture system"	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	6
S1	"Flexible fixture system"	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	
Search date: 2023-02-09			
S4	"Flexible Fixtur* System*" OR MFFS	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	5,317
S3	"Flexible Fixtur* System*"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	23
S2	"Flexible Fixtur* System*"	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	
S1	"Flexible Fixtur* System*"	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	
Search date: 2023-02-17			
S6	"powder bed fusion" AND steel AND microstructure	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	2,002
S5	"powder bed fusion" AND Metal* AND microstructure	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	3,085
S4	"powder bed fusion" AND Metal* AND microstructure	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	4,067

#	Search words	Limits	Results
S3	"powder bed fusion" AND "316l stainless steel" AND microstructure	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	415
S2	"powder bed fusion" AND "316l stainless steel" AND microstructure	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	565
S1	"powder bed fusion" AND "316l stainless steel"	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	1,336
Search date: 2023-02-22			
S20	Near Net Shape Manufacturing Processes AND "cost effectiveness"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	7
S19	Near Net Shape Manufacturing Processes AND "cost"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	316
S18	Near Net Shape Manufacturing Processes AND pbf-lb	Avgränsare - Peer reviewed; Available in Library Collection	2
S17	Near Net Shape Manufacturing Processes AND "additive manufacturing"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	561
S16	Near Net Shape Manufacturing Processes	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	1,636
S15	"cost calculation" AND Near Net Shape Manufacturing Processes	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S14	"cost calculation" AND "net shape"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S13	"cost calculation"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	2,304
S12	"cost calculation" AND "additive manufacturing"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	6
S11	"cost calculation" AND "additive manufacturing" AND steel	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S10	"cost calculation model" AND "additive manufacturing" AND steel	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S9	cost calculation model AND "exposure strategy"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S8	"powder bed fusion" AND "exposure strategy"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	3
S7	"powder bed fusion" AND "exposure strategy"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S6	"powder bed fusion" AND "316l stainless steel" AND "exposure strategy"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S5	"powder bed fusion" AND "316l stainless steel" AND "laser scanning strategy"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0

#	Search words	Limits	Results
S4	"powder bed fusion" AND "316l stainless steel" AND "laser scanning"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	16
S3	"powder bed fusion" AND "316l stainless steel" AND "laser scanning"	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	22
S2	"powder bed fusion" AND 316L	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	1,769
S1	"powder bed fusion"	Avgränsare - Finns i bibliotekets samling Sökinställningar - Hitta alla mina söktermer	
Search date: 2023-03-03			
S10	"post-processing" AND "316l stainless steel"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	98
S9	welding AND post-processing AND "316l stainless steel"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	2
S8	welding AND post-processing AND "316l stainless steel"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S7	“Heat affected zone” AND welding AND "316l stainless steel"	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	77
S6	“Heat affected zone” AND welding	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	9,582
S5	“Heat affected zone”	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	15,180
S4	“Heat affected zone”	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S3	“Double exposure” AND “Heat affected zone”	Avgränsare - Peer reviewed; Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S2	“Double exposure” AND “Heat affected zone”	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0
S1	“Double exposure” AND “Heat affected zone” AND Weld*	Avgränsare - Available in Library Collection Sökinställningar - Hitta alla mina söktermer	0

Appendix B: Literature list

#	Author (year)	Title	Type
1	Lilliesköld & Eriksson (2005)	Handbok för mindre projekt	Book
2	Wu et al. (2022)	A segmented heat source for efficiently calculating the residual stresses in laser powder bed fusion process	Journal article
3	Li et al., (2021)	An approach for optimising the fixturing configuration in flexible machining fixtures	Journal article
4	Bohgard et al. (2015)	Arbete och teknik på människans villkor	Book
5	Wikberg Nilsson et al. (2021)	Design: process och metod	Book
6	Hearn (2023)	Development of Structural Steels for Powder Bed Fusion – Laser Beam	Book
7	Roirand et al. (2022)	Effect of laser scan pattern in laser powder bed fusion process: The case of 316L stainless steel	Journal article
8	Leicht et al. (2021)	Effect of part thickness on the microstructure and tensile properties of 316L parts produced by laser powder bed fusion	Journal article
9	Pauzon et al. (2020)	Effect of the process gas and scan speed on the properties and productivity of thin 316L structures produced by Laser-Powder Bed Fusion	Journal article
10	Carlson (2012)	Effective FMEAs : achieving safe, reliable, and economical products and processes using failure mode and effects analysis	Book
11	Liang et al. (2022)	Effects of rescanning parameters on densification and microstructural refinement of 316L stainless steel fabricated by laser powder bed fusion	Journal article
12	Bi & Zhang (2001)	Flexible fixture design and automation: Review, issues and future directions	Journal article
13	Huang et al. (2022)	High-power laser powder bed fusion of 316L stainless steel: Defects, microstructure, and mechanical properties	Journal article
14	Bragg (2022)	How to calculate cost per unit	Webpage
15	Chueh et al. (2020)	Integrated laser-based powder bed fusion and fused filament fabrication for three-dimensional printing of hybrid metal/polymer objects	Journal article
16	Mussatto et al. (2022)	Laser-powder bed fusion of silicon carbide reinforced 316L stainless steel using a sinusoidal laser scanning strategy	Journal article
17	Hurkmans (2023)	LibGuides: Information Skills Toolbox: How to search for information?	Webpage
18	Arbetsmiljöverket (2022)	Manuell hantering - Arbetsmiljöverket	Webpage
19	Krakhmalev et al. (2018)	Microstructure, solidification texture, and thermal stability of 316 L stainless steel manufactured by laser powder bed fusion	Journal article
20	Cominotti & Gentili (2008)	Near net shape technology: An innovative opportunity for the automotive industry	Journal article
21	Ahmed et al. (2022)	Process parameter selection and optimization of laser powder bed fusion for 316L stainless steel: A review	Journal article
22	Ulrich et al. (2020)	Product design and development	Book
23	Ahn et al. (2022)	Thickness effect on the microstructures, mechanical properties, and anisotropy of laser-	Journal article

#	Author (year)	Title	Type
		powder bed fusion processed 316L stainless steel	
24	Carr Lane (n.d.)	What is Modular Fixturing?	Webpage
25	ASQ (n.d.)	What is Quality Function Deployment (QFD)?	Webpage
26	(Kaynak & Kitay 2019)	The effect of post-processing operations on surface characteristics of 316L stainless steel produced by selective laser melting	Journal article
27	(Chao et al. 2021)	The effect of post-processing heat treatment on the microstructure, residual stress and mechanical properties of selective laser melted 316L stainless steel	Journal article
28	(Vukkum & Gupta 2022)	Review on corrosion performance of laser powder-bed fusion printed 316L stainless steel: Effect of processing parameters, manufacturing defects, post-processing, feedstock, and microstructure	Journal article
29	(Wang et al. 2023)	Post processing of additively manufactured 316L stainless steel by multi-jet polishing method	Journal article
30	(Jiang et al. 2022)	A Study on the Ultrasonic Regulation of the Welding Performance and Residual Stress of 316L Stainless Steel Pipes	Journal article

Appendix D: Concept selection

Concept Selection

Concept selection for fixture solution

Koncept val

Koncept val för fixturlösning

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2023-03-16

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Table of Contents

1. Introduction

1.1 Background

The main purpose of this project is to internally standardize the printing process at Uddeholms AB in Hagfors. One of the segments to achieving this is to develop a new fixture solution to use when printing.

Before this project started, there was a lot of time spent on fixturing hybrid bases to the fixture plate due to not having a standardized way of fixturing parts onto the plate. This caused issues with reference points. Moreover, this took up a lot of time since all the fixture plates were custom made and single use. This is because the vast majority of different geometries of the hybrid bases.

If a standardized fixture solution is created, this will result in reduced cycle times and added sustainability within the Additive Manufacturing department at Uddeholms AB.

1.2 Requirements and wishes

In this section the requirements and wishes that lay the foundation for the concept generation will be presented in Table 1.

Table 1: Requirements and wishes

#	Category	Requirements	Priority (1-5)	R/W
1	Use	Being able to fixture hybrid bases of different size and geometry	5	R
2	Material	Withstand pre-heating up to 200℃	5	R
3	Use	Fit AM-machine: EOS M290	5	R
4	Reference system	The fixture solution must have an accurate reference point system with a minimum of two reference points	5	R
5	Manufacturing	Top face of the fixture solution should be parallel with the bottom face of the hybrid base	5	R
6	Use of AM-machine	Being able to simultaneously fixture more than one hybrid base at a time	5	W
7	Material	Made of in-house materials	4	W
8	Cost	No changes should be made to the AM-machine	4	W
9	Manufacturing	Being able to manufacture the fixture system with tools available at Uddeholms AB	4	W
10	Use	No changes needed to the hybrid bases	4	W
11	Use	Fit AM-machines: EOS M270, EOS M280 and EOS M400	3	W
12	Reference system	Positioning accuracy better than 0,1 mm	3	W
13	Assembly/Use	Weight of build plate < 25kg	2	W

2. Concept generation

2.1 Brainstorming

To generate the concepts a brainstorming session was performed, this was for two reasons, the first reason was to get the thinking as well as summarizing the information from the research and brainstorming is a great tool for this.

The second reason for the brainstorming session was that brainstorming generates a lot of ideas where the focus is on quantity over quality, this is also mentioned by Wikberg Nilsson et al. (2021) which was needed in this stage of the concept generation. Here a very small amount of limitations was present and the requirements and wishes from the requirement specification into was not taken into large consideration.

This naturally generated a lot of ideas that were terminated quickly since the concepts were not plausible to execute.

8 concepts were generated in this stage.

2.2 Scamper

A scamper session is executed through 6 steps, Wikberg Nilsson et al. (2021) describes the 6 steps on page 147 in their book:

1. Generate ideas, solutions and concepts through brainstorming or braindrawing.
2. For each of the solutions ask the following questions: Replace? Combine? Adapt? Modify? Use in a different way? Eliminate? Think the opposite?
3. Let the participants speculate freely about each question and note the ideas.
4. Go through each question for every idea/concept to really make sure that all possible solutions have been thought of.
5. Document.
6. Categorize the new solutions and concepts and evaluate for further work.

Wikberg Nilsson et al. (2021) states that the scamper-session often uses the generated material from an earlier brainstorming-session and aims to further develop the material.

This made the scamper session a natural second stage for the concept generation process.

Here the previous concepts were combined and more rendered sketches of the concepts where made. It was in this stage that the requirements and wishes from the requirement specification (see Table 1) started to play a bigger role in the concepts.

From this session the previous 8 concepts were combined, eliminated, and reworked into 5 concepts that will be presented in more detail section 3. Concepts.

Table 2: Combination, elimination and reworking of concepts.

Original Concepts	Changes / Combinations	Resulting Concept
Concept A + Concept B	The pin-idea from concept A was combined with the reference system from concept B were combined	Concept 1 - Pins
Concept B + Concept C	Parts of the reference system from concept B was combined with the groves from concept C	Concept 2 - Groves
Concept D	The spring idea from concept D remained the same	Concept 3 - Springs
Concept E + Concept F	Here the conventional magnets of concept E were eliminated in favour for the electromagnets of concept F	Concept 4 - Electromagnets
Concept G + Concept H	The clamps idea from concept H was eliminated in favour for the vise from concept G for usability	Concept 5 - Vise

3. Concept overview

In this chapter, a description of the five final concepts will be presented.

3.1 Concept 1 – Dowel holes

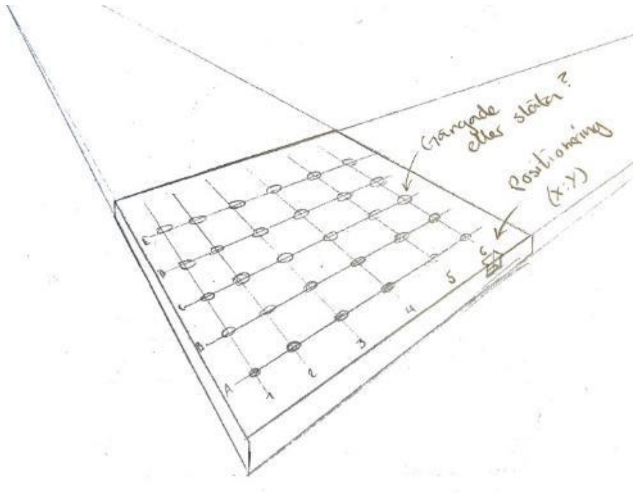

Figure 1: Concept 1 – Dowel holes

The first concept implements the use of dowel pins and a fixed positioning system for the base plate. There are also possibilities for the use of threaded holes to further improve the abilities to fixture different geometries. This concept can be used in combination with different standard components and standardized screws and pins. Moreover, custom made fixture points can be manufactured to suit the customers' needs.

This concept can fixture a variety of different geometries without changes to the base plate and can fixture multiple hybrid bases at the same time.

Another positive aspect of this concept is the reference system. Since the reference system is directly implemented into the base plate it provides an accurate and true reading of the positioning of the hybrid base.

This concept can also fixture multiple hybrid bases at the same time.

There will not be a problem to change the size of this fixture solution to suit other printers in the Voestalpine concern.

3.2 Concept 2 – T-slots

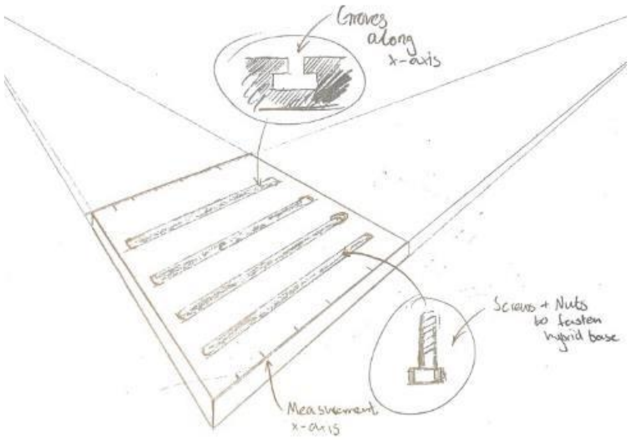

Figure 2: Concept 2 – T-slots version 1

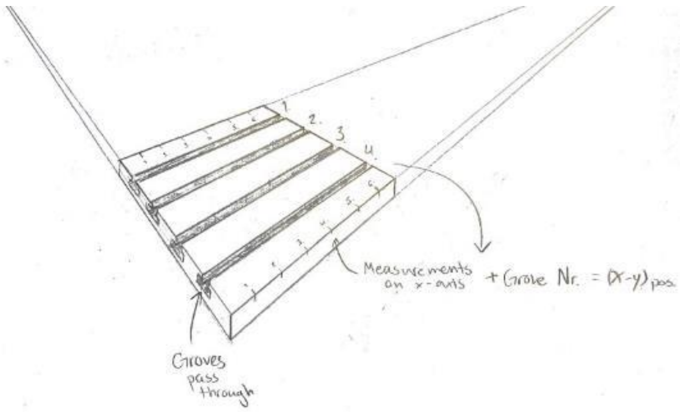

Figure 3: Concept 2 – T-slots version 2

The second concept utilizes T-slots in the base plate along the x-axis. The idea is to use nuts and bolts to fasten the hybrid base. This solution gives a great freedom to fixture different geometries and also provides the opportunity to fixture multiple bases simultaneously.

A "ruler"-system will be used and marked on the base plate, this will give a fixed reference point on the build plate to later use to mark the exact X; Y-position of the hybrid base.

To use this concept, the hybrid bases will need mounting points which will be needed to take into consideration.

There is a possibility to incorporate alternative fastening-fixtures into this design in the future, for example vices that can be bolted down.

3.3 Concept 3 – Springs

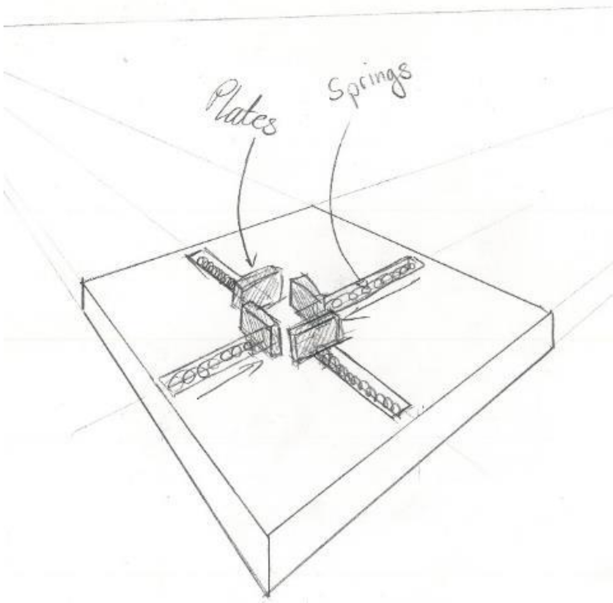

Figure 4: Concept 3 – Springs

The third concept utilizes springs to fixture the hybrid base. Four springs would be mounted in grooves in the fixture plate, compressing the hybrid base in the middle. This concept is very simple but may be difficult to use depending on the stiffness of the springs. Another downside is that the springs will lose a bit of tension when they heat up, which may cause issues keeping the hybrid base fixtured.

Another major problem with this concept is how to implement the reference point system, since it will be very hard to measure exactly where the hybrid base is positioned starting from the build plate edges.

This concept may handle a variety of geometries but does not have the capability to simultaneously fixture multiple hybrid bases.

3.4 Concept 4 – Electromagnets

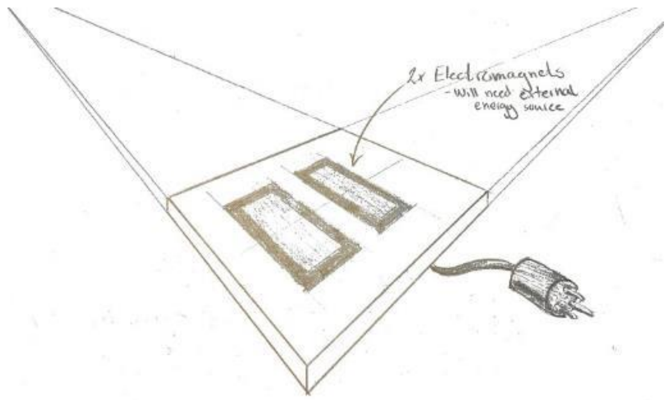

Figure 5: Concept 4 – Electromagnets

The fourth concept utilizes electromagnets to fixture the hybrid base. This concept will have the option to fixture multiple hybrid bases simultaneously.

The problem with this concept is that an external energy source will be needed to activate the magnets. This may then need changes to the printer which is not ideal. On top of this, the electromagnets have a high risk of interfering with the powder in a way that declares this concept unusable.

Another problem with this solution is the reference system. It can be difficult to estimate the exact position of the hybrid base. Although this can be fixed using the ruler-type reference system mentioned in Concept 2 – Grooves.

3.5 Concept 5 – Vise

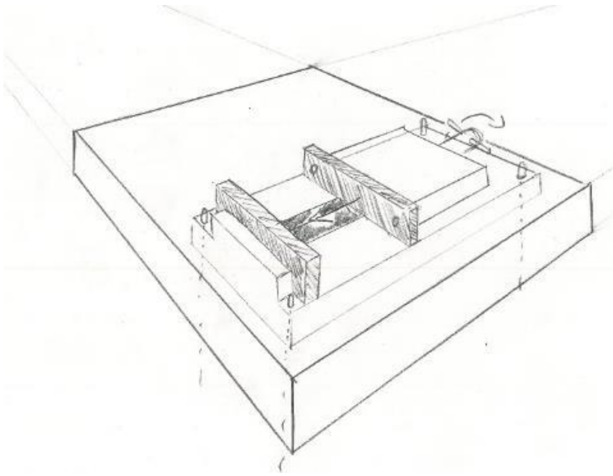

Figure 6: Concept 5 – Vise

The fifth concept uses a vice which will be mounted directly on top of the build plate surface in order to secure the hybrid base. One alternative would be to combine the vice with concept 1 – dowel pins, the hole pattern would allow for multiple vises to be applied in different positions to allow for multiple hybrid bases to be fixed simultaneously.

This combination might prove to be useful and would with a high probability work for one or two prints. The issue would occur after a couple of prints, when steel powder gets jammed in the vise's exposed threads. Unless this issue is addressed, the vise concept will not hold up for repeated use.

Here the reference system will be a problem since there will be hard to have an exact reading every time. Also, since the vise is relatively big compared to some of the other concepts it might interfere with the powder spreader.

4. Concept selection

4.1 Pugh Matrix

The concepts were later compared in a Pugh Matrix where the baseline is the current build plate in use by Uddeholm AB today. This matrix can be shown in figure 8.

A Pugh Matrix “is a decision matrix where alternatives or solutions are listed on one axis, and evaluation criteria are listed on the other axis. The objective is to evaluate and prioritize the alternatives or solutions. The team first establishes and weights the evaluation criteria and then evaluates each option against those criteria.” (Carlson 2012).

Ulrich et al. (2020) also mentions that “The purposes of this stage are to narrow the number of concepts quickly and to improve the concepts.” This was the reasoning to use a Pugh Matrix, on top of this it is a good way to connect the requirements specification and elimination of concepts.

Also, as Wikberg Nilsson et al. (2021) states when talking about concept matrices on page 237, that the aim is to discuss the concepts based on fulfillment of criteria rather than personal opinion regarding the different concepts, this part is very important. The matrix Wikberg Nilsson et al. (2021) discusses is not a Pugh Matrix but the idea is the same for both of the matrices and they share great similarities.

4.2 Screening of the concepts

For the screening and elimination of the concepts, a Pugh matrix was used, see Figure 8. The baseplate currently in use at Uddeholms AB (see Figure 7) was used as a reference and baseline for the Pugh matrix.

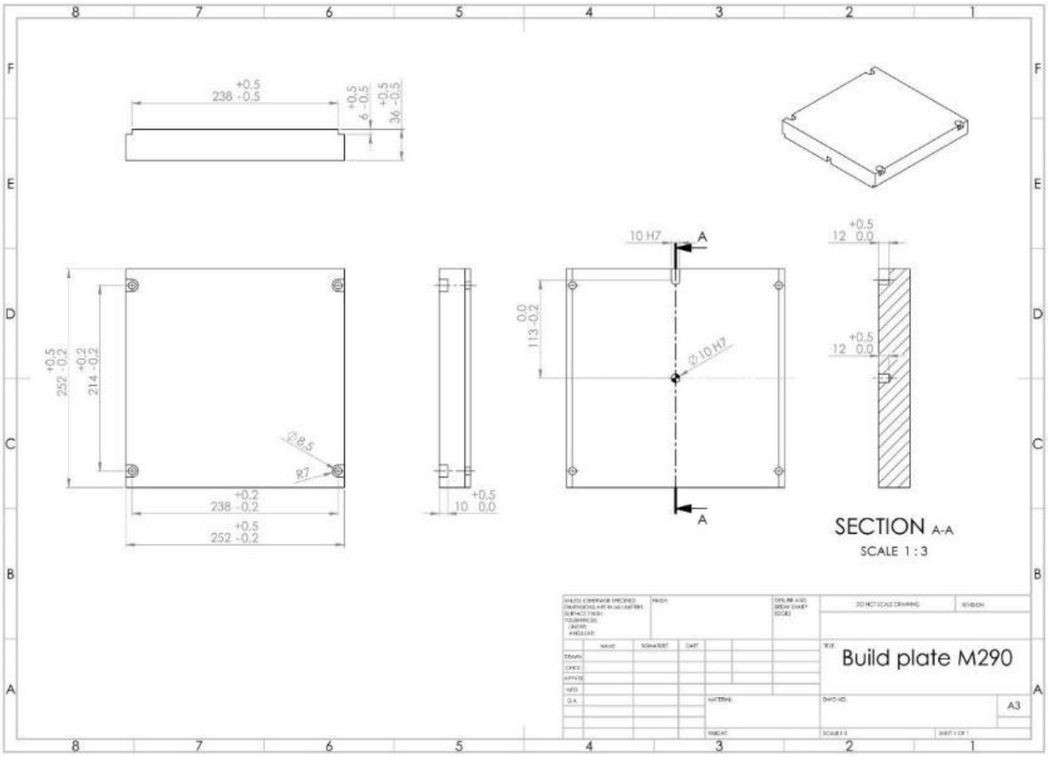

Figure 7: Drawing of the baseplate in use today. (Used by permission from Uddeholms AB)

On the Y-axis on the left-hand side the requirements and wishes from the requirement specification is listed which have been approved by Uddeholms AB prior to this stage, this can be seen in Figure 8.

The total score for each of the concepts from the Pugh matrix (Figure 8) is listed in Table 3.

Table 3: Pugh matrix scores

Concept	Score	Rank
Concept 1 – Dowel pins	6	1
Concept 2 – Grooves	4	3
Concept 3 – Springs	0	5
Concept 4 – Electromagnets	1	4
Concept 5 – Vise	4	2

Based on this data the choice was made to proceed with concept 1 – Dowel holes.

It should be noted that the scores given for each of the concepts regarding some of the specific requirements, for example weight, is an estimate and cannot with complete certainty be confirmed at this stage of the process.

Although the choice can be backed with the argument that the process has been carried out in conjunction with Uddeholms AB and can therefore be declared valid.

Pugh Matrix - Fixture solution

Project: Internal standardization - Uddeholms AB

#	Criteria	Baseline	Concept 1 - Dowel holes	Concept 2 - T-slots	Concept 3 - Springs	Concept 4 - Electromagnets	Concept 5 - Vise	Totals	Rank
1	Fixture hybrid bases	0	+	+	+	+	+	5	1
2	Withstand pre-heating	0	0	0	–	–	0	-2	13
3	Fit given AM-machine: EOS M290	0	0	0	0	0	0	0	
4	Reference point system	0	+	+	–	–	0	0	9
5	Build plate must be parallel with the hybrid base	0	0	0	–	0	0	-1	10
6	Fixture multiple hybrid bases	0	+	–	0	+	–	0	7
7	Made of in house materials	0	0	0	0	0	0	0	
8	No changes needed to the AM machine	0	0	0	0	–	0	-1	11
9	Ease of manufacturing	0	+	+	–	–	+	1	5
10	No changes needed to the hybrid bases	0	+	–	0	0	0	0	8
11	Fit alternative AM-machines	0	+	+	+	+	+	5	1
12	Positioning accuracy better than 0,1 mm	0	+	+	0	+	+	4	3
13	Weight of build plate < 25kg	0	+	+	+	+	+	5	1
	Totals		6	4	0	1	4		
	Rank		1	3	5	4	2		

Symbols	Relationship	Value
+	Better than baseline	1
0	About the same	0
–	Worse than baseline	-1

Figure 8: Pugh Matrix, current base plate in use at Uddeholms AB is used as baseline.

The matrix in Figure 8 shows that concept 1 is the superior concept since it meets the requirements and wishes the best. This concept selection has been approved by Uddeholms AB.

5. Selected concept

5.1 Further description of the selected concept

The idea of the concept is, as previously mentioned, to use a grid-based dowel-hole system, see Figure 9. To open up the possibility of fixturing a plethora of different geometries and sizes a custom-made fixture point will need to be made, see Figure 10: Fixture point feature.

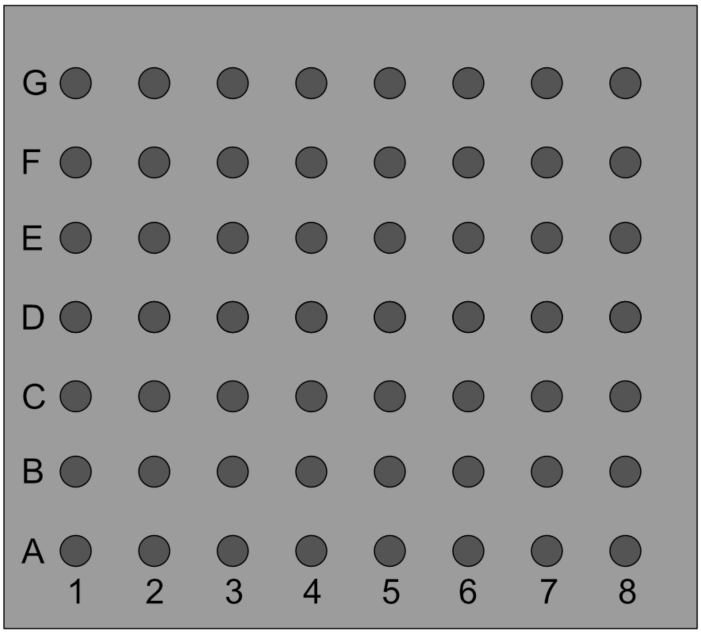

Figure 9: Example of the grid pattern used

The grid pattern displayed in Figure 9 also includes the reference system. To read the position of the hybrid base, the operator uses the coordinate system (A, 1) to get an exact (X, Y)-position.

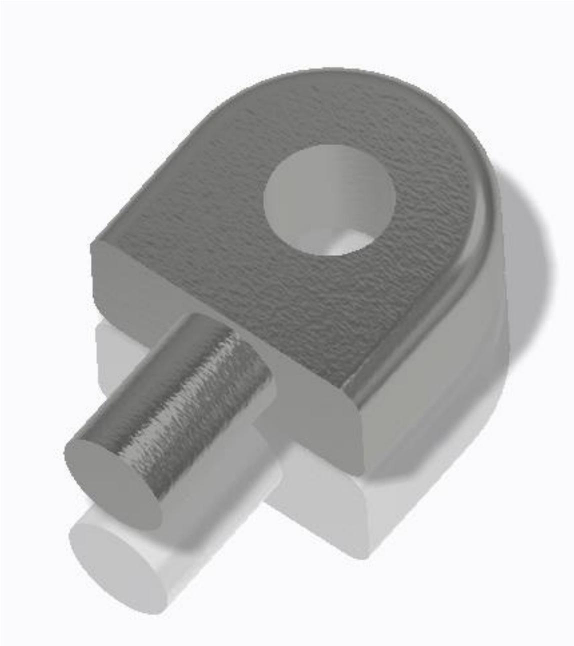

Figure 10: Fixture point feature

These fixture points (Figure 10) opens the possibility for the operator to quickly create a bespoke base plate for every print job in a standardized way. Although, for some print jobs the dowel-pins will be sufficient to fixture the hybrid base and the use of a custom mounting point will not be necessary.

Figure 11 illustrates an example of how the concept is intended to be used.

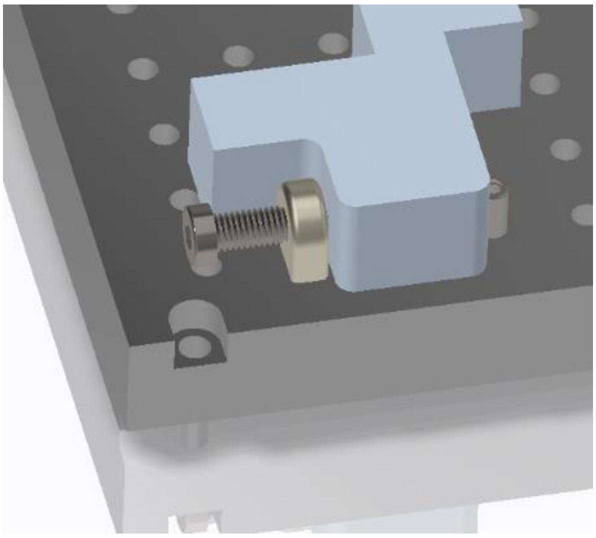

Figure 11: Fixturing example

5.2 Arguments for the selected concept

A brief summary of the arguments to why this is the best solution are:

- Ease of use, no custom-made base plates are needed (*Requirement 1, 5, 6, 10*)
- Ease of manufacturing (*Requirement 7, 9*)
- Easy to change dimensions to be compatible with multiple AM-printers (*Requirement 3, 11, 8*)
- Compatible with different standard components, such as vises etc. (*Extra*)
- Great possibility for the use of custom components if needed (*Extra*)
    - A possibility for potential up-sales with different types of standardized mounting points
- A simple but effective reference system (*Requirement 4, 12*)
- Possibility to mount multiple hybrid bases simultaneously (*Requirement 1, 5, 6, 10*)

This plus the results from the Pugh Matrix (Figure 8) gave enough data to be able to make the decision to select this concept as the one to go forward with.

References

Carlson, C. S. (2012). Effective FMEAs : achieving safe, reliable, and economical products and processes using failure mode and effects analysis. Hoboken: John Wiley & Sons.

Ulrich, K. T., Eppinger, S. D. & Yang, M. C. (2020). Product design and development. New York: McGraw-Hill Education.

Wikberg Nilsson, Å., Ericson, Å. & Törlind, P. (2021). Design : process och metod. Lund: Studentlitteratur.

Appendix E: Drawings

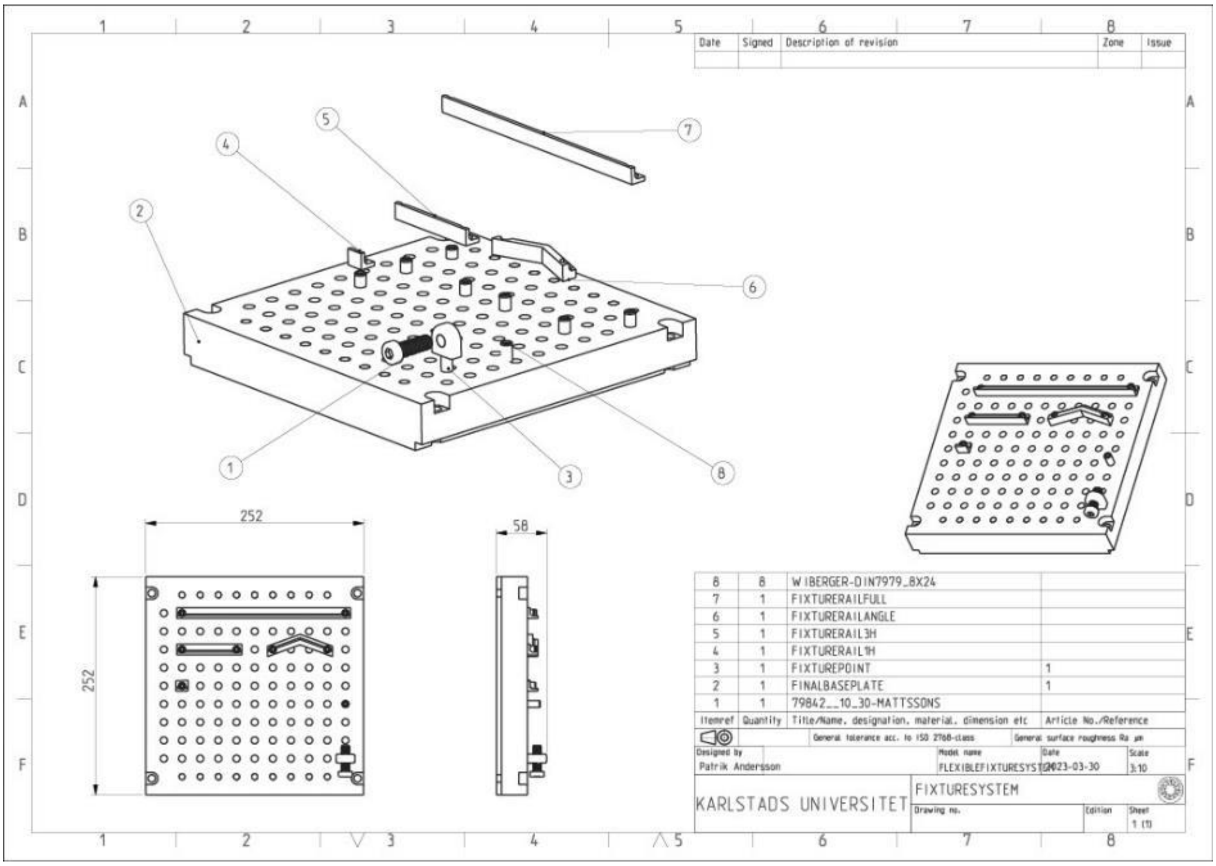

Figure 1: Drawing for the full fixture system

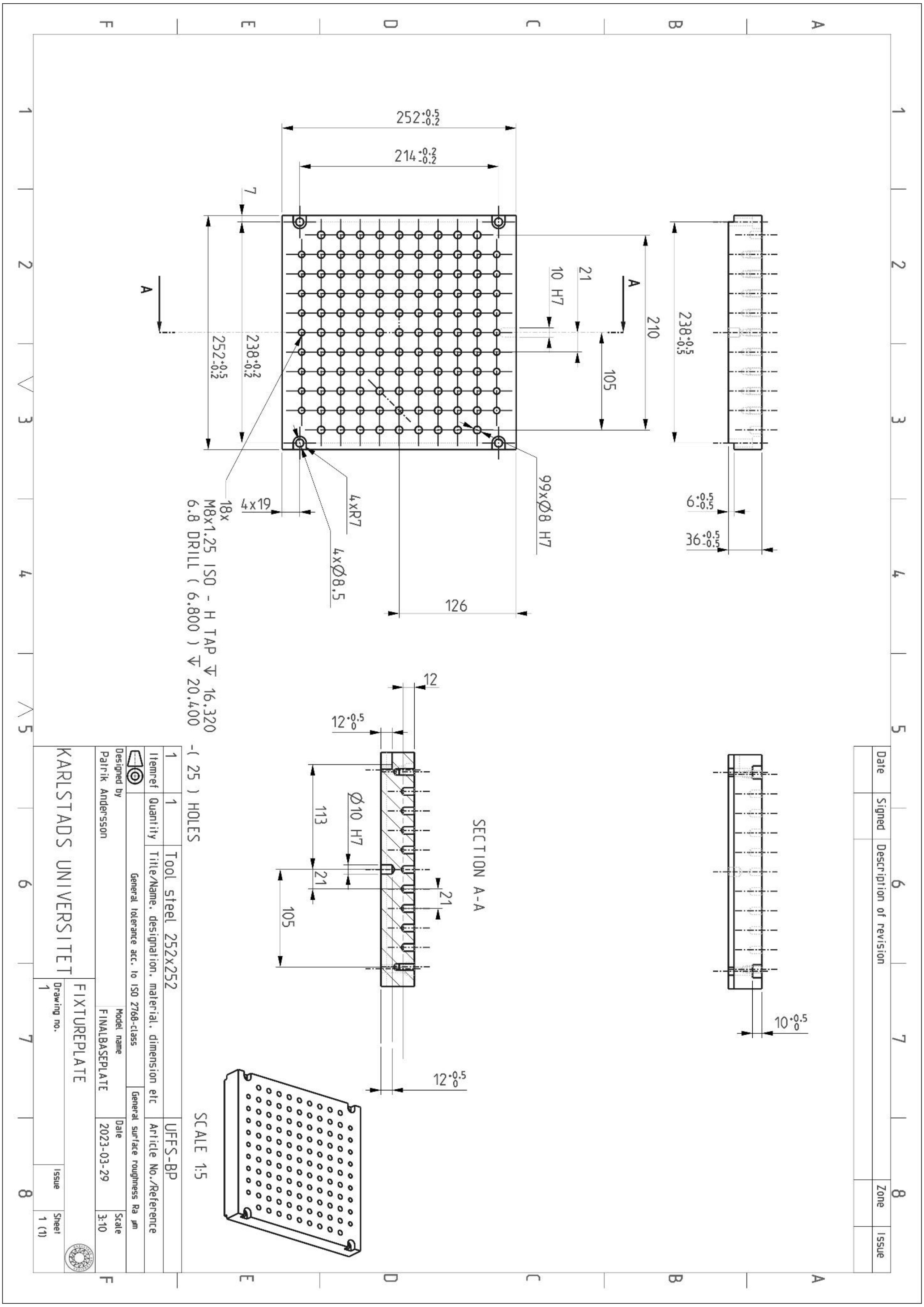

Figure 2: Drawing for the fixture plate

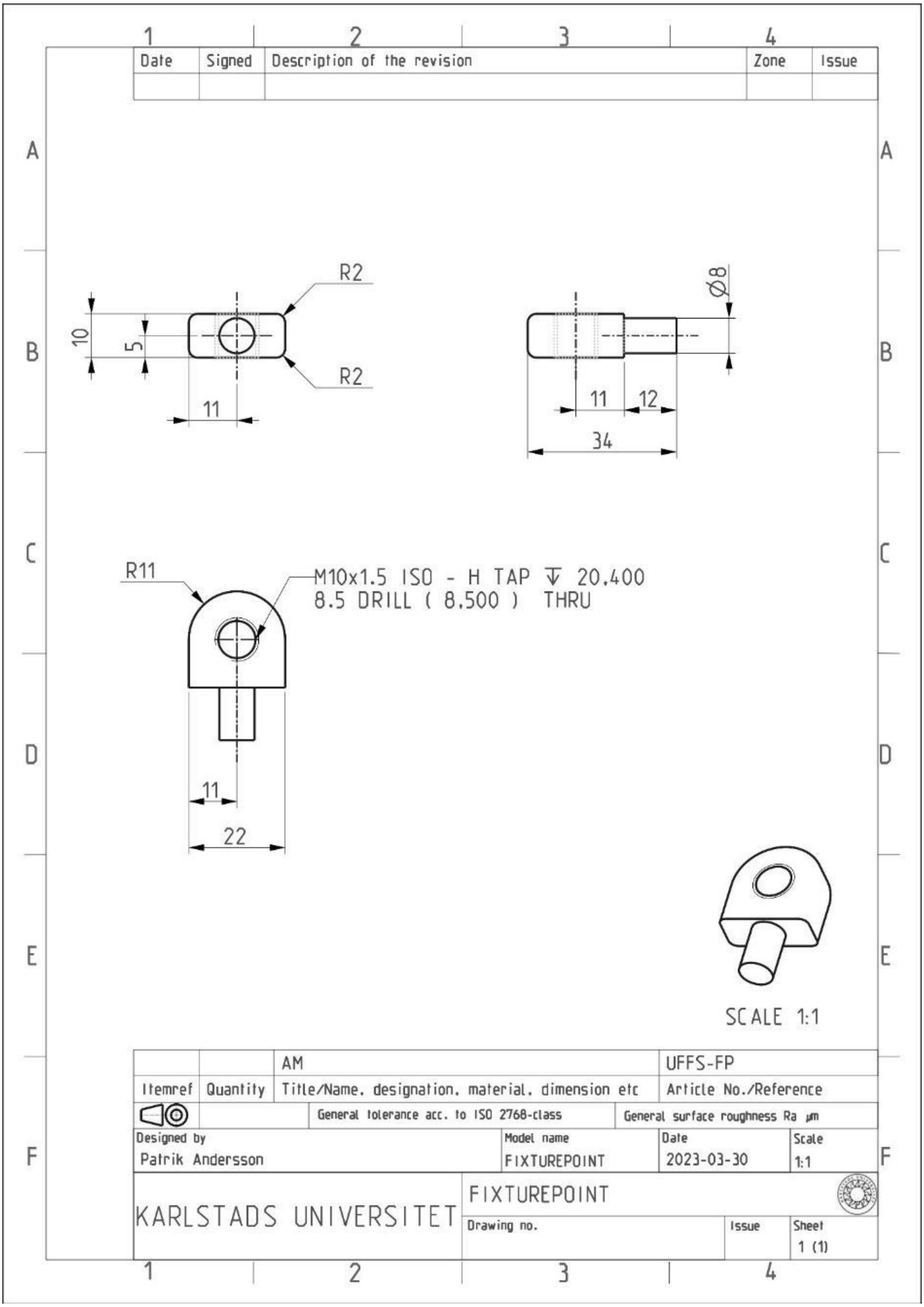

Figure 3: Drawing for the fixture point

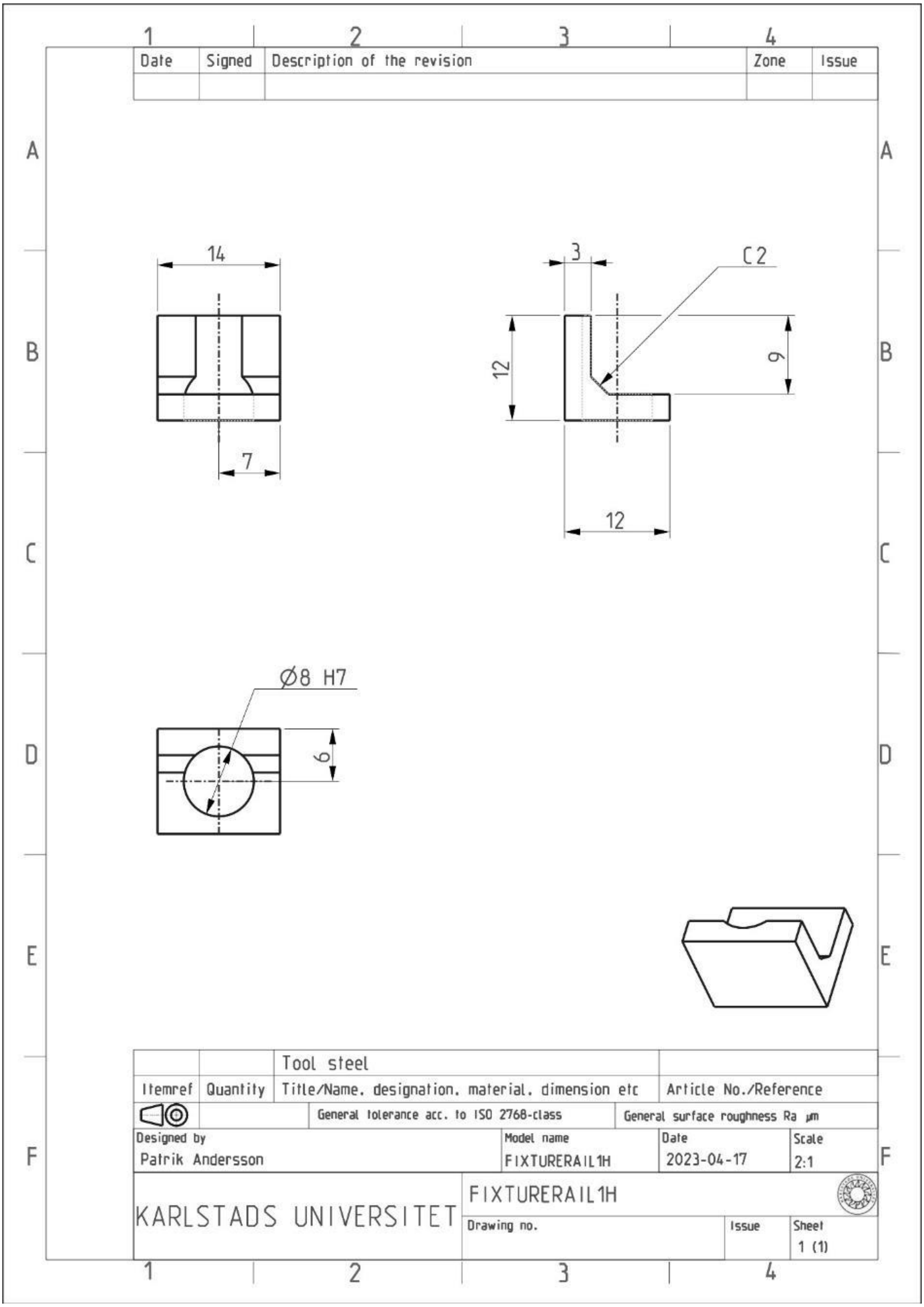

Figure 4: Drawing for the fixture rail (14 mm)

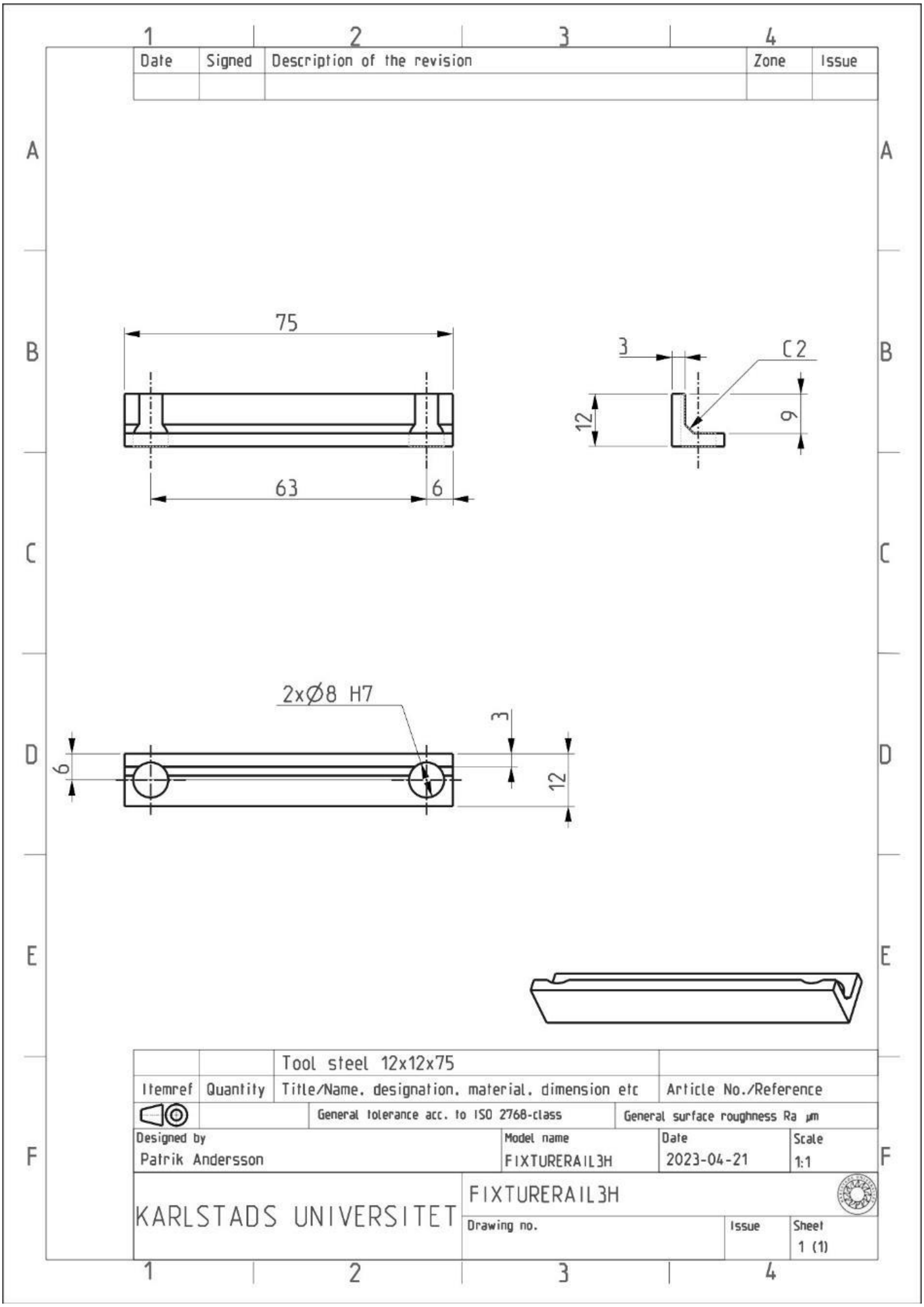

Figure 5: Drawing for the fixture rail (75 mm)

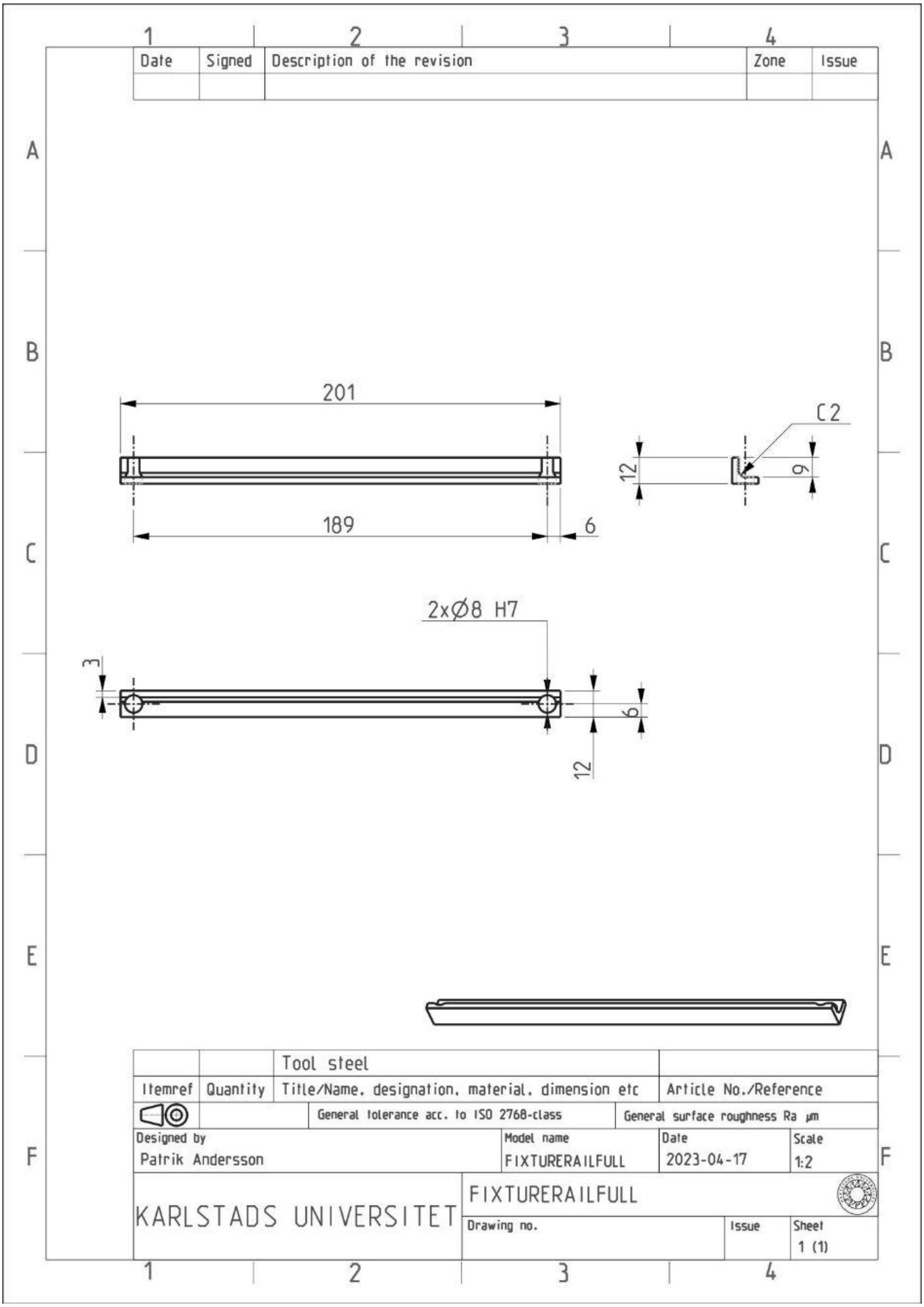

Figure 6: Drawing for the fixture rail (201 mm)

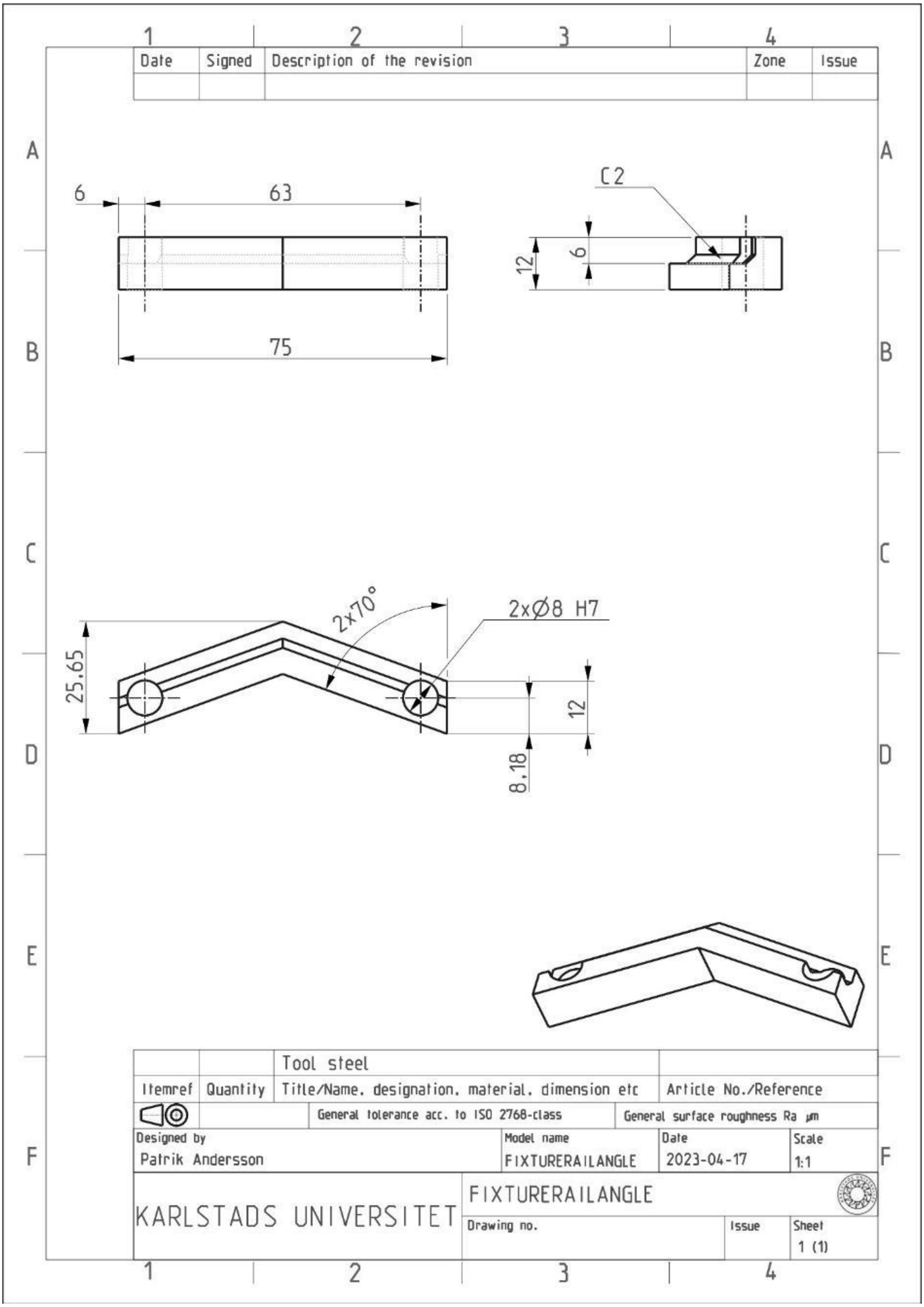

Figure 7: Drawing for the fixture rail (angle)

Appendix F: Hardening curves

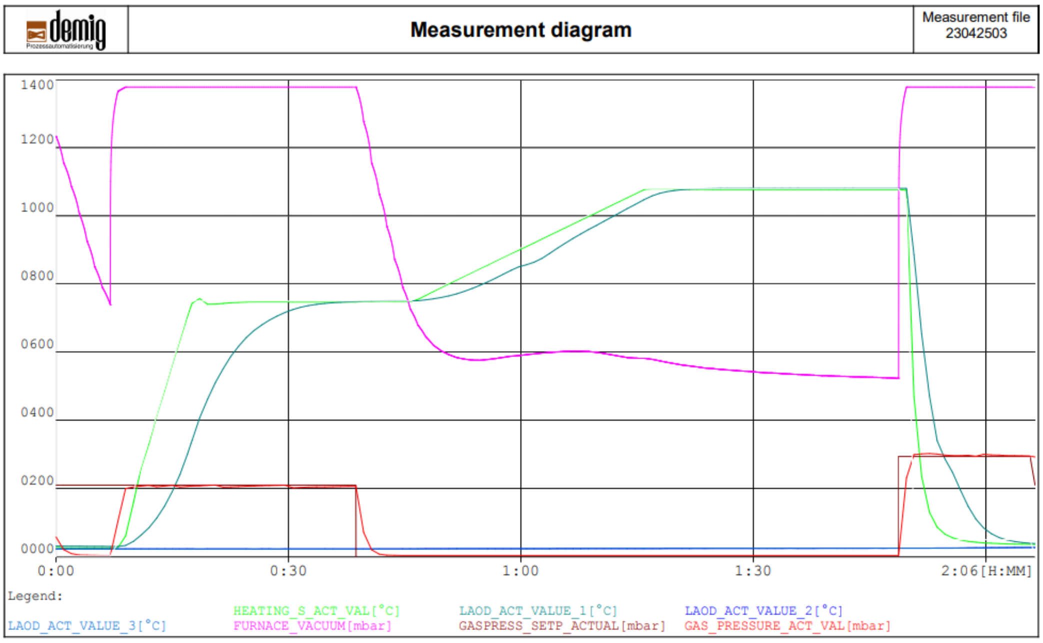

Figure 1: Hardening curve, where the green line is the temperature of the furnace and the light blue line is the temperature of the test specimen

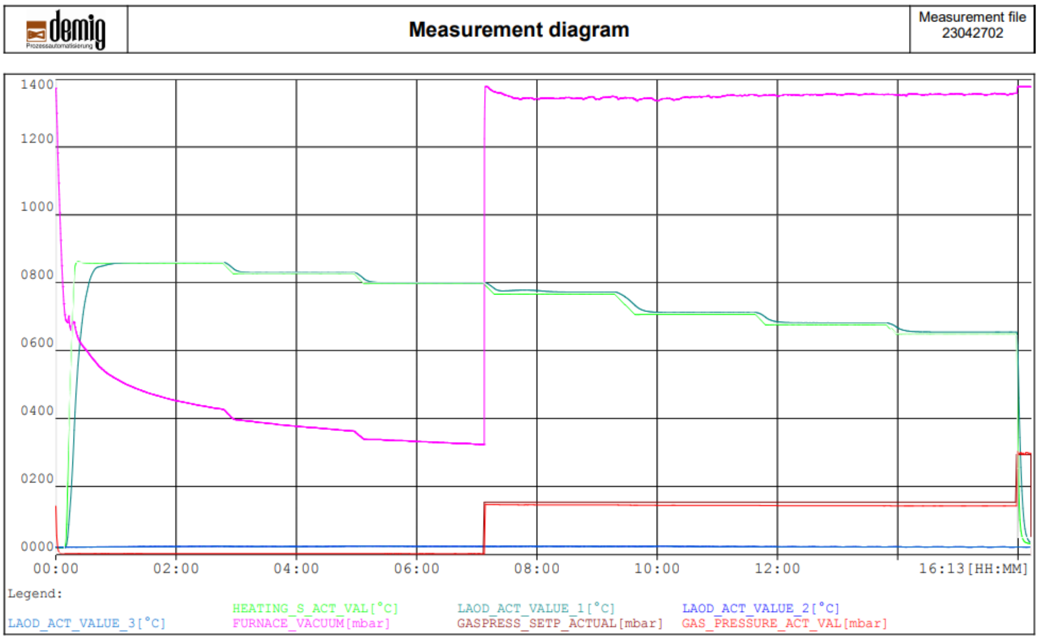

Figure 2: Annealing curve, where the green line is the temperature of the furnace and the light blue line is the temperature of the test specimen