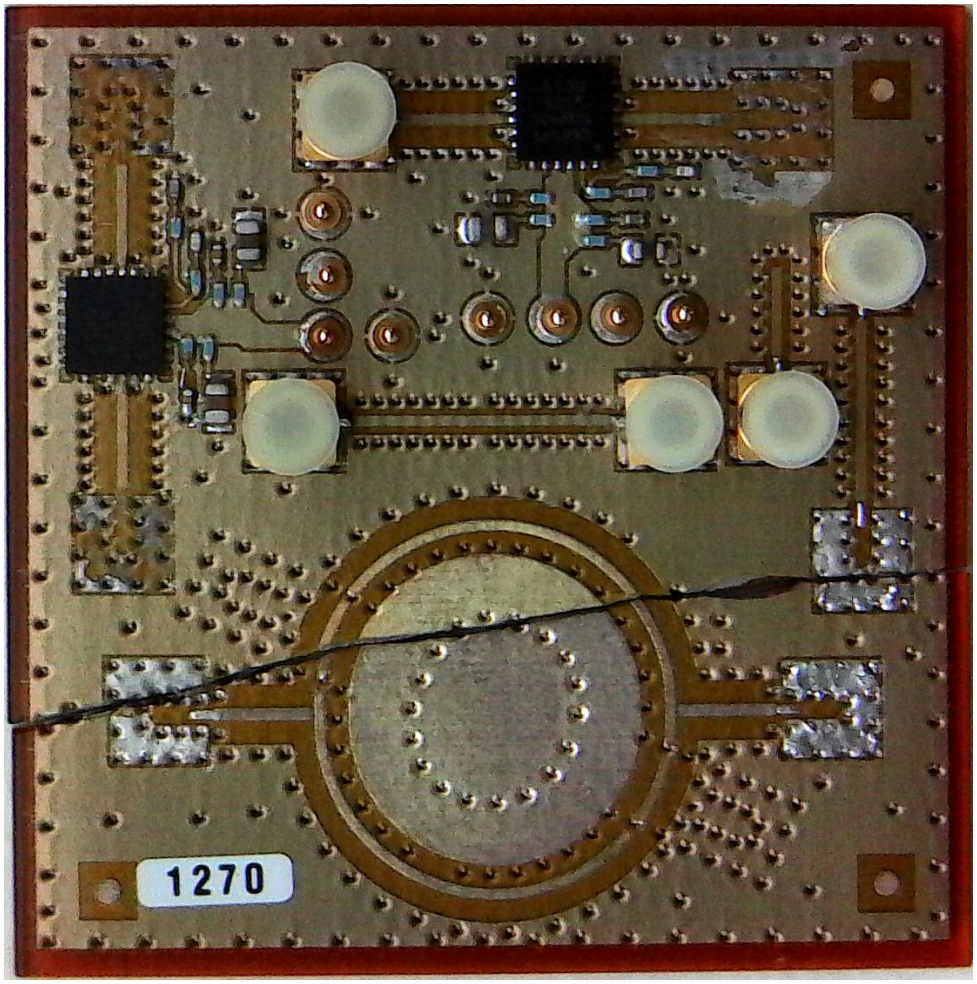
CHALMERS
UNIVERSITY OF TECHNOLOGY



Evaluation of emerging additive technologies for circuit board manufacturing

In production and development projects

Master's Thesis in Product Development

Gustaf Almquist

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Evaluation of emerging additive technologies for circuit board manufacturing

In production and development projects

Master Thesis Report

Gustaf Almquist

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Evaluation of emerging additive technologies for circuit board manufacturing

In production and development projects

Gustaf Almquist

Examiner: Eduard Hryha

Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Cover: Printed evaluation board after assembly and soldering,
More information found in the chapter on Evaluation Board Development on page 33.

Department of Industrial and Materials Science
Göteborg, Sweden 2019

Abstract

This thesis is focused on introduction of the state-of-the-art additive manufacturing process for circuit board manufacturing in the development process. Project was carried out at Saab AB during 2018 and is done in collaboration with the department for Industrial and Materials Science at Chalmers.

Focus of the thesis is to evaluate the possibilities and limitations of the recently developed manufacturing technology, that allows for additive manufacturing of a Printed Circuit Board (PCB). The technology was developed and launched by Nano Dimensions Ltd in the autumn of 2017. The additive manufacturing technology used is based on modified material jetting process that utilizes an ink containing silver or copper nano-powder in one printing head, and dielectric ink in other. This allows for simultaneous printing of both materials.

After printing, green part is cured at elevated temperature in order to sinter metal nano-powder and cure dielectric material. This is done by exposure to light from a photonic curing lamp after each layer is deposited. This allows to produce complex two- and three- dimensional circuit boards, providing the possibility to significantly speed-up process of PCBs development and prototyping. It also allows for manufacturing 3D PCBs, not possible with the conventional technologies.

Focus is on the evaluation of the performance of the PCBs, made by new technology, extensive characterisation of the microstructure of the PCBs, as well as defects and flaws that can affect its applicability. The results were used to estimate applicability of this technology at Saab. Product Lifecycle (PLC) for the PCBs made by this technology was evaluated as well.

Thesis also covers development of a method for evaluation of the new processes for PCB development following lean testing and qualitative methodology. While including stakeholders in the process and managing risks, it also discusses current state of additive manufacturing of electronics. For this purpose, an evaluation board was developed and printed using the new process. Unfortunately, the board broke during assembly, but material testing and inspections have given insights into the current state of PCB 3D-Printing.

Additive manufacturing of circuits and especially PCBs stand to develop rapidly over the coming years. Even at their current stage they allow to speed up development and allow for quick production of small series for production. Current limitations in additive processes limits its implementations but allows for rapid prototyping of low- to mid- frequency circuits. The technology shows promising results and potential to remove logistic bottlenecks, reduce waste and reduce the need for end of life purchase of components.

Keywords: additive manufacturing, material jetting, PCB, electronic development, prototyping process, DRL

Acknowledgements

Chalmers and my Examiner for allowing me the opportunity to conduct this thesis.

The PCB development department specifically and Saab in general for allowing me to evaluate an exciting new technology and even as a company first for a thesis worker travel to a big technology fair in another nation. Over the course of the thesis I have had helpful discussions with many engineers at Saab and would like to say that you all have been awesome!

Huge thank you to my supervisors at Saab, you helped me with the project and allowed me to utilise your large network to get into contact with experts within the different fields. Outside of my supervisors, two persons at Saab have stood out in the amount of help, to Åsa and Theofilos I say thank you, the evaluation board wouldn't be what it is without you!

A thank you to the management at Pluspole for allowing me to disturb your technicians and engineers with my questions, for mentioned people for answers and discussions. Also, thanks for allowing me to photograph parts of your production and prototyping setup.

A special thank you to Artem Roev, for explaining and showing how PhD students at Chalmers work regarding PCB prototypes, also, for showing some of the challenges that can arise from subpar manufacturing processes.

Nano Dimensions for supplying an evaluation board for testing and for answering loads of questions over email. Especially a large thank you to the representative from Nano Dimensions for answering every question I had over the better part of three hours and even taking time over lunch to do so, I appreciate your contribution.

Acronyms

AM - Additive Manufacturing
BOM - Bill of Material
CAD - Computer-aided design
CAM - Computer-aided manufacturing
CNC - Computer Numerical Control
CW - Continuous Wave
DFA - Design for assembly
DFM - Design for manufacturing
DoD - Department of Defence
DRL - Development Readiness Level
EDX – Energy Dispersive X-ray
FDM - Fused Deposition Modelling
FFF - Fused Filament Fabrication
HF - High Frequency
IR - Infrared Radiation
LS - Laser Sintering
MRL - Manufacturing Readiness Level
NFC - Near Field Communication
PCB - Printed Circuit Board
PD - Product Development
PLC - Product Lifecycle
RF - Radio Frequency
RM - Risk Management
RnD/R&D - Research and Development
RP - Rapid Prototyping
SEM - Scanning Electron Microscope
SLS - Selective Laser Sintering
STL - Stereolithography
TDB - Test Design Build
TLB - Test Learn Build
TFT - Thin-film Transistor
TRL - Technology Readiness Level
UV - Ultraviolet
VIA - Vertical Interconnect Access

Content

Figures

1. Introduction

The thesis is focused on the possibility of involving manufacturing processes in the development process. It was carried out at Saab AB during 2018 and was done in conjunction with the department of Industrial and Materials Science at Chalmers in frame of the Centre for Additive Manufacturing – Metal (CAM^2).

Background

Nearly all not purely mechanic manufactured products incorporate a circuit board in one form or another. Due to the complex structure of these Printed Circuit Boards (PCBs), their development cycle is rather complex resulting in a complex supply chain and long delivery times for manufacturing of the functional prototypes. In many other product areas, implementation of the additive manufacturing technology allows to significantly minimize delivery times that resulted in significantly quicker and cheaper development. However, as PCBs require complex material structure – conductor and dielectric materials printed with high resolution – such a technology was not in place until now.

In addition, due to the complexity of products being developed, companies working with research and development are increasingly faced with a demand for faster development of new products and services. Partly because of shorter product life-cycles but also because of global competition [1].

In order to meet these demands while ensuring quality, companies needs to explore new technologies and continuously work on improving their process. One way to speed up the development is by using simulations instead of physical prototypes. Another is to work on the process and use new tools and technologies [2].

An important part of most technical development projects is the transition from a breadboard to a PCB, both to show function and size. But it also gives an indication of performance and shows progress in a tactile way for developers to help them understand what is happening in the project.

Current processes for PCB manufacturing have a relatively long lead time or are not usable for multilayer applications. A large part of the lead time comes from waiting for deliveries from external manufacturers both for components but also boards. Even when external manufacturers can deliver products quickly, the act of sending intellectual property to external partners carries a risk for the company. Internal manufacture with alternative methods is seldom an option due to the process expertise and production volumes needed to economically make it an acceptable alternative.

Recent development in binder jetting technology allowed Nano Dimension Ltd, to develop a platform that allows the printing of advanced conductive and dielectric inks for manufacturing of high-performance multi-layer PCB prototypes. The first systems were delivered in the late summer of 2017 and machine has a build volume of 200*200*3 mm.

As it is the first additive manufacturing technology on the market when it comes to manufacturing of circuit boards, evaluation of the technology potential for novel design possibilities and

development of new products, possibilities and limitations of the technology and properties of the 3D printed PCBs are of crucial importance [3].

The usage of an additive process for PCB manufacturing might allow for novel design solutions and can most likely be used to reduce the time of prototyping in development of new designs. For example, if PCB boards manufactured by additive are viable, and does only require more time and material for extra layers and complex structures like copper coins and buried VIAs, then it gives complexity without adding additional costs from special manufacturing steps. It also enables in-house prototyping of complex boards with minimal spatial and manpower requirements, while protecting intellectual property from outside threats.

Some of the possible improvements in future machines might be to build in capacitors and resistors in the PCB, thus saving space, logistics and assembly costs. Preparing for and knowing when and how to use it gives an advantage in development time and cost. While many evaluations for visual and structural prototyping with additive machines have been carried out, and companies are using them to speed up development projects, to date nothing similar have been done for PCB prototyping.

LPKF have for many years-built prototype equipment for PCB manufacturing, lately they have started to include lasers to achieve tighter tolerances therefor enabling high frequency prototyping. They have also launched an additive process, adding conductive traces to 3D-structures [4]. This makes them a fitting example of alternative prototyping processes compared to Nano Dimensions.

Aim

The objective of the Thesis is to evaluate functionality and resulting material properties of the additively manufactured PCB compared to an ordinary production process. The work includes detailed characterization of the 3D printed PCB, characterization of its performance, cost estimation and environmental impact of the process as well as impact on the delivery time.

The objective is to evaluate and compare functionality and resulting material properties, between an additively manufactured PCB compared to an ordinary production process. In addition, the environmental impact of the new AM process, compared to the traditional process is investigated.

Project also aims to identify mechanical and electrical methodologies, to study and carry out material testing in real applications such as digital, power, analogue and high frequency, to analyse strengths and weaknesses regarding performance and durability. This will allow for the study to find how to integrate PCB prototyping in the development process, benchmark future technologies and involve engineers in process development.

Project aims to develop principles, methods and solutions to use the new process in conjunction with the current processes inside development projects taking place in the company, to form a basis for quick and efficient evaluation of processes, leading to informed decisions about new technologies in the future

Research questions

Research questions that were established before the start of the project:

a) Technical trends in PCB manufacturing by additive manufacturing

b) Principles for evaluation of alternative PCB manufacturing processes

c) Design and manufacturing principles of 3D printed PCBs

d) Usage of additive manufacturing of PCBs in product development

Limitations

The thesis will not include more than one evaluation card per process type, due to time and cost limitations. The reasoning behind is that the variance in the separate processes is smaller than between processes.

Due to time limitations, no full LCA will be conducted, only partial analysis of internal waste in the process and eventual toxic substances handled for the process or created during the process will be considered. This is partly to allow the thesis to be carried out in the timespan allotted, but mainly because these are the points a company aiming to incorporate the processes in-house, will have to consider.

One crucial limitation of the thesis was the limited time and effort spent, by the author, on creating evaluation boards. Focusing on processes and development, board design used was comparably simple. They also partly reused designs developed in other projects to save time.

While products from full scale production lines will be evaluated in the project, the focus will be on prototyping lines and not full-scale production. This is done mainly because the aim of the thesis is to look at processes used for development and not for volume manufacturing.

The rise of the maker movement and the tech start-up trend have resulted in a few alternative additive processes, mainly V-One from Voltera and Squink from BotFactory. These while mentioned in the final report will only be further evaluated in case of time and resources. The focus will be on professional processes resulting in finished PCBs comparable to those from manufacturing processes used for finished products.

2. Methodology

This thesis starts with a thorough literature reviews and interviews with subject matter experts to determine status and trends in additive manufacturing, complex electronic components including PCBs, recent PCBs development and manufacture methods.

Thesis compares and investigate how the use of the different methods proposed by Maylour and Wheelwright that sets the foundation of PD (Product Development) education at Chalmers. In combination with how current processes compare to the process proposed in LPD (Lean Product Development) and what parts of the process might benefit from new and alternative production processes.

Evaluations carried out in the thesis are based on the test to failure method from LPD to learn the limits of the different technologies and their applications. Platform and modularization methods like the Contact and Channel method was utilized, to identify and build test systems while maintaining easy to evaluate sub-systems, to save on number of boards while keeping test-features for evaluation.

The project started with looking at as many technologies as possible before grouping them together depending on defining characteristics, to make it easier to compare to each other. This was followed by collecting information about process, materials and use-cases to build a better understanding of the process, to build knowledge to bring to experts at a later stage to set base requirements used evaluating the gathered concepts. Input from stakeholders and lead users was used to refine the requirements during the project, allowing their expertise to fill in the gaps in the available knowledge of the processes.

To conduct the evaluation of new processes, a new method was created by building on existing methods used to evaluate related fields. The proposed method can be found in the theoretical framework in section 4.

Research approach

Following is a description of how information has been gathered during the thesis and how quality was assured. To guarantee the quality of sources used in the project the aim has been to only use the following type of material:

- Work published by government agencies such as NASA (National Aeronautics and Space Administration) or universities that disclose partners and sources of funding for the research.
- Articles published in credible journals after being reviewed and that have been cited in other works, lecture material and course literature from relevant courses at Chalmers University.
- Interviews with Lead-Users and experts from the industry conducted after informing them of the intended use of the information, and when the interview have been conducted a transcript has been sent to the interviewed person for review. This is to allow for correction of misunderstandings and to remove any sensitive information from the documentation.
- Information given by manufacturers will be used as a credited source after verification by testing it or cross referencing it with information given by other manufacturers.
- Finally, all source material used should be written in English and be easily accessible to allow for inspection and review of cited material.

First when no source filling these criteria was available, other sources have been used, and then only for minor parts of the thesis. When information must be gathered outside of literature available, a qualitative approach has been used since the time and resources are too limited for a quantitative study.

Ethics and environmental concerns

During an evaluation about using a new production process, it would be unacceptable to not investigate health and environmental aspects and how it will affect the operators and those around it. During the duration of a thesis it can only be done to a limited amount, but it is something I have taken into account whenever it was possible.

Ethics when it comes to methods and evaluations

It is interesting to reflect over the ethics of looking into ways for a defence company to work more efficiently, when developing new products. But the core of the thesis is to make all development more efficient, hopefully leading to better products but primarily less wasted resources. The more efficient the process, the larger amount of good can be done with a set amount of resources.

Putting my trust into humanity to work towards a better more sustainable future, I am only looking into how to evaluate and utilize new technology to reach there faster with less waste on the way.

One primary focus during the thesis have been to look at everyone involved and affected by the process to identify risks to health or environment. Things like harmful substances, work environment, waste and potential bodily harm, have been investigated and considered during the course of the thesis.

As a guide the IEEE code of ethics [5] , have been used, especially the following paragraphs:

> **§1:** "to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment."
>
> **§3:** "to be honest and realistic in stating claims or estimates based on available data."
>
> **§5:** "to improve the understanding of technology, its appropriate application, and potential consequences."

This has been used as the basis for the considerations done and the decisions taken during the project.

Environmental concerns as part of thesis work

As stated in the introduction, no full LCA was carried out to look at the environmental impact of using any of the processes. What was done is looking at available studies of health and environmental impacts from the materials, also, what hazards and concerns stated in the material declarations are available.

3. Theoretical framework

This thesis and report have been carried out at a high-tech company that develops new products using the latest technologies, this sets requirements at a higher level compared to a more mid-tech company.

Without a basic understanding of what a PCB is, how a circuit is developed, and which manufacturing methods are used to produce PCBs, it is impossible to follow the practical part of the evaluation. Hence the DRL method should also be usable for evaluating processes that are not geared towards manufacturing electronical products and should be understandable on its own.

Evaluation and rating methods

The problem of including new technologies and processes in a development project is that evaluation and rating methods focus on a finished product built on or with a new technology, not for usage within a part of a development project. To conduct the thesis, it became paramount to create a method that does this.

Before trying to create a new method, it was needed to build knowledge on available methods and how they are used. It was also decided that it would build on and include parts from established methods but try to create something useful for the specific case. One restriction, set to ensure quality is that all methods need to be tried, tested and recognised by companies around the globe that uses them. When this was found to be true, the methods were considered for use during the thesis. Following is a short description of the methods evaluated and used during this thesis.

Technological Readiness Level (TRL)

Launching a large project based on a promising new technology that at a later stage is found to not work as intended or fail to deliver the required performance, can lead to expensive redesign of a product in the later stages of development. If the technology shows to be unsuitable enough it can also lead to delays, sub-par performance or even cancelation of the project.

To reduce the likelihood of such a situation NASA developed the TRL method [6], it is a rating system that aims to allow for comparison between different technologies while helping with keeping track of progress. Used by both NASA and DARPA (Defence Advanced Research Projects Agency) to help with decisions regarding the inclusion of a new technology in a project or to start a project based on a new technology.

Following is the different levels as defined in Mankins white paper, with a short description of what should be reached to fulfil the requirements for that level [6].

> **TRL 1:** The most basic of principles observed and reported, this can be as simple as material properties. Scientific studies are transferred into applied research.
>
> **TRL 2:** Formulation of possible applications for the technology, it can still be speculative concepts of use with no supportive evidence but the possibility of using a certain property in an application needs to be there.

TRL 3: At level 3 analytical and experimental proof of critical function or proof of concept are needed.

TRL 4: Level 4 is proving functionality in a laboratory, either on a component level or a basic PCB/Breadboard.

TRL 5: TRL 5 builds on level 4 with moving the system to the real/representative environment with relevant support elements.

TRL 6: A representative prototype system tested in a representative environment.

TRL 7: To reach TRL 7 a prototype needs to be tested with or near the planned system that will be used in conjunction with the prototype.

TRL 8: At TRL 8 the system should function in the final system during expected conditions.

TRL 9: A technology reaches level 9 when it has proven full functionality when being used for its final function at operational conditions.

While called levels, the different stages of TRL can be seen as milestones for development of a new technology, because a technology will be at a certain level first when it fulfils all demands for that level.

Using TRL in practise means that the levels must be represented with actual requirements corresponding to the field of technology and the planned usage of the technology. The newer and more novel the technology is, the stricter the adherence to the method and the higher the requirements will be set.

However, as stated in the recommendations of the CECOM (U.S. Army Communications-Electronics Command) report [7]: "Much of the value of TRLs comes from the discussion between the stakeholders that go into negotiating the TRL value."

By sitting down with relevant stakeholders to discuss and negotiate the readiness level, it becomes a communication tool that hope to lead to a common understanding of the technology while removing personal biases from affecting the requirements and the perceived readiness.

Manufacturing Readiness Level (MRL)

Some spectacular failures have resulted from developing a product around a manufacturing process that is not ready for use. A situation that often arises from using immature or misunderstood manufacturing methods is the need to redesign the initial design late in the project to accommodate the usage of an alternative manufacturing method.

One example of a company struggling with having developed a product for a manufacturing technology that wasn't ready is Intel. Intel has been working on a manufacturing method that can create transistors on the 10nm scale since before 2014 when they released their 14nm based processors. They planned to release a processor built using that method as early as 2016, delays lead to an initial release during 2018 with scale production planned for 2019 [8] [9].

Manufacturing Readiness Levels was developed partly to reduce the risk of something like that happening but also to serve as a compliment to TRL. Since MRL is meant to complement the TRL method, MRL 1-9 can only be reached if the technology is on the corresponding TRL [10].

MRL was developed by Department of Defence (DoD) and is used extensively by NASA, DoD and DARPA to prevent the starting of a project that plans to use a manufacturing method that hasn't shown to be capable enough. Therefore, reducing the risk of delays due to redesign or even scraping of the project if the manufacturing technology fails to deliver [7].

MRL is a substantial framework for evaluating manufacturing methods. To fully represent MRL in an understandable way would take the majority of this report, hence the following is the MRL definitions as laid out in the MRL handbook released by the DoD [10].

MRL 1: Feasibility Assessment
Studies and laboratory work show a feasible concept.

MRL 2: Concept Defined
Identified concept shows capability of building a prototype part.

MRL 3: Proof of Concept Developed
Basic validation of the manufacturing technology, materials and processes have been characterized.

MRL 4: Laboratory Demonstration
Process assessed in laboratory with plans to deal with identified deficiencies, cost driving parameters found and realistic cost approximation for further development set.

MRL 5: Process Development
Enabling or critical technologies have been identified, process sequences identified, inspection, tooling and strategy procedures identified and are in development. Performance is demonstrated in production relevant environment.

MRL 6: Functional system or sub-system producing in process environment
Critical systems have been produced and tested in planned process environment. Testing carried out on a pilot line demonstrating function and giving insights into yield, reliability and costs.

MRL 7: System or subsystem production
On this level the focus is on proving the capability and initialising the six-sigma process. A plan should be in place to reach full production with targets and tracking for process parameters. Work on optimization and cost reduction should be on the way.

MRL 8: Pilot line production
Low Rate Initial Production (LRIP) ready process that is controlled to 3-Sigma, is established and data from test runs is used to update cost models and the yield analysis.

MRL 9: Proven process producing products
To reach level 9 the process must be proven to function fully at a low rate and be ready to scale up to high rate production. During the low rate production, it must be controlled to 6-Sigma standard or equalling rating system.

MRL 10: Lean production implemented on full scale production line
Proven process with well-developed Lean production practices. Development is limited to cost reduction and quality improvement measures.

Manufacturing Capability Readiness Level (MCRL)

MCRL Manufacturing Capability Readiness Level is developed by Rolls-Royce to introduce a new manufacturing technology at later stages of a product lifecycle to move production to the new process [11].

MCRL is divided into three phases and nine levels, what follows is a short description of both phases and levels according to a report published by Rolls-Royce in 2011 [11].

Phase 1
Assessment and evaluation to show function, proving the basis of the technology and includes level 1 – 4.

MCRL 1: Concept proposal
MCRL 2: Validity demonstrated
MCRL 3: Proof of concept
MCRL 4: Laboratory validation

Phase 2
Preproduction consist of levels 5-6 and is focused on creating an operational production line.

MCRL 5: Functional production on the equipment
MCRL 6: Process optimization for maximum production rate

Phase 3
Start of production contains level 7 – 9 and is the introduction of the technology into actual production.

MCRL 7: Builds on level 6 but requires sustainable production with economic output and with no major changes to the process.
MCRL 8: Ramp up to volume production
MCRL 9: Volume production with extended production runs, all requirements needs to be meet and the manufacturing technology is ready for full scale use.

Risk Management (RM)

During a project or around a business there will always be risks. Managing those risks is important to ensure both a safe conduct, but also the continued profitability of the organisation. Risk is often considered something more physical like an accident or a fire. Risk in a business consists of many aspects. The risk of missing out or to be left behind is one of the driving factors behind this study and a risk that often is overlooked.

Including new manufacturing processes or new technologies in a project is a risk. To manage this, risk management was introduced as a tool included in business planning. Following is how risk management is defined by NASA in the Risk Management Handbook [12].

$$RM \equiv RIDM + CRM$$

As stated in the Risk Management Handbook by NASA, "Risk Management as the Interaction of Risk-Informed Decision Making and Continuous Risk Management"

To work with RM, a continuous work with both Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM) is needed, were one goes into the other in a never-ending loop. But to do this and still be effective in moving the project forward, is where the challenge begins. Following is how RIDM is defined by NASA in the Risk Management Handbook [12].

Risk Informed Decision Making (RIDM)

Part 1: Identification of Alternatives
Find and identify alternative solutions and opportunities.

Part 2: Risk Analysis of Alternatives
Analyse the risks of the different alternatives as part of setting up the technical requirements.

Part 3: Risk-Informed Alternative Selection
Evaluate alternatives according to risk and reward followed by selection of the best alternative after careful deliberation.

Continuous Risk Management (CRM)

Step 1: Identify
Identifying and capturing risks is done by finding perceived risks the stakeholders have and collecting those with their conditions in a database.

Step 2: Analyse
Analysing the risks collected into the database with focus on how likely they are and what ramifications will follow. This is done to rank the risks against each other to allow focus to be put on the most imminent and critical risks first.

Step 3: Plan
Setting up a plan for how to handle and mitigate the different risks going forward in the project. There are five categories of actions that can be taken in the planning stage and those are: **Accept** the risk, work actively to **Mitigate** the risk, **Watch** the risk continuously, continue **Research** into the risk, **Elevate** the risk to a higher threat level or deem it unimportant and **Close** the risk file.

Step 4: Track
Risks are not static, and the tracking face is used to continuously look for how the work with risk management is going and to re-evaluate the risks being monitored. This can be reclassifications of old risks and introduction of new.

Step 5: Control

Should the tracking step indicate that the work with mitigating a risk isn't performing within an acceptable level the control step includes actions to assure that the planned action is successful. This can be extra resources or moving it to people with higher permissions. After a control action a risk will need to be re-evaluated on the planning stage to better handle it in the future.

All steps and actions depend on proper communication between all involved stakeholders and documentation of the steps, plans and actions.

One of the most important things to understand with risk management, is that in order to move forward, a business needs to find acceptable risk levels for operation and go forth, while doing the best they can to systematically mitigate the possible fallout. To not take any risks at all, leads to stagnation and obsolescence and that is a risk to the entire organisation. In the introduction to this report the risk related to being behind in development processes was mentioned as a prime example of why investigating and evaluating new technologies and processes was important to be competitive.

To summarise this chapter, it is important to emphasize that the risks associated with being left behind needs to be balanced with the risk associated with being in the forefront of technology. This should be done while working with minimising the fallout of an accident and the chances of one occurring.

Summary and conclusion on available evaluation methods

The problem of including new processes or technologies into a new project is something that has been studied a lot and methods to mitigate the risks are already developed and tested. The problem for both TRL and MRL, are that focus have been on having a new technology in the final product or use a new method for producing a product and not looking at including it at a stage of the process while having the option of leaving it in or out of the final product. MCRL investigates replacing an existing process for an existing product using the foundation and thinking of MRL. Risk assessment has been built around this and can be used to mitigate the risks that come from using an unfamiliar technology or method in a project.

The lack of a process for evaluating manufacturing processes for usage in development projects lead to the combination of method to show TRL during a project, it is described in the **Development Readiness Level (DRL)** chapter.

Development process and workflow

A short summary of a few product development processes and how they work with prototypes.

Agile Development and Scrum

Since many companies have started working with Agile methods for product development outside of programming, it becomes interesting to see the difference between the different fields that is programming, mechanical and electrical development. Developed for programming projects and workflows, Scrum focuses on short cycles or sprints to rapidly create core functionality that can be tested and verified, creating the basic functions while programming and going from there to create a final program only containing what the customer needs [13].

Scrum is built around Scrum Teams working in Sprints to complete tasks in the product backlog. The Team is built around three roles while the process has five main steps. Following is the three roles in a Scrum Team and the five main steps of the process according to Jeff Sutherland's Scrum Handbook [13]:

Scrum Team

1: **Product Owner**
The Product Owners role is to identify product features that the customer wants and prioritize among them, so the Team can work on the most important features. Interactions between product owner and the Team is personal were the Product Owner looks at the progress of the sprint and relays the most important features to the Team. Prioritising and deciding on features are solely the domain of the Product owner.

2: **Team Members**
The Team is a cross functional and self-organising team consisting of between five and nine persons. Developing the features prioritised by the Product Owner by dividing it into tasks and committing to solve those tasks within each sprint.
The Team does its own testing to build knowledge on what works and how to improve the product.

3: **Scrum Master**
The Scrum Master serves the Team and works to provide whatever the Team needs to succeed in their task. One additional task is being the layer between the Team and distractions like the Product Owner wanting to swap some prioritized features during a Sprint.

Scrum Process

1: Product Backlog
The Product Backlog is created and maintained by the Product Owner. It can contain a multitude of tasks from solving a problem and creating a feature to research and correcting an old mistake. The Product Owners role is to identify product features that the customer wants and prioritize among them, so the Team can work on the most important features in the Sprint.

2: Sprint
A Sprint is a work period of between one to four weeks within which the Team does the development work with no alterations to the Backlog. Team members commit to solve tasks and works towards completing the backlog during the set time period.

3: Sprint Planning
At the start of a Sprint there is a first Sprint meeting, it involves everyone in the Sprint team, the Scrum master and the Product owner. In the first meeting the features in the Backlog are discussed with a focus on their context and requirements. Then the Scrum Team selects a few features they commit to complete during the Sprint. Following the first meeting is a second meeting were the selected features are divided into tasks to be completed.

4: Daily Scrum Meeting
During the duration of the Sprint the Scrum Team has a daily meeting to update each other on the current situation. The meeting is done standing up and should not take more than fifteen minutes.

5: Sprint Review and Retrospective
Following a completed sprint, the completed features are committed and presented to the Product Owner during a Sprint Review. During this review the Team and the Product Owner discuss what have been done and what's next. After the review the Team gathers for a Sprint Retrospective to go through what have worked during the Sprint and what needs improvement before the next Sprint.

Even if Scrum started out as a development process for programming, today Scrum is used for entire development projects. This demands collaboration between disciplines in teams tasked with delivering something to test or to test on after a short sprint. It is easy to build and test code using simulations, evaluation boards or even on the final system.

However rapidly delivering iterative prototypes of mechanical systems takes longer time since the computer designed and simulated parts needs to be manufactured before testing. Comparing the time, it takes to compile some code for testing, to manufacture components by 3D-Printing polymers or metallic for testing, the time needed for the latter is significantly larger. Even if 3D-printing mechanical structures allows for quick or rapid manufacturing of mechanical prototypes it functions on timescales of hours, not minutes like the compiling software. Add to that the need for assembly and cost inherent to additive manufacturing, and the mismatch between the two becomes apparent.

Electrical prototyping is in many cases the link between programming and mechanical engineering, making a system a functioning mechatronic component. The big difference between making electric prototypes and mechanical ones, is the need for special components with lead times, add to that the time it takes for a PCB to be manufactured and delivered and it can take even longer time to iterate an electrical prototype compared to a mechanical.

The core idea of Sprint is to rapidly develop something and then test it, to learn from it before doing another iteration to add extra features. This requires a rapid prototyping approach to keep within the mandated Sprint cycles.

Lean Product Development (LPD)

Lean Product Development is a development method developed by Toyota. The foundation of the method was built on the way the Wright brothers developed the first airplane and today it has become one of the dominating methods when it comes to product development.

Lean is often described as a toolbox, and both the tools and the usages vary between different companies. In this thesis the focus has been on how and why it was implemented at Goodyear and Harley Davidson. Their available material has been used as the primary sources of information about the methods. Further focus was put into Knowledge based product development, The Swirl Model, set based development, Trade of curves and the Test to Failure method. Following is a short description of the parts of these methods and tools used in this thesis.

Knowledge based product development is an adaptation of Lean done by Harley Davidson, where the goal is to find the best alternative to develop further. This is done by gathering knowledge from many different possibilities in a process called "concurrent engineering". This leads to the final decision to what will serve as the final solution being postponed until enough knowledge is gathered [14]. The reason this is important is that at the beginning of a development cycle a lot is unknown, both about the technologies but also the market and what the customers' demands. Hedging your bets instead of going all in on one solution until you have a clear indication of what will be the winning solution.

Using an LPD method for testing called Test to Failure [14]. In contrast to Test to Specification, Test to Failure searches for the point when something breaks or fails to fulfil its purpose. This means that each test is more extensive and therefore more expensive, but should the requirements change and therefor the specifications, no new tests need to be conducted. Testing to Failure have the data for the possible design space readily available while a new test to Specification will be needed to attain that knowledge [14].

The Test to Failure approach goes into the Test Design Build (TDB) cycle of LPD and Test Learn Build (TLB) cycle of Norbert Majerus. Both focus on start with testing to learn what you don't know before starting on any design work [15]. This contrasts with the older standard Design Build Test (DBT) cycle used in many development methods.

One example of the difference between Test to Failure and test to Specification used by Harley Davidson [14], is testing an engine with fuel containing 30% ethanol because of Brazilian regulations allow for that specific mixture, compared to running a full test series mapping the range between 0% and 100% ethanol. This would give knowledge no matter the ethanol content of the market, without additional testing. This is often used in conjunction with Trade of curves that is a tool to visualise the available design space and trade-offs between different solutions. Plotting them in a dual axis graph is done to show how they compare depending on two attributes.

One description of how ideas and suggestions transition from a simple idea to a project or change in the organisation is the Swirl model. In the Swirl model ideas, concerns and possible solutions exist in a Swirl. Inside of the Swirl they are discussed and debated before fading away or rising towards the top. This process can take years but when they raise through the Swirl, they are both in the awareness of the organisation and driven by an individual or group that believes in it and wants to carry it further. At this stage, the idea needs to pass a filter made by upper management. Nothing should come as a surprise to management and any suggestion reaching the filter stage

should be well thought out with answers to questions to why they are needed and what the root cause of the problem is [14].

Waste is a common theme when it comes to Lean but instead of focusing on wasted movements, etc. LPD focuses on wasted ideas, knowledge and time. Not using the full capability of all employees is a huge waste when it comes to an organisation's human capital. According to Norbert Majerus there is a core group of inventors in a successful R&D organisation that interacts with each other and stands for a disproportionally large part of all development within an organisation. One additional observation was that identified inventors need to have the possibility to invent or they will regress to a similar output as an average employee [15].

Waiting is the largest of the eight wastes in research and development and often there is no cost associated with it. To put a cost on waiting time Goodyear introduced Cost of Delay (COD) as a measure to translate waiting time into a cost in dollars. When looking at waiting as a cost and being able to compare it to the investments needed to reduce the waiting time, the problem becomes easier to confront and solve [15].

One additional waste is the reinventing the wheel that is done due to forgotten knowledge. It can be knowledge leaving with employees when they leave the organisation or hidden in a cumbersome data management system that makes it easier to relearn than finding it again.

4. Development Readiness Level (DRL)

Looking at the evaluation methods available for analysing new technology and manufacturing methods, it is clear that they focus on including new technology in projects only when they are fully developed and are considered for final production.

Unless the technology evaluated for adaption into the development process is developed in-house, any new technology will be at one of the higher levels of TRL when it is made available for the development team.

Implementing MRL and using the process with all its stages and steps designed for the DoD and projects on the cutting edge of technology, is a monumental task. If it can be scaled down to fit to the size and complexity of the situation, it becomes useful even for evaluating technology for inclusion in the development process. This is similar to, what happened when MCRL was developed to facilitate the move from one manufacturing technology to another, but instead of moving the finalised product between technologies it looks at how different technologies can be used at different stages of development.

Combining parts from the different methods to make a method to use both during the thesis and as a proposed method for continuously evaluating new manufacturing technology in the future. This was done following the knowledge-based product development core idea, that instead of early putting all money into developing one idea that seems to be the most promising. Spend some money on investigating many ideas and commit to one idea only when you know it will work.

Definitions

Like in the MCRL method there are three phases of DRL, they are shown in Figure 1 as an iterative stage gate process. DRL tries to involve people in searching, testing and evaluating so their ideas, knowledge and experience can be used to help guide the company forward.

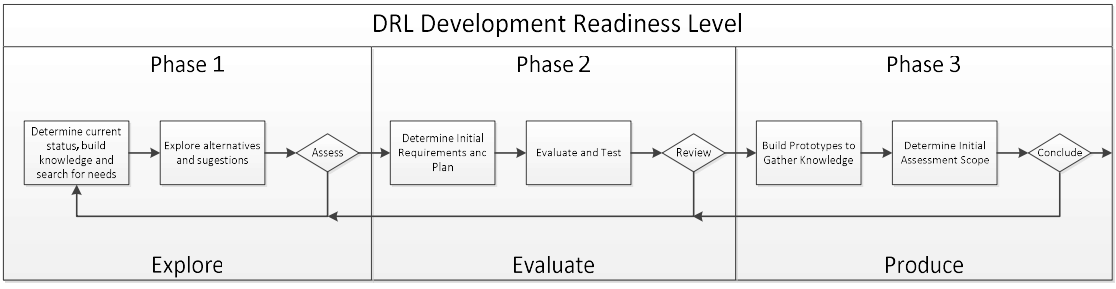


Figure 1: General overview of the proposed DRL method

The advancement along the levels can be seen as a climb up a ladder and building on the Lean philosophy. The climb up the ladder should be communicated to and with all affected parts of the organisation.

Phase 1 - Explore: The goal of phase 1 is to identify needs and possible solutions, it can be seen as a pre-study. With the final aim of only going forward with technologies showing a great deal of promise for expanding the capability of the organisation.

However, it needs to be stated that the amount of information needed varies with the goal. To start phase 2 with the goal of reaching DRL 6, it starts when a possible solution being assessed show promise of reaching MCRL 7. While if the needs correspond to DRL 5 it can start when a process have reached MCRL 5.

Phase 1 should be part of the work with continues improvements within the organisation and people should be able to partake while continuing their ordinary tasks. It is a continuous and iterative phase that builds on learnings from earlier projects and iterations, it does not need any specific source but should be done by everyone in an organisation.

In a way Phase 1 is operating as the funnel in the product development process proposed by Ulrich & Eppinger in the way that it gathers information from a wide pool of knowledge within and outside the organisation and funnels it towards a decision point [16].

The entirety of phase 1 and the first level of phase 2 is also a formalisation of the Swirl model with the gate moved to an earlier stage.

> **Level 1:** is reached after evaluation of existing needs found after looking at work flow and asking people working at different stages what they think is bottlenecking the process. When the status is known and measured then it is time to explore alternatives on how it can be solved.
>
> **Level 2:** Level 2 is the process of searching for possible solutions to investigate further. It can be seen as reached after alternative solutions to the problems and discrepancies identified in level one has been found and thoroughly discussed between different stakeholders.
>
> **Assess Gate:** Up until this point a low amount of time, effort and resources should have been put into both looking at the problem and for finding possible solutions. To get past the gate a clear and concise picture of the problem with the reasons why it exists and why it is a problem needs to be presented, together with a simple plan for time and resources needed to conduct phase 2.

Phase 2 - Evaluate: Phase 2 begins when management think that a technology shows enough promise to be investigated further. To get to this stage will often need a sponsor since now personnel work actively on evaluating the technology, this means that it will use resources that could have been spent on other projects. The focus of phase 2 is like in phase 1 about finding information, but now the effort is done actively with a budget, set goals and the aim of delivering a report for evaluation at the review gate.

> **Level 3:** Finding the requirements needed to assess a technology can be as tricky as discovering the need for change. By finding stakeholders and experts the usage of focus groups or other tools can use the experience to set objective requirements and details for evaluation.

One way to find requirements and gaps in knowledge of a process is to reuse requirements from real stages in the process but only if they correspond to something real and quantifiable.
Reach out to process owners to gather what data can be found without investment and survey the possibilities for testing.

Level 4: Level 4 is the stage when the technology starts to be tested in a more practical way. What needs to be evaluated and possible ways to do it should be set at level 3 but there is the possibility to adapt the evaluation to changing circumstances.
Test on hardware, according to the test to failure philosophy to gather the needed knowledge. This is done to get a good measure of how the technology corresponds to TRL and MRL but primarily to see the limits and how they correspond to the set requirements. After testing the results needs to be review and presented to the stakeholders to either be passed to the review gate or iterated on. This process of test, review, and redesign should continue until enough knowledge have been accumulated and builds on the test, learn, and build cycle of Norbert Majerus.

Review Gate: To pass the review gate the technology needs to be well understood with few or no unknown properties, it should also show a real promise to improve the internal development process.
Alternative outcomes are halting of the evaluation process or a restart at a previous level. The important part is that knowledge is shared and stored in a usable way.
Should the technology pass the review gate the next step is to acquire access to the technology to allow for development teams to make use of the technology.

Phase 3 - Produce: Phase 3 begins when a new technology has been introduced to an organisation and has started to be used for prototyping by development teams.

Level 5: means that the process can be used to produce prototypes for at least TRL 4 verification and should be made accessible for development teams to build knowledge and evaluate the technology further. At this stage development teams needs to be made aware of the new technology, the limitations and advantages. Active encouragement might be needed for the teams to use the technology in order to continue building knowledge to allow for further advancement of the process.

Level 6: is reached when the process has shown MRL 8 and the process can be used to manufacture subsystems for the final product in a relevant production process.
At level 5 a sufficient knowledge base should have been built to quickly do an MCRL and MRL evaluation to use the new process in conjunction with or to supersede the old process. Findings should be summarised and presented to management to decide on future implementation.

Concluding Gate: Borrowing from Scrum and other iterative cycles the conclusion is reached when the project is done, it is used to evaluate the process and how the project was carried out. This is the stage when the people involved in the process come together and try to find what went wrong, well and how it can be improved for the next time. It also the stage when a report for upper management is finalised and when the project with its findings is presented to the organisation. The report should not come as a surprise to

management and all stakeholders need to have been involved in the process to build awareness and support.

Usage of the DRL method

Using the DRL method before and during the beginning of the thesis that would correspond to Phase 1 was not an option since the method came about during the thesis. However, the process leading up to the thesis resembles Phase 1. A second note is that the thesis only conducts the first iteration of phase 2 not including the review gate, leaving further iterations and phase 3 unexplored.

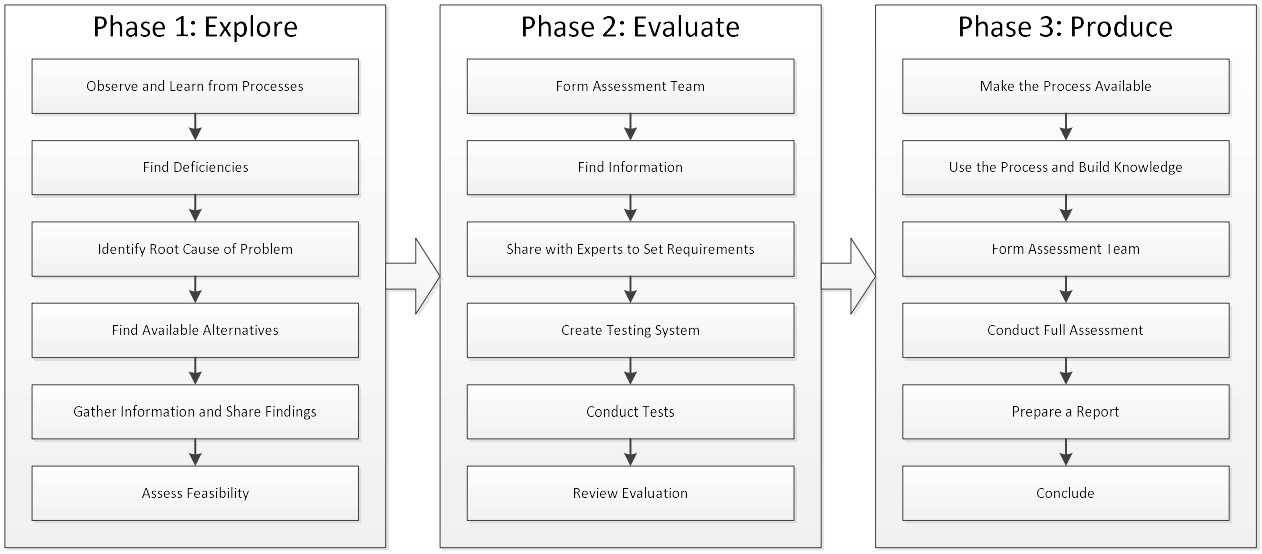


Figure 2: Detailed overview of the different stages of the proposed DRL method

Following parts of the project follows the proposed DRL process and can be seen in an alternative form in Figure 2.

5. Evaluation of PCB prototyping methods and their materials

Even if Phase 1 of the proposed DRL method was conducted and approved before the beginning of the thesis, a short summary of the most interesting, of the identified manufacturing methods will be presented, followed by the materials used and implications of how those materials affect health and environment.

Manufacturing methods

During the beginning of the thesis several possible manufacturing methods were briefly examined. Following is a brief description of the methods and the technology that goes into them.

Material jetting

In material jetting both conductive and nonconductive Inks are used to build a multilayer PCB layer by layer. The chosen manufacturing method used as an example of material jetting is the Dragonfly 2020 Pro produced by Nano Dimensions [3]. Following is the specifications and technologies specific to the Nano Dimensions printer.

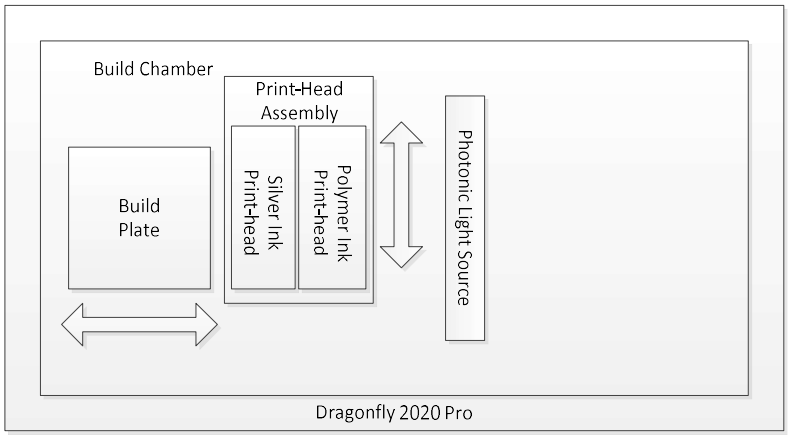


Figure 3: Dragonfly 2020 Pro Internal Layout

Internal core components of note, when it comes to the Dragonfly are the Print-Head assembly and the photonic light source. These are the components that in combination with special materials make the printing of a PCB possible.

The heated Build plate moves back and forth below the print heads to allow for material deposition before entering under photonic light source allowing for photonic exposure, partly sintering the silver and curing the polymer. This is done by exposing the materials to short burst of a certain wavelength of light causing the solvent to evaporate and the Nano material to sinter [17].

The Print-Head assembly consist of two sets of Print-Heads, jetting both the conductive and the nonconductive Ink needed to build a multilayer PCB.

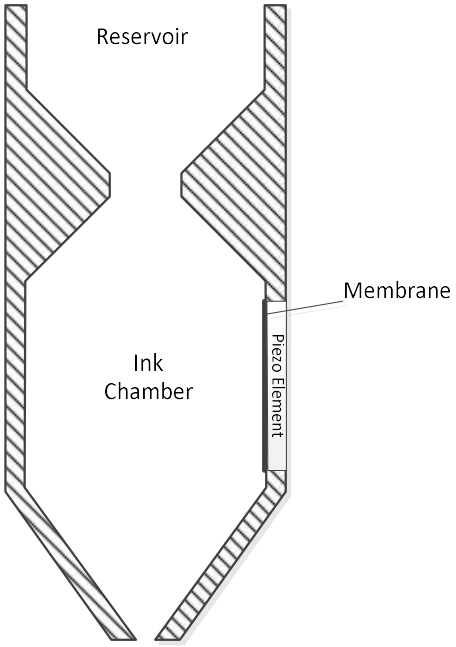


Figure 4: Model of a piezoelectric printing nozzle

The Print-Heads build on piezoelectric printing nozzles that eject a droplet on command by operating the membrane on the Piezo element. This is the same principle that is used in Piezo Drop on Demand inkjet printing which is widely used in computer printers.

The Print-Head assembly deposit one layer of material on the print bed that continues in below the photonic light source, were the inks are cured creating one solid layer.

Etching

Following is a short summary of the etching process for manually manufacturing PCBs as described by MEGA Electronics, it is slightly different from a full-scale production line but builds on the same principles [18].
Etching is done on laminates with conductive material sandwiching a substrate, often with a photo resist pre-applied. For simplification the process of etching copper will be used as an example.

After designing the layout, a negative need to be created. The negative is used to transfer the layout to the laminate by using an UV exposure unit and either harden or break down the photo resist on the board.

After exposure the board needs to be immersed in developer fluid to remove unwanted photo resist and allow the etching fluid access to etch away unwanted copper.

Etching fluid, normally Ferric Chloride is used to etch away the copper using the following chemical reactions:

$$FeCl_3 + Cu \rightarrow FeCl_2 + CuCl$$
$$FeCl_3 + CuCl \rightarrow FeCl_2 + CuCl_2$$

This process leaves Ferric Chloride, Ferrous Sulphate, Cuprous Chloride and Copper Chloride as waste products from the etching process. These chemicals need to be sent to a waste treatment facility.

After etching the board needs to be rinsed and leftover photoresist removed by a cleaning process and any eventual holes needs to be drilled. The drilling process does as in milling release particles from the board and the substrate that might need to be filtered.

For more than two layers, boards are stacked on top of each other with pre-fab materials in between before being pressed together while applying heat. Additional steps for VIAs to connect the different boards are also needed.

TFT Circuits

TFT circuits are made by printing conductive Nano silver traces on a thin film that in many cases are made of PET to create the layout on the thin film before photonic curing is used to sinter those traces leaving a functional circuit. Additional steps to add semi-conductive layers can be done to print entire assemblies [19].

External manufacturing

Instead of using an internal resource for manufacturing, it is possible to use an external supplier. Using an external supplier to manufacture evaluation circuits gives access to all previously mentioned methods and even full-scale production lines. Advantage of using this approach is that, having focused on what they are good at, leads to mastery of their techniques.

One alternative to have an internal prototyping line is to work closer with a PCB manufacturer This method is in many cases recommended, especially in the supply network of Lean Production, since it lets experienced suppliers make small series of the prototype with the same material and manufacturing method of the final product.

Production line at PCB manufacturers vary in capability and quality, but what these lines have in common is the size and need for skilled workers. Then again, the supplier of prototyping board does not have to be the same supplier as the one that produce the final product, even if using the same supplier allows for prototyping using the same manufacturing technique as the final product. However, involving an external supplier adds some things to consider such as working conditions at the supplier and waste disposal.

The risk associated with using an external manufacturer is connected to the loss of control over intellectual properties and the risk that comes from sending vital information about products in development to another party.

Summary and selection of method for further evaluation

Production size, both in actual board size and in numbers limits what methods are applicable for different projects. The prototyping lines and machines considered in the study have a relatively small maximum board size compared to full scale production facilities.

When it comes to volume production, of circuit boards running on the prototyping lines, is not an option and here comes an important question for the end of phase 1: Will it only be usable for small scale production, like prototypes or can it be usable for serial production?

Even if a process only is usable for small scale prototypes, it is a step up from not having any process for prototyping at all, so it can be advantageous to investigate further. To summarize the initial chapter on manufacturing methods, the method chosen for further evaluation was Nano Dimensions Dragon Fly. This is because the printer produced by Nano Dimensions is the only printer for PCBs available on the market.

Materials for Additive Manufacturing, their properties, health risks and environmental impact

Additive manufacturing of PCBs is new and to understand the challenges and limitation a basic understanding of the materials used is needed. This is because material properties in conjunction with the process set the technical limitations for the properties of the final board.

In the same way as when it comes to PCBs, it is not only the materials going into the final board, but the materials used during and around manufacturing, needs to be taken into account when evaluating the materials and any possible environmental impact they might have.

Materials used for additive manufacturing of PCBs

In additive manufacturing the challenge for printing with two or more different materials is that adhesion can suffer if the thermal expansion and curing temperatures are to different. If they do not match, the print will risk failing.

PCBs have conductive and electrically isolating materials. When it comes to printed conductors the most common material is silver in the form of nano-particles that is delivered in paste, powder or Ink form. To prevent particles from clustering together and to ease application while preventing oxidation, additional chemicals are added to the inks and pastes. When it comes to the nano silver ink, a solvent is added to both, keep it from clogging, but also to give it the correct viscosity for printing. It can also be used to prevent particles from spreading in the air. Additionally, the size of the nano-particles affects the melting point and therefore the curing temperature [20].

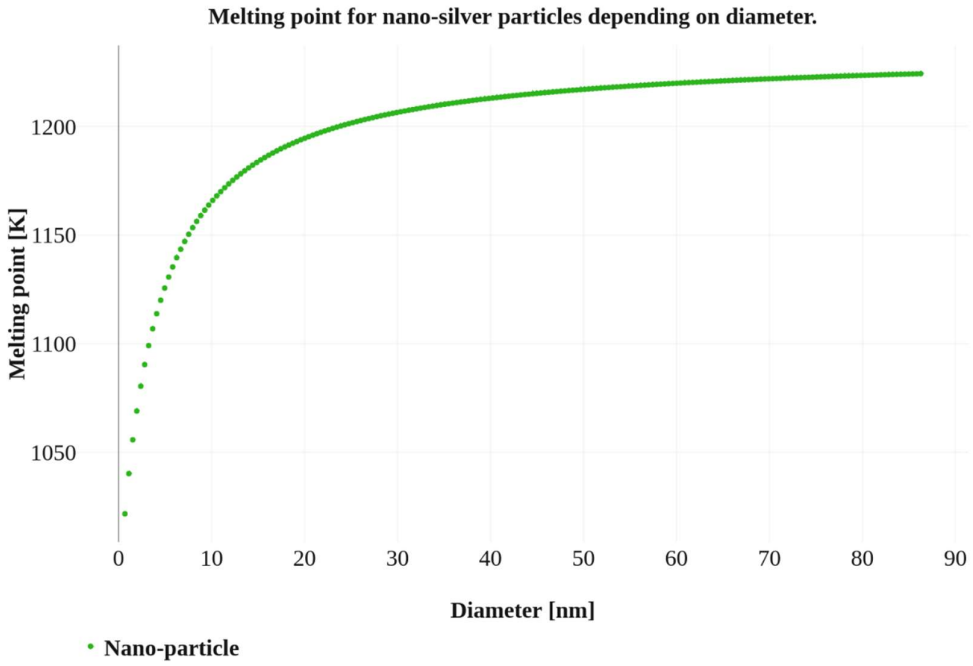


Figure 5: Melting point of nano-silver particles depending on diameter. Source of data VSParticle [20]

One alternative material for printing the conductive traces is copper, but due to the risk of oxidation in the absence of a protective atmosphere, it will need a protective atmosphere during printing, as stated in the interview with a Nano Dimension Representative [21].

Present literature on photonic curing of nanoparticle silver inks shows that silver nanoparticles have wide spectra absorption rate of almost 90% between 200-800 nm with a noticeable dip to 65% at ~330 nm [22]. It also concludes that photonic curing, most probably is connected to the solid-state sintering processes.

The limiting factor for both conductivity and curing time is the maximum temperature tolerance of the substrate. With higher temperature the curing time goes down and the conductivity increases.

Health

Considering the health impact of using one technology over another is for the largest part outside the scope of this thesis, but there are some factors that need to be understood when evaluating processes for PCBs that have been investigated.

This is normally part of the risk assessment done before introducing a new process but for simplification of evaluation, only physical health has been investigated, mental health has been left for future evaluations.

Exposure to harmful substances

Any operator working with traditional methods for producing PCBs will be exposed to the risk of encountering harmful substances. Therefore, it is important to read the material declaration for the material and chemicals used in the process. This should be done to understand the risks involved and put appropriate safety measures into place.

Etching is for example, done using an acid, in many cases ferric chloride. Milling on the other hand, has some risks because the standard substrate, that is called FR4, is a glass-reinforced epoxy laminate. When milling and drilling it is possible that small particles will be released into the local atmosphere and leads to a risk for operators in the vicinity.

When it comes to 3D-printed electronics, the conductor is normally made using nanoparticles of silver. While studies done on rats show no genetic toxicity in the bone marrow in vivo caused by exposure to nano silver, but it indicated that inhaled nanoparticles are systematically distributed in mammalian tissues [23].

The ink used in the Dragonfly 2020 is a product delivered by Nano Dimensions and they did not release a full material declaration for this study, therefor another ink was studied instead. Since the composition of Nano Silver Inks differ between manufacturers and application, it will not be the same as using Nano Dimensions ink, but it is the closest alternative available. The differences between inks are the size of the particles, different concentration and alternative non-declared additives like solvents and flux.

Nano silver particles are used in sportswear to reduce odour and have medical use in hospitals, but the wide usage of silver nano-particles have raised concern for future health and environmental impact. Evaluation of environmental concerns is done later in section 5.2.3, Environmental concerns. Looking at the current state of research when it comes to the potential health hazard of silver nano-particles, it is evident that there can be a potential risk from particles entering the body from air or liquid suspensions [24].

Risk of physical damage

When it comes to manufacturing methods it is not unlikely that they involve high voltages or currents, moving parts, heavy loads, chemicals and lasers. Analysing the risks allows for the creation of an education program for operators to be put into practise. This reduces the risks for physical damage even if it does not remove it.

There are also the operations during installation, service and repair that needs to be considered to create a safe working environment. In the case of the Dragonfly printer, everything is enclosed and there are security measures in place to hinder the operator from operating the machine should the enclosure be breached.

Etching using acids leads to the risk of physical damage to operators from contact with the acid. The automation of processes removes some risks for an operator, like the handling of hazardous substances but the automated machine can be a risk for anyone around it. No matter the precautions and steps taken to keep people safe, the risk of harm will not disappear, only lessen.

Environmental concerns

While small local emissions at the first stage are a concern for operators working with and close to the machine, waste and emissions from different stages of the production process risk ending up in the environment.

Handling waste with care and disposing it in the correct way limits the amount released into the environment from the process, but knowing what can happen and how it will affect the environment is critical for any risk assessment and implementation planning carried out before incorporating a new technology in a company process.

Focus of this chapter was placed on nano silver ink, how it is manufactured, and environmental concerns connected to Nano Silver Particles being released into the environment. Only looking at one of the materials and its impact on the environment if it finds its way out into the environment is not a sufficient pre-study for implementing a technology on a larger scale, it would be needed to also look at sourcing the material and process steps needed to have a usable material for production of all materials used in the process.

Environmental impact of using the different processes from an LCA point of view have not been a focus of this thesis, what have been investigated is the local impact during production when it comes to chemicals, fumes and waste. Some have been mentioned in the chapter on health, but that is a local perspective focusing on human health especially that of the operators of any production process.

The Long-term Environmental impact of Nano Silver Particles is unknown, but studies carried out show little in the form of harm and legislation limiting emissions are still in the drafting stage [24].

One thing that affects the environmental impact is the recyclability of the finished product. The trouble when it comes to recycling circuit boards is the amount of different chemicals bonded together in a small unit, for example: substrate, pre-fab, VIAs, conductor, solder mask, silkscreen, plating, solder, adhesives, thermal compounds and components [25]. Adding to this that the board, often is mounted inside a casing, sometimes bonded with adhesives or inside a locked enclosure, then recyclability becomes a complex issue. This is something that must be considered when evaluating a manufacturing method and it will be especially important for anyone planning to use a new manufacturing method for production of a commercial product. However, due to the limited time of this thesis this was not considered in detail.

6. Evaluation Board Development

Developing the testing hardware followed a standard procedure found internally at Saab but the information gathering process used to find requirements is described in the chapter on DRL and is shown in Figure 1.

What to test and how to test it

Identification of Lead users and Stakeholders

Identification of lead users was done by sourcing the internal structure of Saab for experts from different fields. Additional external lead users were consulted to get different viewpoints on how PCB development can be done. Some external input was also used from engineers working in a smaller organisation for another market. Also, hobbyists doing electrical circuit development on their free time was interviewed to get a feeling for how they go about PCB development.

Internal lead users found by sourcing the departments and divisions developed over time by process experts. This led to the identification and inclusion of four experts that could help with reviewing collected information and identify missing knowledge.

Identified areas of PCB design from this evaluation:

Power Electronics
Signals and high frequencies
Antenna construction
PCB Designers both Schematics and Layout
Design for Manufacturing/Assembly

After assembly there is usage and testing which brings users of designed parts.

System integrators
Technical Engineers
Test Engineers

Interviews with:

Product Developer from Saab
Production engineer from Pluspole
Assembly Technician from Saab
System Integrator from Saab
Lead Technical Engineer at Nano Dimensions

Identified user needs

During the research part when looking into lead-users and stakeholders a few different use cases for prototyping and small-scale production were identified.

One of a kind: Can be a test rig, adapters, and repair of equipment or can be a single unit for sale.

FUM: Functional model, a specific type of prototype used to test a specific function in a real environment using dummy hardware for other functions.

Prototyping: To test both functions and designs, also to use for testing to build knowledge.

Research: Changing small parameters and creating multiple unique designs to check against the latest simulations, very similar to iterations but more focused on understanding a specific part compared to rapid development.

Iterations: Working with rapid development using prototypes and FUMs require rapid paced manufacturing and assembly.

Evaluation: New parts and modules are released all the time, in order to evaluate these in the absence of an EVB from the manufacturer or to test closer to the application when an EVB isn't desirable.

Production: Produce PCBs for production of components for sale.

Building evaluation boards after expert input to test the most critical functions and parameters, to do this the test design and evaluation was done in cooperation with experts and according to LPDs test to failure principle.

Requirements

After identifying use cases, lead users, stakeholders and experts, focus shifted to finding the requirements that a process would need to meet to be usable for that stakeholder. To determine

what to test, the lead users were given a presentation on the proposed testing methodology and all the gathered information about the processes, available technologies and available information from available material.

The initial meeting was used to find what requirements each lead user had for the process and what information was lacking. After the meeting, the information gathering process continued with finding what information was available by asking process developers and what would only be obtained from testing.

After receiving answers on some of the questions and finding additional information partly from an interview with a Nano Dimension representative, a second meeting was called. In the second meeting the new information was presented, and the focus shifted to how to test to find the limits of the technology.

Schematic of evaluation board

From the requirements given by the lead users a set of circuits was proposed and decided upon. After designing the circuits, a circuit diagram is done by drawing the circuit inside of a CAD tool. When the circuit diagram is drawn in the CAD software one additional task consist of component choice, both specific part but also size, directing the possible layout at the next step of PCB development.

The fact that component size and characteristics is set in the schematic stage before part placement in the layout step leads to one of the more common design loops in PCB development. Amplifier circuit built on existing design with recorded test values and was built using the same components as previously.

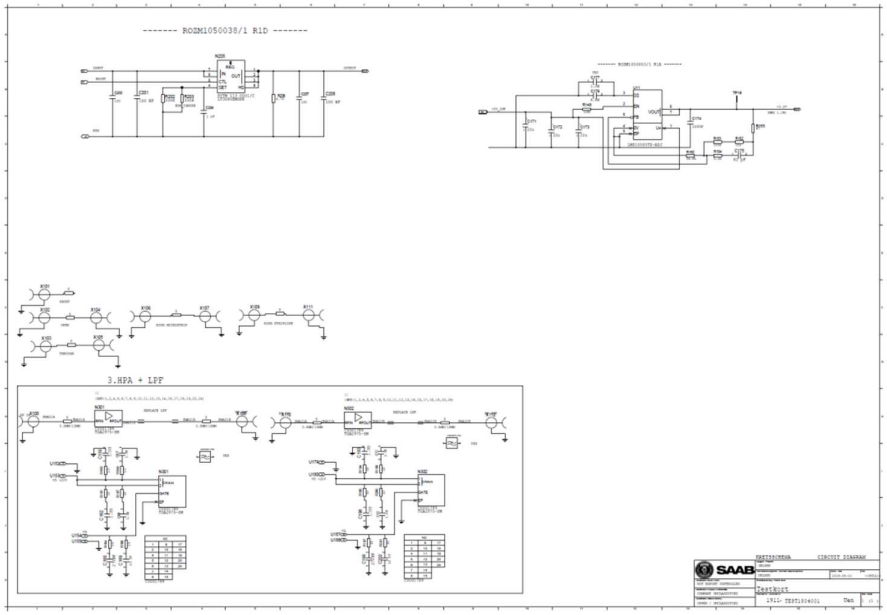


Figure 6: Schematic of Evaluation Boards

In Figure 6 the final schematic for both evaluation boards can be found, full size schematic can be found in the Appendix.

Layout of evaluation board

Implementing the circuit from the schematic into an ECAD tool to create a manufacturable Gerber-file is done in the layout step of the process.

Part of the routing process is component placement. When placing components most footprints are available in the ECAD software but structures like filters and ring oscillators must be imported from the electrical simulation software. When placing the components, the router needs to be aware of EMI and EMC, otherwise the design might not work as intended.

Rules given by Nano Dimensions were used to define the rules of the PCB. The routing software checks the rules against the design and gives an indication if any violations are found. During the routing process some care needs to be invested in creating a manufacturable design, a process referred to DFM and that will be checked in the final board review.

One of the prerequisites placed by Nano Dimensions was that any board design must fit within 50x50x3 (mm)(WxDxH). This is the constraints that lead to the Evaluation Board being transformed into two boards.

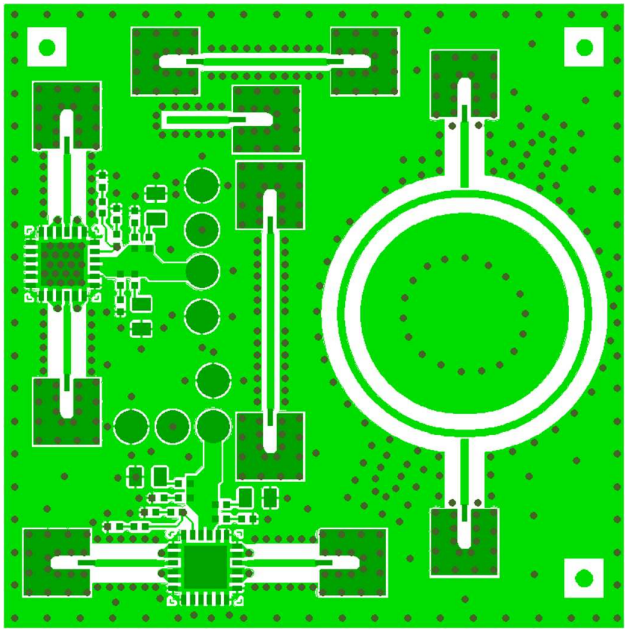


Figure 7: Top layer layout of Evaluation Board 1

The full Layout for every layer of evaluation board 1 can be found in Appendix B and the corresponding information about board 2 can be found in Appendix C.

Special structural components on the PCBs

Functional structures and structural components are an important part of a PCB and following is a short description of structures included in the developed evaluation boards.

Calibration traces

When measuring an RF circuit on a PCB, the traces to and from the component interfere with the measurement. To remove or at least reduce the interference calibration traces are used to measure the interference. They are also used for calibration of test equipment, to allow for precise measurements of the components being evaluated.

Filters

The two sets of filters included on the evaluation board were simulated according to given values by Nano Dimensions. Both microstrip and stripline filters were produced this way, both being bandpass filters and the filters will be tested over the entire span in accordance with the Test to failure philosophy.

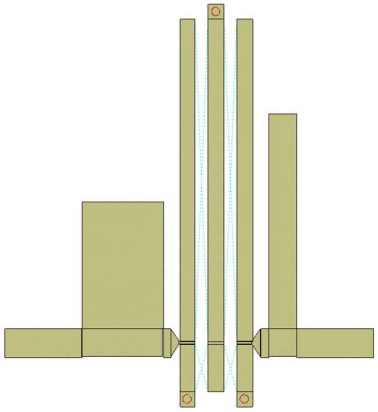


Figure 8: Microstrip Filter Layout

Figure 8 show the computer-generated layout for the microstrip filter produced for the evaluation board.

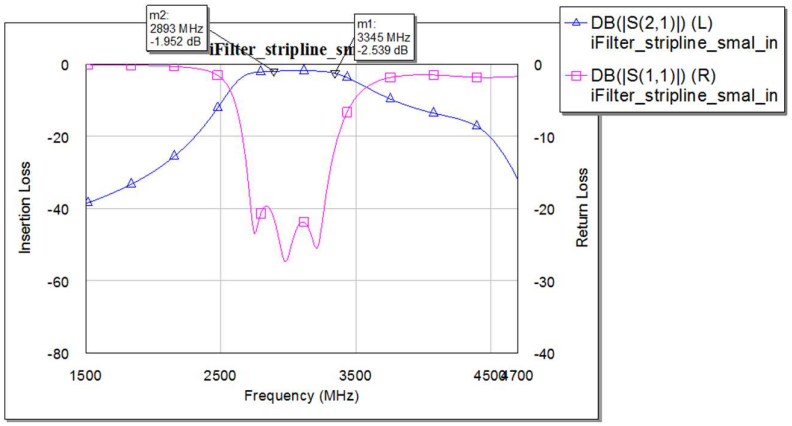


Figure 9: Simulated frequency response of the Stripline filter

Figure 9 shows simulated characteristics of the stripline filter. The aim with the planned testing, is to compare the simulated and the measured values for the filter and see how they differ.

Ring oscillators

Two ring oscillators was included in the design to measure material constants. The structure to the right in Figure 7 is the microstrip ring oscillator layout.

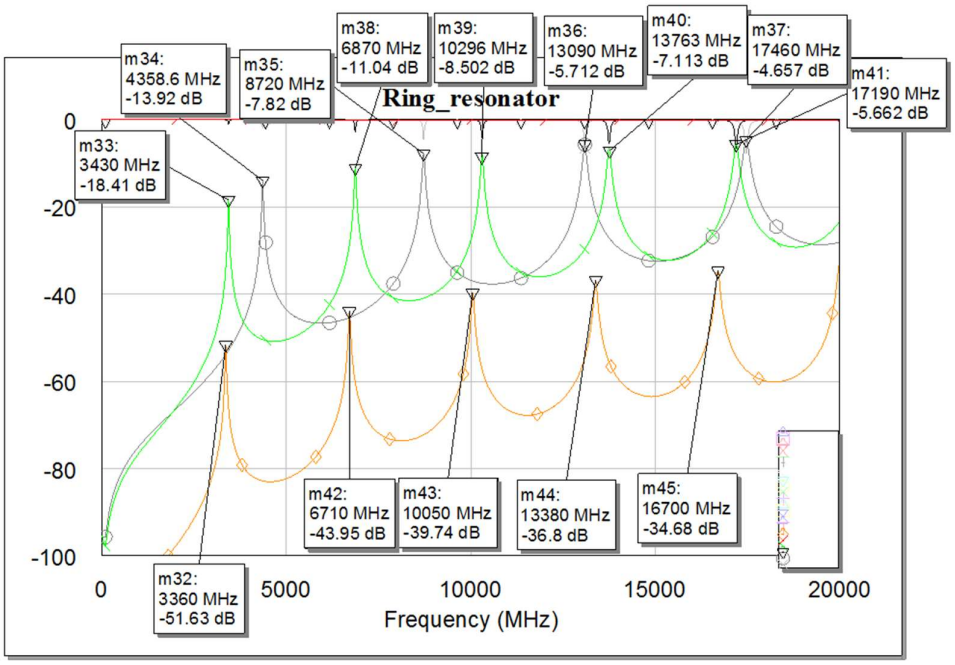


Figure 10: Simulated frequency response of microstrip ring oscillator

Figure 10 shows the ring oscillator frequency response simulation, in the planned evaluation it will be compared to the measured response from testing an actual board.

Copper coins

Some components are limited in operation by the amount of heat that can be conducted away from them. Since the area below and around that can be used as a heat conductor or sink is limited, the thermal performance of the material sets the operational performance of this type of component. The normal way of handling this is to use coins as they conduct heat away from components. Normally a coin is press fitted within a drilled hole, but it can also be any mill able contour.

Alternatives to using coins or VIA arrays is fitting a heatsink on the component or using a large area on the board to sink heat into and draw it away from the component.

For thermal dissipation of heat from the amplifier and to conduct conductive testing two different copper coins were included in the design. One of the coins was made cylindrical in order to allow measurements of the thermal conductivity of the nano silver ink. The other is a more formfitting cube below one of the amplifiers, that is used to cool the amplifier by conveying heat away from the component.

The cheaper alternative of using multiple VIAs in an array, instead of a coin was used to cool the other amplifier. This has the advantage that it allows for signal traces to be routed between the VIAs even if the thermal conductivity is reduced compared to a solid coin.

Final assembly and verification thereof

Before testing the completed assembly, a few inspection steps were carried out. These included optical inspection of solder joints and components to look for tombstoning and incomplete reflow.

Conductive testing looking for breaks and short-circuits was planned but after the first optical inspection it was clear that everything except two calibration traces were broken beyond repair. This meant that no functional testing of separate components before full testing was needed.

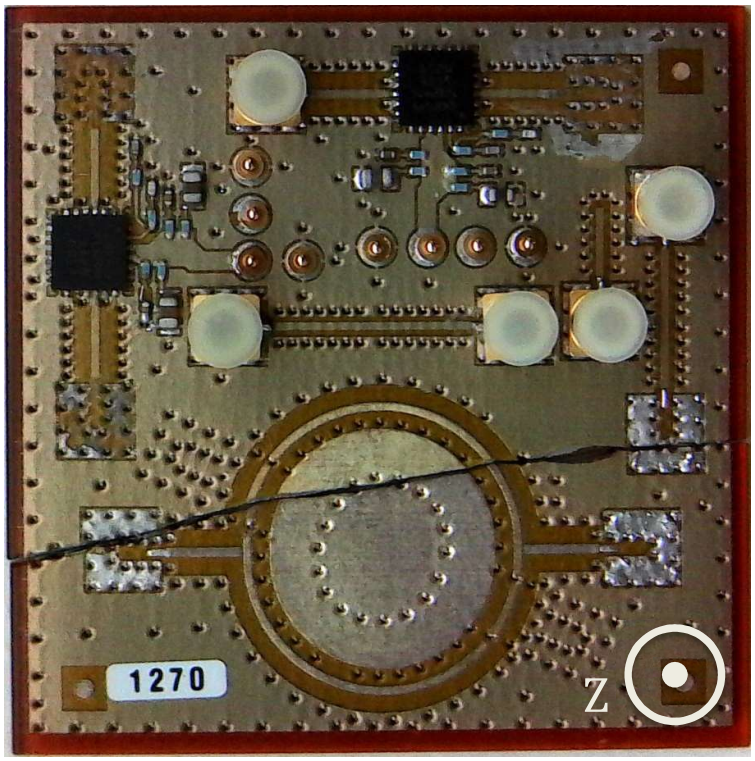


Figure 11: Evaluation Board after assembly

Assembly of the evaluation board was done by a rework engineer and was done in two steps. First, solder paste was applied to the pads and melted, this was done since the lack of available equipment made it difficult to apply the paste without smudges threatening to short-circuit the board. Secondly, the components were placed onto the pads before the board was heated using an Infrared (IR) heater from below and a hot-airgun from above.

Difficulties with re-melting the solder, lead to increased temperatures being used. This resulted in warping of the board when it contracted from the heat. An attempt by the rework engineer to straighten the board caused it to break into two parts, leaving a broken board that is not usable for electrical testing.

Summary

After discussion with Stakeholders it was decided that no relevant data could be acquired by doing most of the planned measurements and that another approach was needed. Therefore, focus was put on evaluating the microstructure of the PCB.

7. Results and findings

Testing of the properties and characteristics of the evaluation board was planned to be done using the LPD method for testing. With only one board delivered during the duration of the thesis, this limited the amount of destructive testing that could be carried out since it could lead to inability to evaluate other properties in subsequent tests. Initial evaluation was done using microscopes, before parts of the board was cut for closer inspection.

Microstructure evaluation of AM fabricated PCB

Optical inspection of the evaluation board before and after assembly was performed. A visual inspection to locate areas of interest revealed some irregularities in the trace of the upper ring oscillator as seen in Figure 12: Indention from buried VIA in conductive trace.

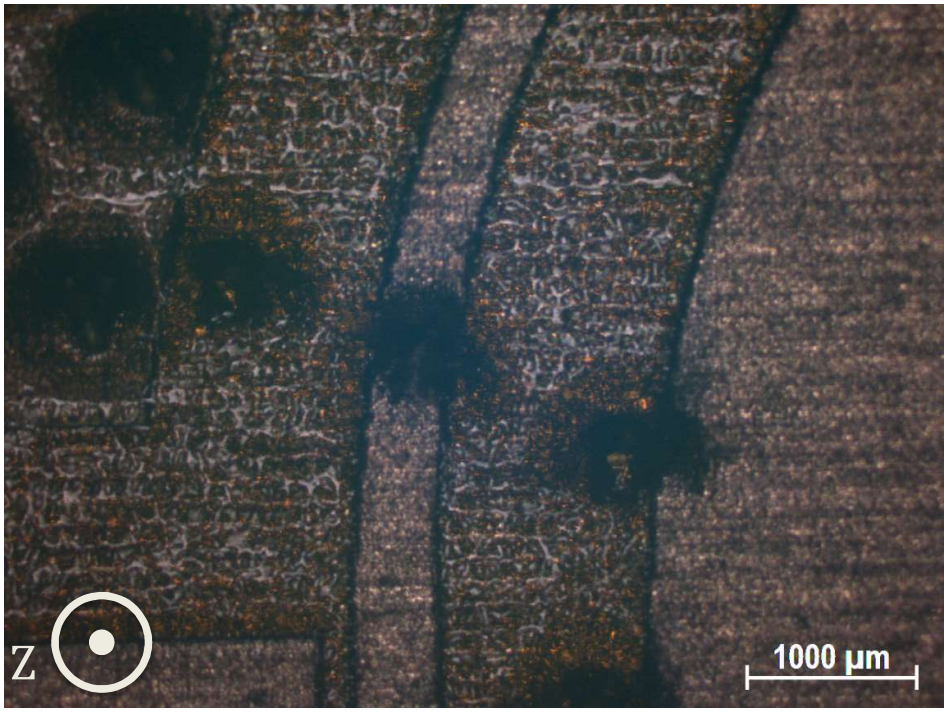


Figure 12: Indention from buried VIA in conductive trace

The next step was to use an optical microscope with attached camera and associated software to study the components of the PCB in detail. This allowed up to 1000x magnification of the object. As seen in Figure 12, the buried VIA below the trace have caused an indentation in the trace and while the trace is still connected, there is an obvious distortion in the shape and a reduced trace width.
Inspection of VIAs using the microscope reveals a cavity that have formed on top of the VIA, in Figure 13 the cavity is can be seen, this will be expanded upon in Figure 19.

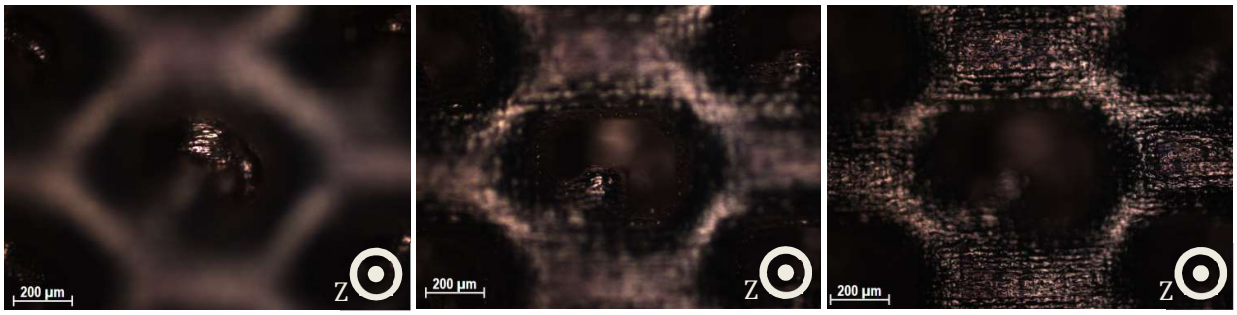


Figure 13: 3 different focus depths on VIA cavity, Bottom, Middle and Top

Looking at VIAs close to the edge of a border region between conductor and substrate a slight distortion can be observed. For example, a distinct wave pattern emerges caused by the VIAs extending the pad by causing the edge to bulge out into the substrate.

One thing that was observed using the microscope but could not be seen using an SEM was the leakage of silver droplets distributed in the substrate. The length of some of these traces excided the normal distance between traces and brings a risk for short-circuiting the board.

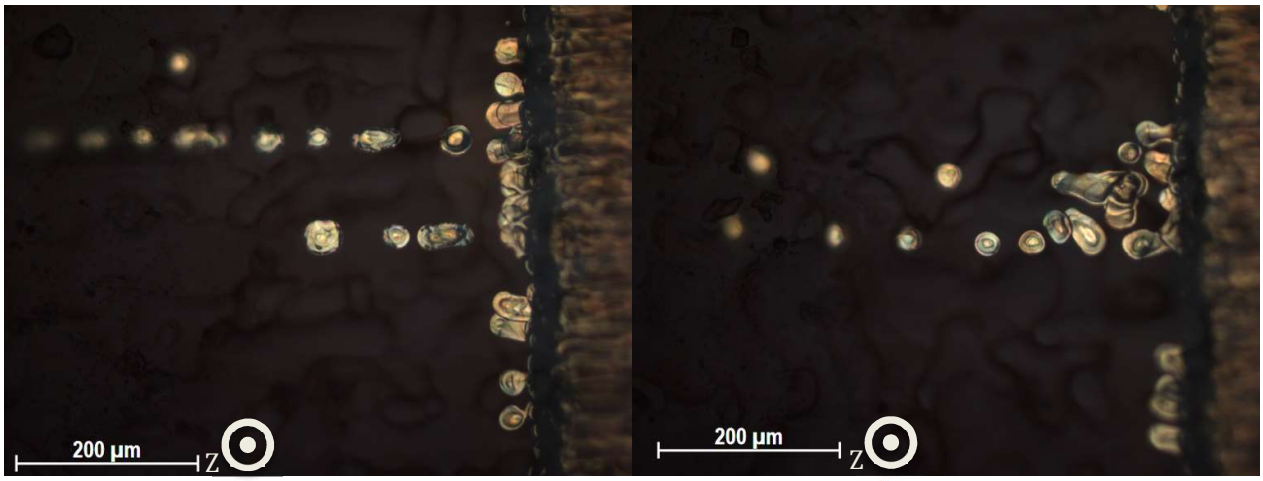


Figure 14: Nano Silver Leakage: lines of leakage extending from the edge of traces

Observing Figure 14 it is obvious that there is a large number of impurities between traces and that most of the leakage is in rows, indicating that the Piezo drop control of some nozzles seems to be faulty since it drips more consistently from some nozzles then other. Different focus levels for the droplets indicating that they are dropped in different layers during the printing process.

After a discussion with a material engineer at Nano Dimensions it was made clear that this leakage is the primary driver for having a minimum trace separation of 125 µm when the stated accuracy of the process is 1µm and each individual drop is below 50 µm in diameter.

SEM Scanning Electron Microscope inspection

To get a better understanding of the structure of the evaluation board, an SEM study was conducted.

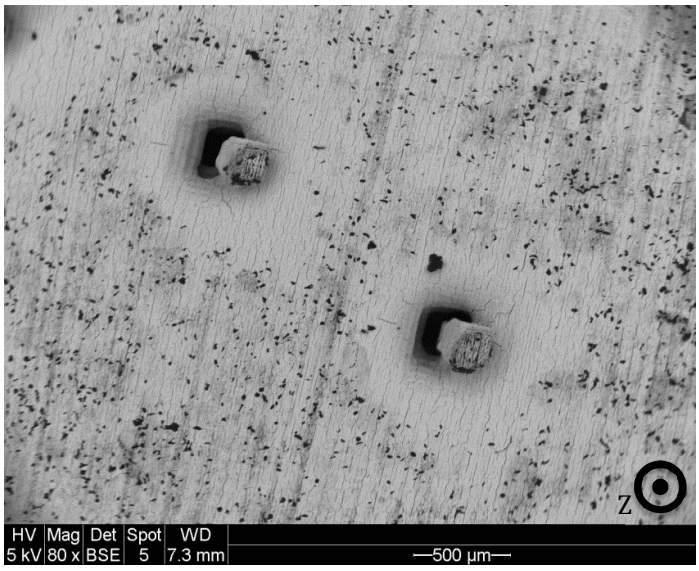


Figure 15: Two VIAs on a ground pour

By analysing Figure 12 it is easy to see that the buried VIA below the trace have affected the layers above. In order to get a better picture of how the trace have been affected the same area have been inspected using the SEM. The results from this can be seen in Figure 16.

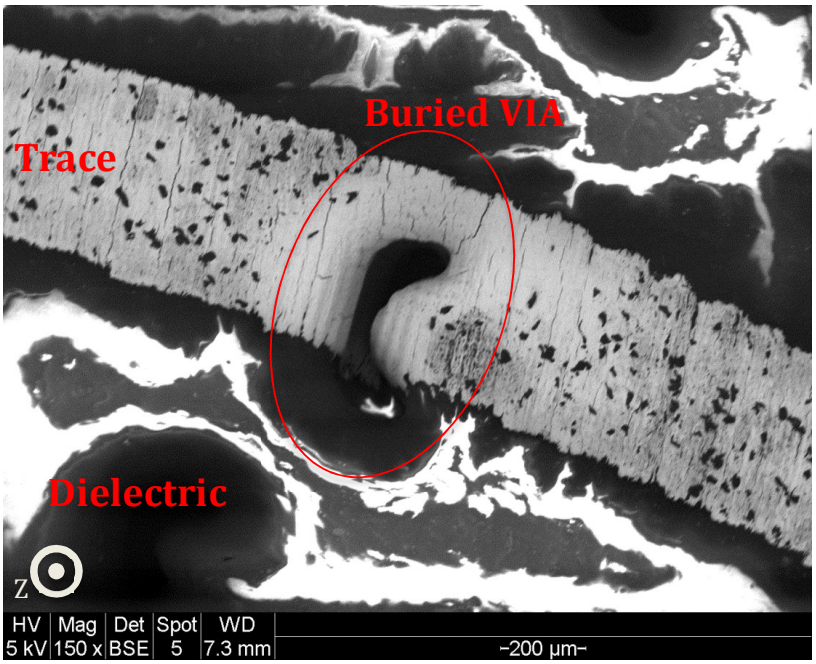


Figure 16: Trace over buried VIA

Figure 16 shows that buried VIAs cause indentations to form on layers above. It also shows what looks like cracks across the trace. Using SEM to look at the border region needs to be done quickly, since the substrate builds charge and becomes hard to distinguish after multiple scans.

From Figure 17 it is clear that the waves observed during the optical inspection can be observed using the SEM as well. Interesting observation is that the wave pattern only appears on one side of the connector.

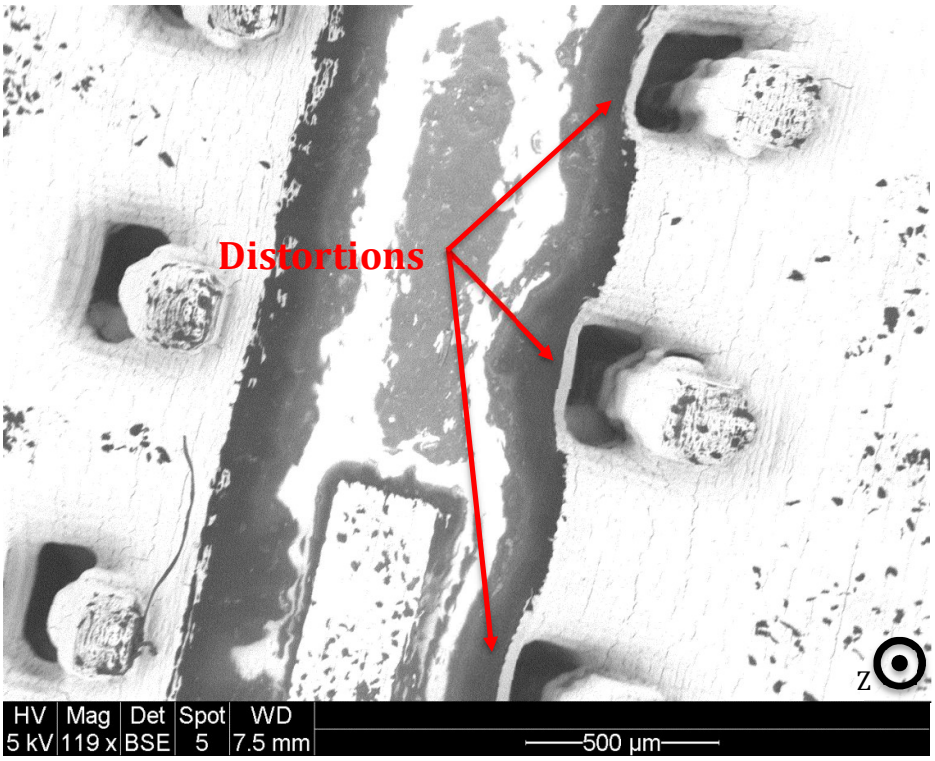


Figure 17: SEM picture of a connector pad

As seen in Figure 15 and Figure 17, there are impurities on the silver surface, but in a circle around every VIA there is none or very little. Figure 17 also shows the VIAs creating a wave effect by distorting the pad on one side.

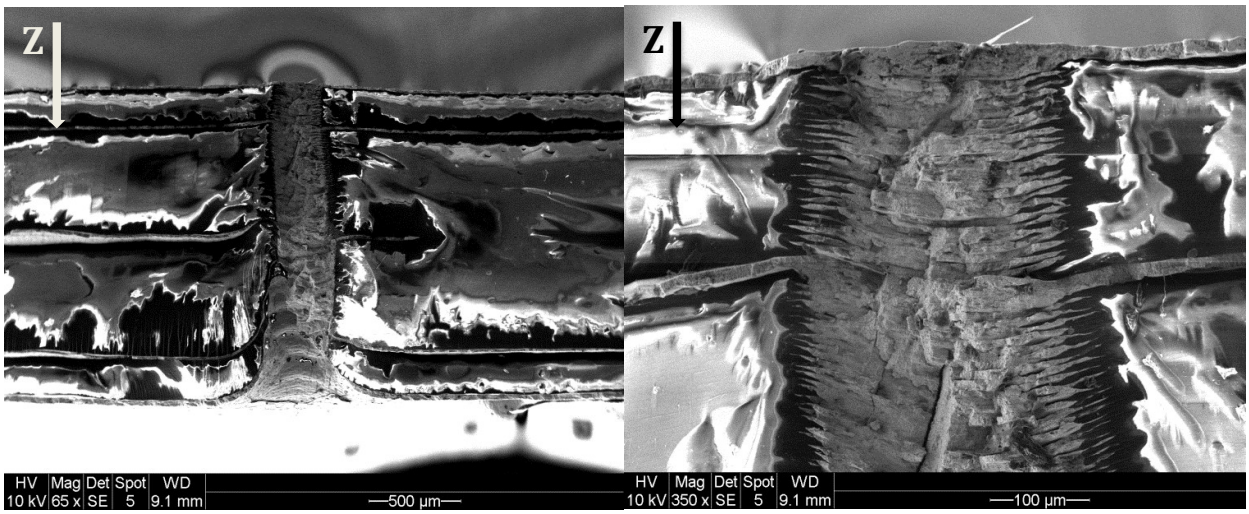


Figure 18: VIA Cross-section (Left), zoom in on bottom part of the cross-section (Right)

Figure 18 gives a view of the cross-section of the PCB, were the layered structure created by the additive manufacturing method used by Nano Dimensions is evident. It also shows that there is overlap between the conductive silver and the substrate.

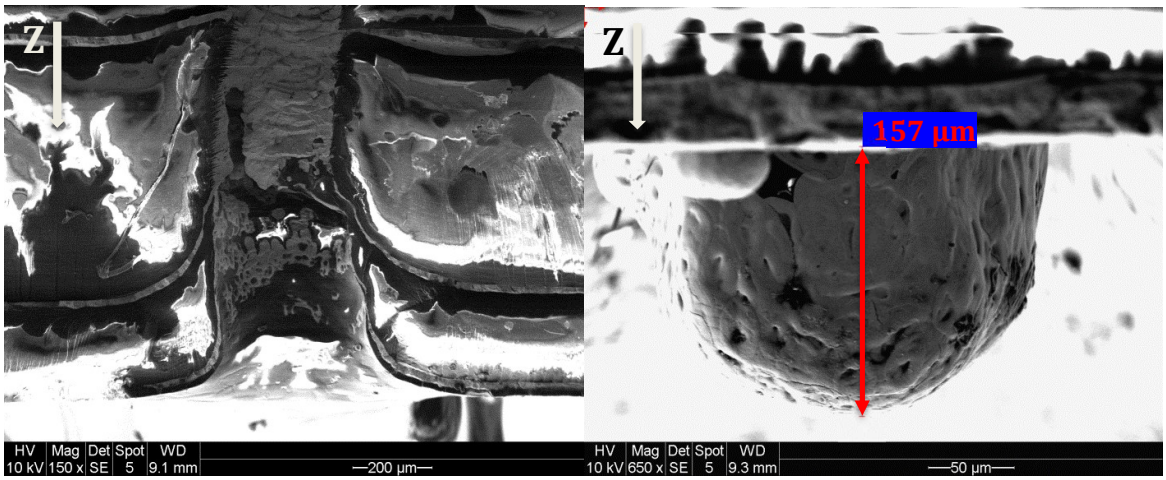


Figure 19: Cross-section of top cavity (Left), side view of VIA bump (Right)

Figure 19 shows a cross-section of a VIA and a side view of the bump forming on top of VIAs.

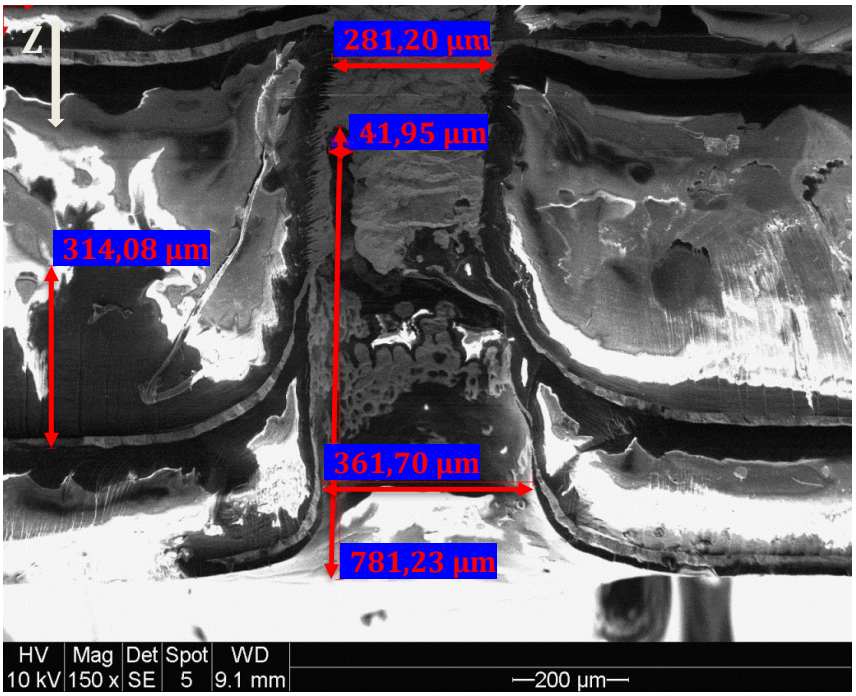


Figure 20:Cross-section of top cavity with measurements of cavity dimensions

Figure 20 shows a detailed view of the cross-section showing the depth and form of the cavity.

Summary of SEM inspections

Cracks forming between printed lines and spheres forming on top of VIAs leaving a grove consistently on one side perpendicular to the print orientation. Impurities around the sphere seems to be pulled to the forming sphere. Grove formation affects layers above and warps the board in the direction opposed of the sphere formation, creating a wave formed curvature if placed close to the border region between conductor and substrate.

Material composition

The material composition measurements were done by analysing the energy dispersive X-ray (EDX) -spectrum, measured at the sites the solder and conductor. This was with the aim to, analyse signs of impurities as well to get indications to why the assembly failed. There are three materials of interest when it comes to the evaluation board, those are the conductor, the solder and the substrate.

Conductor

Measurement of the conductor material was done by analysing the EDX spectrum emitted from two VIAs in the break, one of the VIAs was polished before the measurement was taken. The results can be found in Appendix F-G and shows 100 wt.% silver content in both VIAs.

The problematic part of doing EDX analysis to look for contaminations from the polymer substrate and an organic solvent is that both will show as Carbon. Since Carbon is detected in all samples handled in a non-clean environment its most often excluded from the spectrum report.

Solder

From the Phase Diagram provided by NIST it can be seen that the eutectic point for Bi-Sn solder is at 57 wt.% Bismuth and that the melting point is 139˚C. This corresponds to the material composition and melting point of the Bi-Sn solder paste used for assembly [26]. It can also be found that pure Bismuth has a melting point of 271˚C while pure Tin melts at 232 ˚C. This shows that a change in composition would lead to a higher temperature being needed to melt the solder.

Analysing the solder when it had been soldered to a pad on the evaluation board lead to the material compositions seen in Appendix F: SEM+EDX analysis- Solder surface 10 kV. To conduct the analysis measurements were done both on the surface layer and inside a scratch using a 10kV acceleration voltage. This was followed by additional measurements using a 20kV acceleration voltage.

The surface measurements gave the following results: measurements at the surface using acceleration voltage of 10 kV gave a material composition of pure Bismuth (100 wt.%), while the measuring at 20 kV gave 62 wt.% Bismuth content. This is connected to the fact that Kα for both, Bi and Sn is far above 20 kV and Lα for Sn is 3,443 and Lα for Bi is 10,837. Therefore, considering that proper excitation of the analysis lines requires as minimum double energy, proper analysis of a solder would require as minimum 20 kV acceleration voltage. In addition, possible segregation of the elements during solder solidification and following oxidation can result in different composition of the solder surface. Therefore, additional material tests were conducted on a scratched surface of the solder. The reason for this was to bypass segregation or surface oxidation/contamination, mentioned above. These measurements gave the following material composition: 39.62 wt.% Bismuth at 10 kV and 49,65% Bi at 20 kV with traces of oxygen (~3,96 wt.%).

From these relatively basic measurements it looks likely that the initial soldering caused a separation or a partial segmentation of the two components, leading to a higher melting temperature. This, combined with the presence of oxygen, indicates the possible presence of oxidation in the soldered paste that have the potential to increase the melting point even further.

Combining this with the observations done by the assembly technician, it is clear that the re-melting of the solder might have affected the properties of the solder. This can in part explain why the assembly went the way it did.

Substrate

Due to the substrate being a polymer, a spectrum analysis would not show any results other than high carbon content and wasn't carried out.

Electrical testing

High frequency, Ring oscillators and filters

All structures for high frequency testing were broken during assembly. The same is true for both ring oscillators and could therefore not be used for measurements. Also, since all filters were designed on evaluation board 2, that was not delivered before the end of the study, no measurements could be carried out.

Conductivity

Calculating the conductivity or resistivity of a material can be done by measuring the resistance over a known conductor and using the transposed Equation 1, called Pouillet's law found in Equation 2. After acquiring the resistivity of the material, the conductivity is defined as the inverse as seen in Equation 3.

ρ - Electrical Resistivity
R - Electrical Resistance (Ωm)
A - Area of the cross-section (m^2)
l - Length of the cross-section (m)
σ – Conductivity (S/m)

Equation 1: Electrical Resistivity

$$\rho = R\frac{A}{l}$$

Equation 2: Pouillet's Law

$$R = \rho\frac{l}{A}$$

Equation 3: Conductivity

$$\sigma = \frac{1}{\rho}$$

Resistivity testing was done by measuring the longer calibration trace using a milliohmmeter to conduct a 4-wire measurement. For accurate calculation of the material constant the actual size of the conductor would be needed, but for simplicity the specified size from the Gerber file was used to calculate the conductivity. This was used in combination with the value supplied by Nano Dimensions to see the discrepancy between the ideal and the printed trace.

Resistivity		
Date: 20180815		
Ambient Temperature: 20.9˚C		
Humidity: 62.6%		
Equipment: METRAHIT 27 I milliohmmeter		
Calibrated: 20180414		
4-Wire @ 1A		
Minutes	Value (mΩ)	
1	200	
2	201,2	
5	201,52	
8	201,7	
10	201,8	
4-Wires @ 200mA		
Minutes	Value (mΩ)	
1	198	
5	196,3	

Table 1: Results from resistivity measurements

One alternative measure that would have been of interest is how much the conductor dampens a signal at different frequencies. This would have been done as part of the measurements of the amplifier circuit and is therefore not done during this thesis.

Summary of testing

Since only a small amount of actual testing could be done due to the evaluation board breaking during assembly, a larger focus was put into observing and analysing the structures and materials of the board compared to what was planned.

8. Discussion

Additive manufacturing is a field that is advancing at a rapid pace and this is especially true when it comes to printed electronics. The time between the first printed transistor in a lab and large-scale production of TFT for products was only a few years. If 3D-Printed PCBs follow the same development speed there will be a rapid development of new machines and large advances in the technology over the coming years. This brings the need for continuous evaluation of the technology to keep on top of development.

Where is the current state of the art when it comes to additive manufacturing of PCBs when it comes to DRL? Limitations in size and volume of the printed board in combination with the need for special solder-paste, lower soldering temperatures and reduced mechanical strength reduces the MRL rating even for lower frequency applications. This leaves prototypes and small series production of sensitive boards

Volume production is outside of the capabilities of current machines, there are no physical limitations hindering implementation of the technology into a line for volume manufacturing. The amount of development needed to get rid of leakage and vertical artefacts is unknown, but a line-printer is a possible future implementation of the technology.

The largest knowledge increase in companies when it comes to more ordinary additive processes is the design rules and guides built on experience from testing the technology. Something similar for additive manufacturing with machines for PCB printing is needed before companies can find the correct use-cases for printed PCBs. One way is to continue with an evaluation of design principles for additive PCBs.

One of the areas that ordinary additive manufacturing is emerging is spare parts. Instead of having every possible part in stock at every location a 3D-printer prints the required part on demand. This allows for space and cost reductions while delivering the required service and is one additional area were PCB printers will need to be continuously evaluated. Identifying a lead partner might allow for an organisation to become a Beta tester, both to gather knowledge on upcoming technologies but also to direct development towards a product fulfilling internal demands. Should it be impossible to get involved in the development, a more direct approach is to purchase the systems for evaluation. This can be done in collaboration with companies and educational institutes to spread the cost and widen the pool of ideas.

The aim of all approaches is to build internal knowledge so that the right technology can be utilized at the right time for the correct application. Ideas for possible use cases came from PCB designers, test engineers and others interested in the project. Many of these were outside the scope of this thesis but to fully evaluate the possibilities with the current additive machines, a follow-up study looking into 3D-design and component printing will be needed.

For example, smooth transitions for conductors allowing for more organic circuit design and 3D-structures not only in 2D, allowing for structures like antennas and coils to be built into the PCB. Additional structures that would allow for design decisions impossible with other manufacturing technics is branched heat conductors allowing for both, larger transferee area and easier signal routing.

One other possible way of utilising additive manufacturing of PCBs is to try to integrate passive and active components into the PCB either by placing them while printing or printing them within the PCB to save space and assembly time. Look into if it is possible to build the PCB as part of other printed components, like a printed panel to reduce the number of parts for assembly and save space in the final product.

This thesis has looked at new manufacturing processes from a product development perspective focusing on the different phases and needs of the development cycle. There is a lot of work done in process development to evaluate new processes for manufacturing. Looking at it from another perspective to see if the conclusions differ. In the next step, continuing from those findings, see if it is possible to find a middle ground between manufacturing and development, when it comes to new processes.

Evaluating the performance of process without being able to do measurements, only studying the structure, does not give any real numbers to put on the performance but it gives an indication of what is the state-of-the-art in the field, and what the limiting factors might be.

However, analysis of the structure of the printed PCB provides important conclusions about expected performance and limitations of the technology at the current state-of-the-art. Layers overlapping along the height of the VIAs, rough edges along traces and line separation between conductive materials dispensed by different nozzles, indicate poor high frequency performance due to losses from the skin effect.

While these defects from the printing process limits the high frequency performance, they can be used as built in lowpass filtering, should it be possible to alter the design to amplify the dampening effect or control the cut off frequency. If the limitations are known, then they can be used as design elements when designing for the process. Outside of PCBs the technology might give other possibilities, for example printing conductive 3D-structures will allow for the creation of complex antennas. In these cases, the performance would need to be compared to antennas made using standard manufacturing methods and other additive processes.

When it comes to evaluation of the proposed DRL method, it is not enough with two companies to build a basis for how to apply product development principles on PCB development. But given limited time and resources it is the one way that leaves time to focus on evaluation of technology.

One of the core principles when it comes to engineer utilization in projects is that, working on two projects or tasks in parallel allows for swapping focus during unescapable wait times, deliveries etc. Splitting focus between more than two projects leads to lower utilization [1]. Furthermore, utilization of resources in development should be kept at 80% or lower to allow leeway when problems occur [15]. To stop road blocks from forming from minor setbacks in one project, the total utilization of R&D resources should be kept below 60%, but it is worth noticing that the higher the total capacity, the more projects can be fitted within those 60% [15].

Therefore, it is often better to have an organisation that is quick and efficient allowing each engineer and researcher to focus on a maximum of two projects and newer need to wait on both projects at the same time.

The problem with trying to do everything inhouse is that it is hard to be better at a function outside of the focus of the organization compared to a sub-supplier fully focusing on that specific

function. One core aspect of Lean Production is to make your suppliers grow with you and to build long-term commitments. [14]. When using a process for manufacturing prototypes that is different from the process that will be used to manufacture the final product, the aspect of interchangeability becomes a major aspect to consider while working with DFM and testing.

Some processes for prototype production are simply scaled down versions of the volume production lines, while others build on entirely different processes. When the only difference is in scale, interchangeability while still needed to be considered, is not as large of a concern compared to the alternative processes composed of entirely different steps, materials and technologies. Regardless of approach to product development, it is a multi-disciplinary approach to producing a new product and efficient testing is a needed part.

Looking at evaluation tools like MRL and TRL, raise the question of how high on the MRL scale does a manufacturing technology need to score, to be useful in indicating sub-solution or concept function at different levels of the TRL scale. The goal of this thesis is to find a method to evaluate found technologies with suggestions for finding new and not how to implement them into an organization after an evaluation shows them to be beneficial and ready for implementation.

Like the different demands in each category for TRL, the requirements and demands for different fields and stages, differ when it comes to board development. Even if it does not fulfil the requirements for high frequency applications, it can still be perfect for high power applications and might be used, with module thinking to allow for tests and evaluations, even in those fields that it cannot fill the requirements of on its own.

The last part when it comes to evaluating a new process is to do an economical evaluation, looking at a hard to define added value approximation, compared to an easily calculated cost. Each evaluation goes faster and is easier since most of it, if not all is pre-defined if everything is kept up to date allowing for the continued building upon already collected knowledge. In the end, having access to the correct resource at the right time allows for better flow in the entire process.

9. Conclusion

This thesis aimed to analyse the current state-of-the-art in additive manufacturing of PCBs, create a method for evaluating similar technologies and bringing the development process into the readiness level approach.

The current state of additive manufacturing of circuit boards is at the beginning of its S-curve even if TFT circuits have had a few years to develop. This means that as materials and process progress the number of printable features will increase, especially when additional steps to add semi-conductive layers can be done to print entire assemblies in one machine. The driving factor behind current development of additive circuit manufacturing is done in the field of TFT circuits.

At the current state-of-the-art the technology is still limited compared to standard processes especially when it comes to high frequency applications. The main thing holding the performance back when it comes to high frequencies is the trace edges and line separations found in the printed traces in combination with the layering found inside in the VIAs. These features function as low-pass filters by dampening high frequency signals.

Additional drivers for limited print performance are the metal particle inclusions in the dielectric polymer. This leakage of silver ink during printing, limits the minimum line separation and excludes some use cases from being possible due to size limitations. There is also the need for special processes when it comes to assembly that excludes the technology from being interchangeable with standard processes when it comes to production. Had this project been a review of the technology for a company the result from the gate would be to take what has been learnt and redo the evaluation with a newly printed evaluation board.

The principles for evaluation of alternative PCB manufacturing processes or any proposed technology are laid out in the proposed DRL method. It needs to be expanded and adapted to be useful for a company, but the brief definition given in this thesis can be used as a sketch to get started. The issues it aims to address are real and companies needs to address them or risk falling behind in a competitive environment.

It is important to always investigate new technologies, compare them to currently used and evaluate what they can do. The largest risk is to ignore development because you will be left behind. DRL is a method that gives a quick way to evaluate new manufacturing methods, improvements to current processes and allowing for companies to keep themselves updated. Per the definition of DRL given earlier in the report, the highest level given to the current process would be a 4. This rating is mostly due to the evaluation board breaking then what might have come from a full evaluation, a best approximation of how the process should perform would place the process at DRL 5, but the level varies with the frequency requirements of the application.

When it comes to the usage of additive manufacturing of PCBs in product development the needs differ between departments and projects. Mapping the company or project specific requirements when it comes to TRL and MRL values of different technologies, allows for additional options when choosing a manufacturing method for prototypes at different stages of the project. This can allow for shorter development times if used correctly. It is clear that the largest advantages of additive manufacturing remain when it comes to electronics and electronic design, but to leverage it fully both the technology, the material and the software needs to be developed further.

10. References

[1] S. C. &. C. K. B. Wheelwright, Revolutionizing Product Development, Free Press, 1992.

[2] H. Maylour, Project Management 4th Ed, 2010.

[3] N. Dimensions, "DRAGONFLY 2020 PRO 3D PRINTER FOR PROFESSIONAL ELECTRONICS".

[4] "LPKF: Get PCB Prototypes Sooner with: In-House Rapid PCB Prototyping," [Online]. Available: http://www.lpkf.com/_mediafiles/1931-brochure-inhouse-rapid-pcb-prototyping-en.pdf. [Accessed 24 03 2018].

[5] "IEEE," Institute of Electrical and Electronics Engineers, [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed 31 05 2018].

[6] J. C. Mankins, ”TECHNOLOGY READINESS LEVELS: A White Paper,” Office of Space Access and Technology NASA, -, 1995.

[7] P. Caroline P. Graettinger, S. Garcia, J. Siviy, R. J. Schenk and P. J. V. Syckle, “Using the Technology Readiness Levels Scale to Support Technology Management in the DoD’s ATD/STO Environments,” Pittsburgh, 2002.

[8] P. Bright, “ars TECHNICA,” Advance Publications, Inc., 16 07 2015. [Online]. Available: https://arstechnica.com/gadgets/2015/07/intel-confirms-tick-tock-shattering-kaby-lake-processor-as-moores-law-falters/. [Accessed 02 07 2018].

[9] Intel Corporation, “Intc,” Intel Corporation, 26 04 2018. [Online]. Available: https://www.intc.com/investor-relations/investor-education-and-news/investor-news/press-release-details/2018/Intel-Reports-First-Quarter-2018-Financial-Results/. [Accessed 02 07 2018].

[10] OSD Manufacturing Technology Program, Manufacturing Readiness Level (MRL) Deskbook V2.0, -: -, 2011.

[11] S. T. H. a. J. F. M J Ward, ”A readiness level approach to manufacturing technology development in the aerospace secto: an industrial approach,” *Proc. IMechE,* vol. 226, nr B, p. J, 2011.

[12] Dr. Homayoon Dezfuli et al., NASA Risk Management Handbook, Washington: NASA Center for AeroSpace Information, 2011.

[13] J. Sutherland, Jeff Sutherland’s Scrum Handbook, Boston: SCRUM TRAINING INSTITUTE PRESS, 2010.

[14] D. P. Oosterwal, The Lean Machine: How Harley-Davidson Drove Top-Line Growth and Profitability with Revolutionary Lean Product Development, AMACOM, 2010.

[15] N. Majerus, Lean-Driven Innovation: Powering Product Development at The Goodyear Tire & Rubber Company.

[16] K. T. Ulrich och S. D. Eppinger, Product Design and Development Fifth Edition, McGraw-Hill/Irwin, 2012, 2012.

[17] S. C. M. a. W. F. F. K. A. Schroder, ”Broadcast Photonic Curing of Metallic Nanoparticle Films,” NSTI-Nanotech, Austin, 2006.

[18] Mega UK, ”Mega UK,” Mega Electronics, [Online]. Available: https://www.megauk.com/producing_a_pcb.php. [Använd 13 07 2018].

[19] Noh et Al., ”Key Issues With Printed Flexible Thin Film Transistors and Their Application in Disposable RF Sensors,” *Proceedings of the IEEE,* Vol. %1 av %2Vol. 103,, nr No. 4,, pp. 554-

566, 2015.

[20] VSPARTICLE, “VSPARTICLE,” VSPARTICLE, 09 07 2018. [Online]. Available: https://www.vsparticle.com/nanoparticles/view/?tx_userperiodictable_periodictableplugin%5BperiodicElement%5D=534&tx_userperiodictable_periodictableplugin%5Baction%5D=show&tx_userperiodictable_periodictableplugin%5Bcontroller%5D=PeriodicElement&cHash=d845f. [Accessed 09 07 2018].

[21] U. Zamwel, Interviewee, *Nano Dimensions new DragonFly 2020 Pro.* [Interview]. 11 04 2018.

[22] M. C. S. S. a. J. S. J. West, ”Photonic Curing of Silver Nanoparticle Based Inks,” NSTI-Nanotech, 2010.

[23] Jin Sik KIM et Al., ”In vivo Genotoxicity of Silver Nanoparticles after 90-day Silver Nanoparticle Inhalation Exposure,” *Safety and Health at Work,* vol. 2, nr 1, 2011.

[24] Renat R. Khaydarov et al., “Environmental and Human Health Issues,” in *Environmental Security and Ecoterrorism*, Springer Netherlands, 2011, pp. 117-127.

[25] Kemikalieinspektionen, ”Kemiska ämnen i elektroniska komponenter,” Kemikalieinspektione, Sundbyberg, 2012.

[26] NIST, “National Institute of Standards and Technology (NIST),” U.S Commerce Department, [Online]. Available: https://www.metallurgy.nist.gov/phase/solder/bisn.html. [Accessed 28 08 2018].

[27] A. E. e. a. Ostfeld, “Screen printed passive components for flexible power electronics,” *Nature Scientific Reports,* Vols. Rep. 5,, no. 15959, 2015.

[28] X. Z. T. G. J. Z. Joseph Chang, ”Fully printed electronics on flexible substrates: High gain amplifiers and DAC,” *Organic Electronics,* 2014.

[29] Pochiang Chen et Al., ”1.Fully Printed Separated Carbon Nanotube Thin Film Transistor Circuits and Its Application in Organic Light Emitting Diode Control,” *Nano Letters,* Vol. %1 av %25301-5308, nr 10.1021/nl202765b, 2011.

[30] G. F. a. S. Zehle, GUIDE TO BUSINESS PLANNING, London: Profile Books Ltd, 2004.

[31] S.Schwyn, E.Garwin and A.Schmidt-Ott, “Aerosol generation by spark disharge,” *Aerosol Science,* vol. 19, no. 5, pp. 639-642, 1988.

[32] H.Burtscher och A.Schmidt-Ott, ”Enormous Enchantment of van der Waals Forces between Small Silver Particles,” *Physical Review Letters,* vol. 48, nr 25, pp. 1734-1737, 1982.

[33] Voltera, ”Voltera,” [Online]. Available: https://www.voltera.io/faq/. [Använd 6 April 2018].

Appendix A: Evaluation Board Schematic

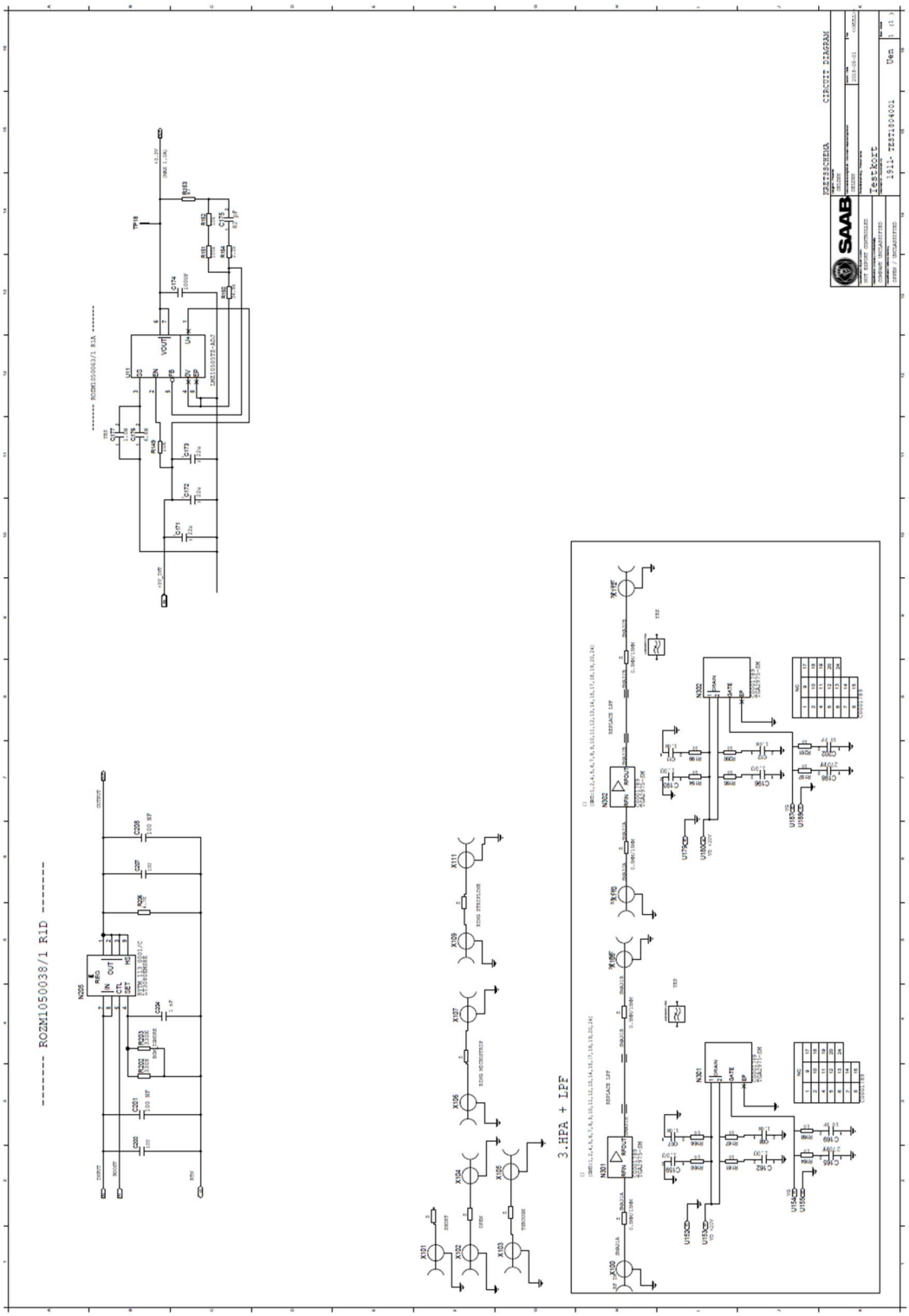


Figure 21: Evaluation Board Schematic

Appendix B: Evaluation Board 1 Layout

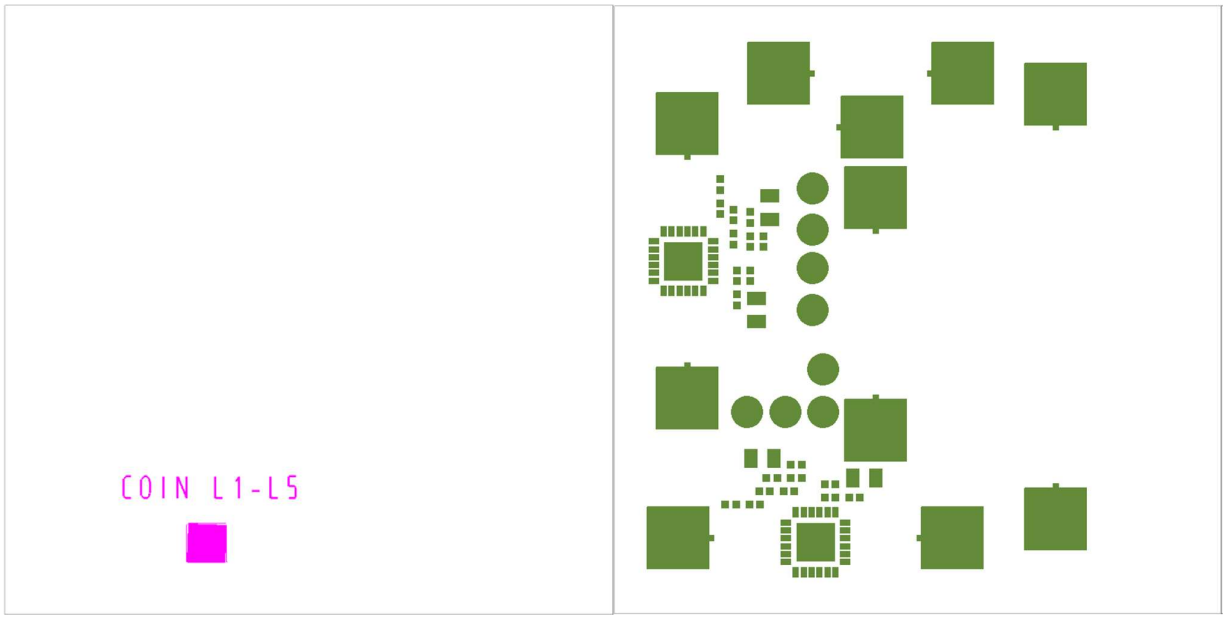


Figure 22: LH Coin layout board 1; RH Top solder mask board 1

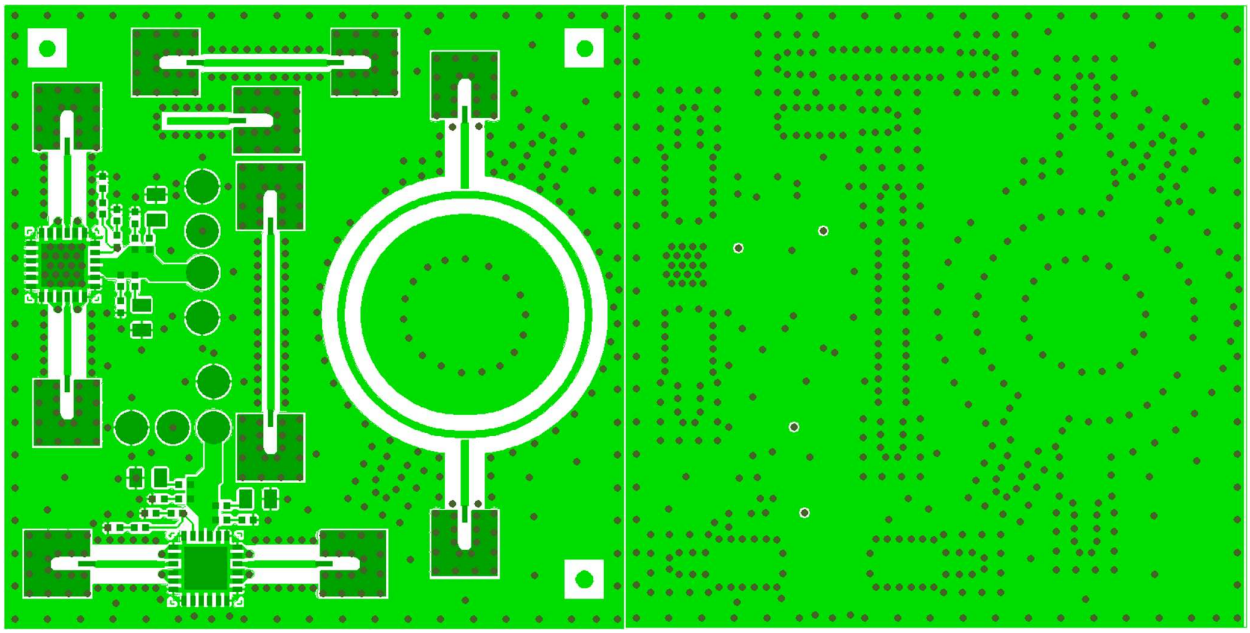


Figure 23: LH Layer 1 board 1; RH Layer 2 board 1

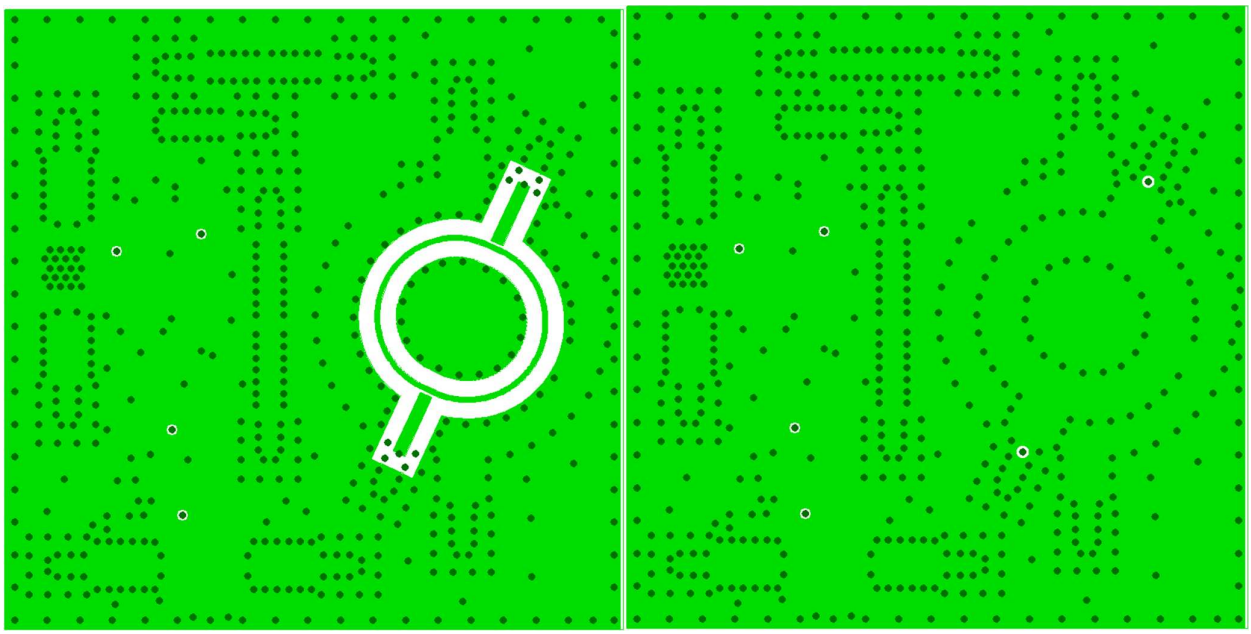


Figure 24: LH Layer 3 board 1; RH Layer 4 board 1

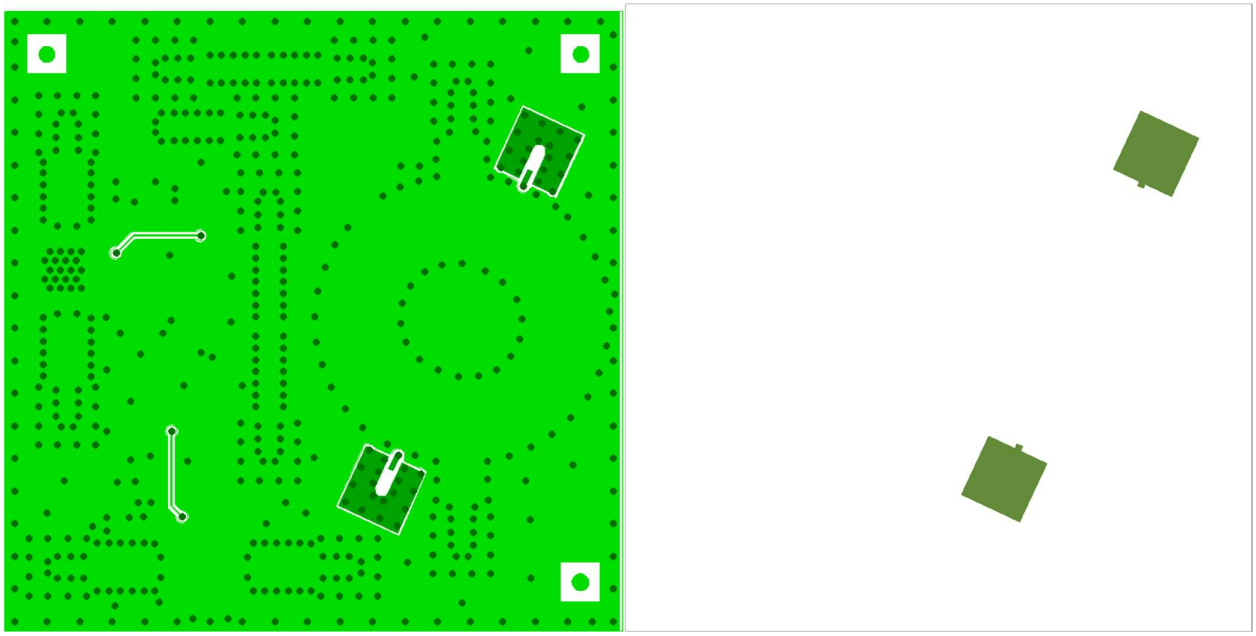


Figure 25: LH Layer 5 board 1; RH Bottom solder mask board 1

Appendix C: Evaluation Board 2 Layout

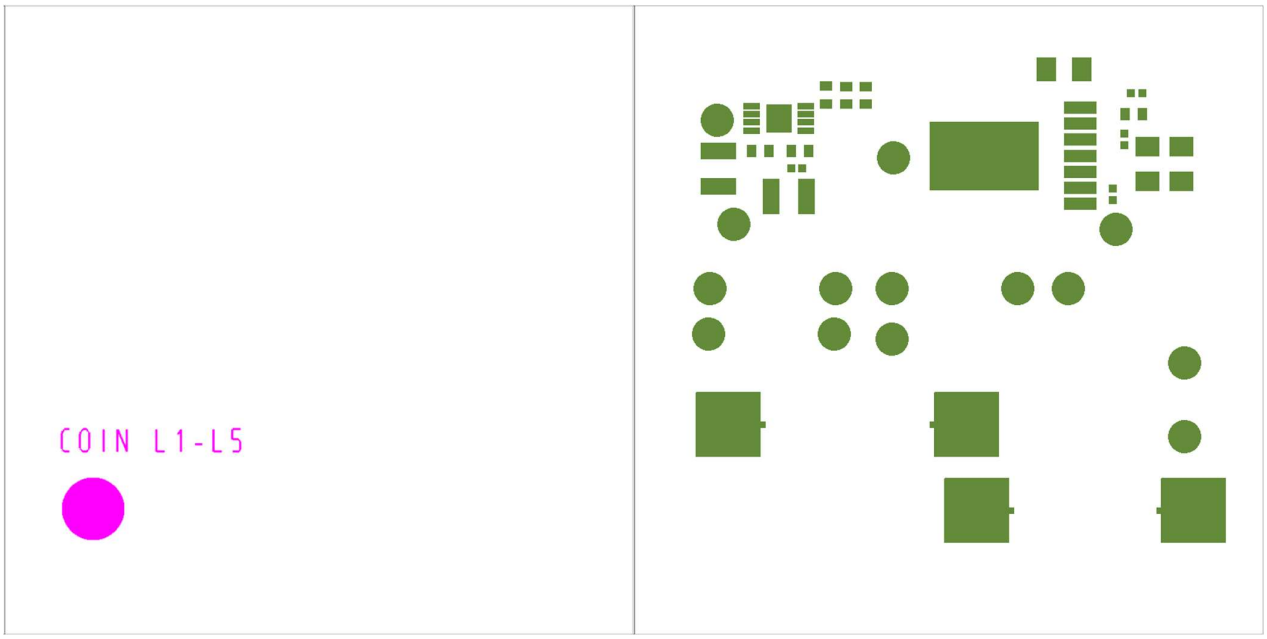


Figure 26: LH Coin layout board 2; RH Top solder mask board 2

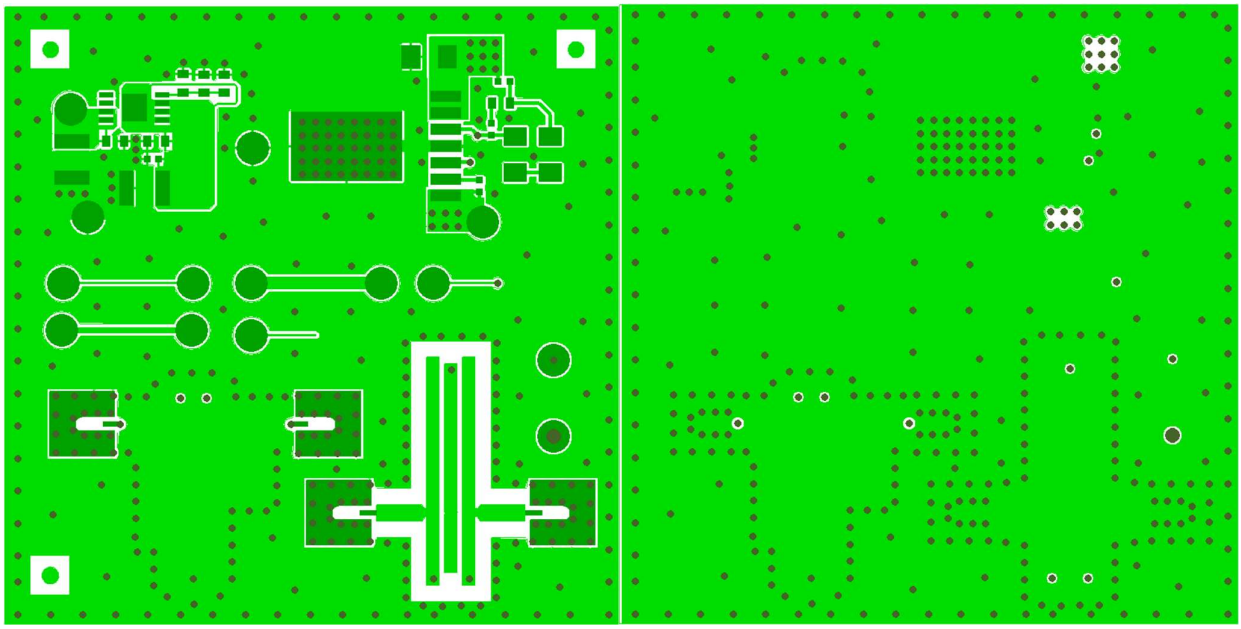


Figure 27: Figure 23: LH Layer 1 board 2; RH Layer 2 board 2

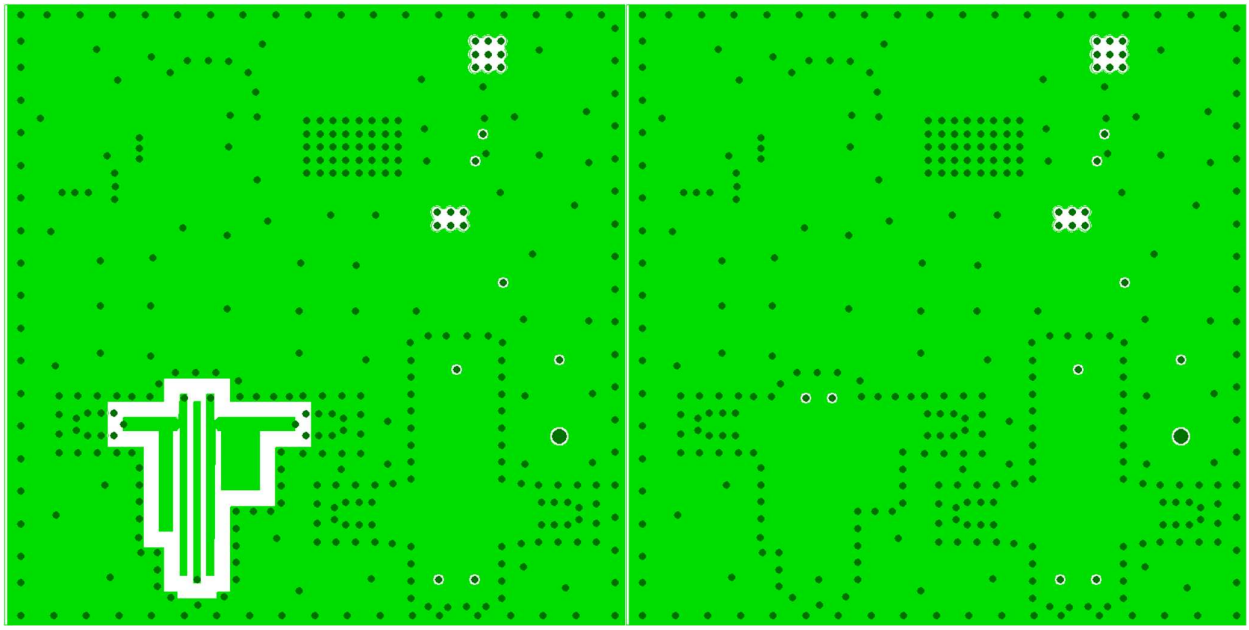


Figure 28: LH Layer 3 board 2; RH Layer 4 board 2

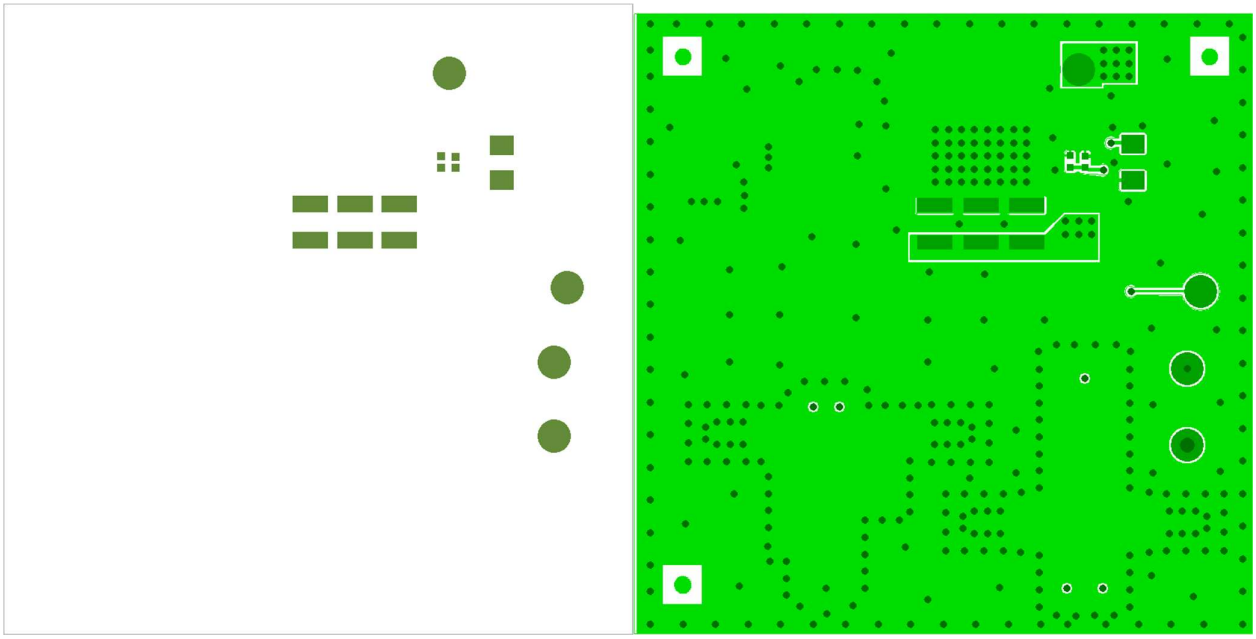


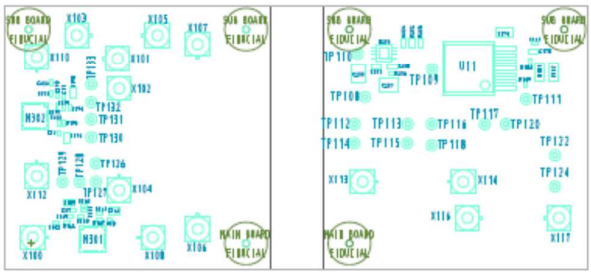
Figure 29: LH Layer 5 board 2; RH Bottom solder mask board 2

Appendix D: Evaluation Board BOM

Condensed Bill of Material Evaluation Board

SYM_NAME	COMP_DEVICE_TYPE	COMP_VALUE	COMP_TOL	COMP_CLASS	QUANTITY	REFDES
REP-0402-BYZ	REP622_BYZ-REP 622 655/1,10K,1%	10k	1%	DISCRETE	1	R149
REP-0402-BYZ	REP622_BYZ-REP 622 652/47,47,1%	47	1%	DISCRETE	1	R153
REP-0402-BYZ	REP622_BYZ-REP 622 654/22,2.2KA	2.2k	1%	DISCRETE	1	R154
REP-0402-BYZ	REP622_BYZ-REP 622 652/1,10,1%	10	1%	DISCRETE	12	R160;R161;R164;R166;R167;R168;R194;R195; R197;R199;R200;R201
REP-0402-BYZ	REP622_BYZ-REP 622 654/47,4.7KA	4.7k	1%	DISCRETE	1	R206
REP-0603-BYZ	REP623-REP 623 646/33,330K,1%,B	330k	1%	DISCRETE	1	R202
REP-1206-BYZ	REP68507-REP 685 0725/348,34.8A	34.8k	1%	DISCRETE	1	R150
REP-1206-BYZ	REP68507-REP 685 0726/1,100K,1A	100k	1%	DISCRETE	1	R151
REP-1206-BYZ	REP68507-REP 685 0725/1,10K,1%A	10k	1%	DISCRETE	1	R152
RJC-0402-BYZ	RJC464302_BYZ-0402-RJC 464 302B	1.0n	10%	DISCRETE	4	C07;C08;C11;C12
RJC-0402-BYZ	RJC463302_BYZ-0402-RJC 463 302B	270pF	5%	DISCRETE	2	C165;C198
RJC-0402-BYZ	RJC463302_BYZ-0402-RJC 463 302A	10 pF	5%	DISCRETE	2	C169;C202
RJC-0402-BYZ	RJC464502_BYZ-0402-RJC 464 502A	6.8n	10%	DISCRETE	1	C176
RJC-0603-BYZ	RJC463303_BYZ-0603-RJC 463 303B	82 pF	5%	DISCRETE	1	C175
RJC-0603-BYZ	RJC464353-RJC 464 3536/1,RJC 4A	100 nF	10%	DISCRETE	2	C201;C208
RJC-0603-BYZ	RJC463303_BYZ-0603-RJC 463 303A	1 nF	5%	DISCRETE	1	C204
RJC-0805-BYZ	RJC464354-RJC 464 3547/1,1.0U,A	1.0u	10%	DISCRETE	4	C159;C162;C193;C196
RJC-1206-B-BYZ	RJC464406_BYZ-RJC 464 4069/1,1A	100uF	10%	DISCRETE	1	C174
RJC-1210-D-BYZ	RJC378-RJC 378 1168/22,22U,10%A	22u	10%	DISCRETE	3	C171;C172;C173
RJC-1210-D-BYZ	RJC378-RJC 378 1118/1,10U,10%,A	10u	10%	DISCRETE	2	C200;C207
RPT268-1-BYZ	RPT26802_BYZ-RPT 268 02/03,SMOA			IO	1	TP18
RPT268-1-BYZ	RPT26802_BYZ-RPT 268 02/04,SMOA			IO	25	TP108;TP109;TP110;TP111;TP112;TP113;TP114;TP115; TP116;TP117;TP118;TP120;TP121;TP122;TP123;TP124; TP125;TP126;TP127;TP128;TP129;TP130;TP131;TP132; TP133
RPT368-2-M-SMD	RPT368405_BYZ-RPT 368 405/2,19A			IO	17	X100;X101;X102;X103;X104;X105;X106;X107; X108;X109;X110;X111;X112;X113;X114;X116; X117
RYTM-MSOP8-9-SMD	RYTM1130001_SMD-RYTM 113 0001/A			IC	1	N205
RYTM-QFN5X5-25-SMD	C0001789_SMD-C0001789,TGA2975-B			IC	2	N301;N302
RYTM-TO-PMOD-8-SMD	RYTM1130028_SMD-RYTM1130028/1,A			IC	1	U11

Appendix E: Evaluation Board Mounting Drawing

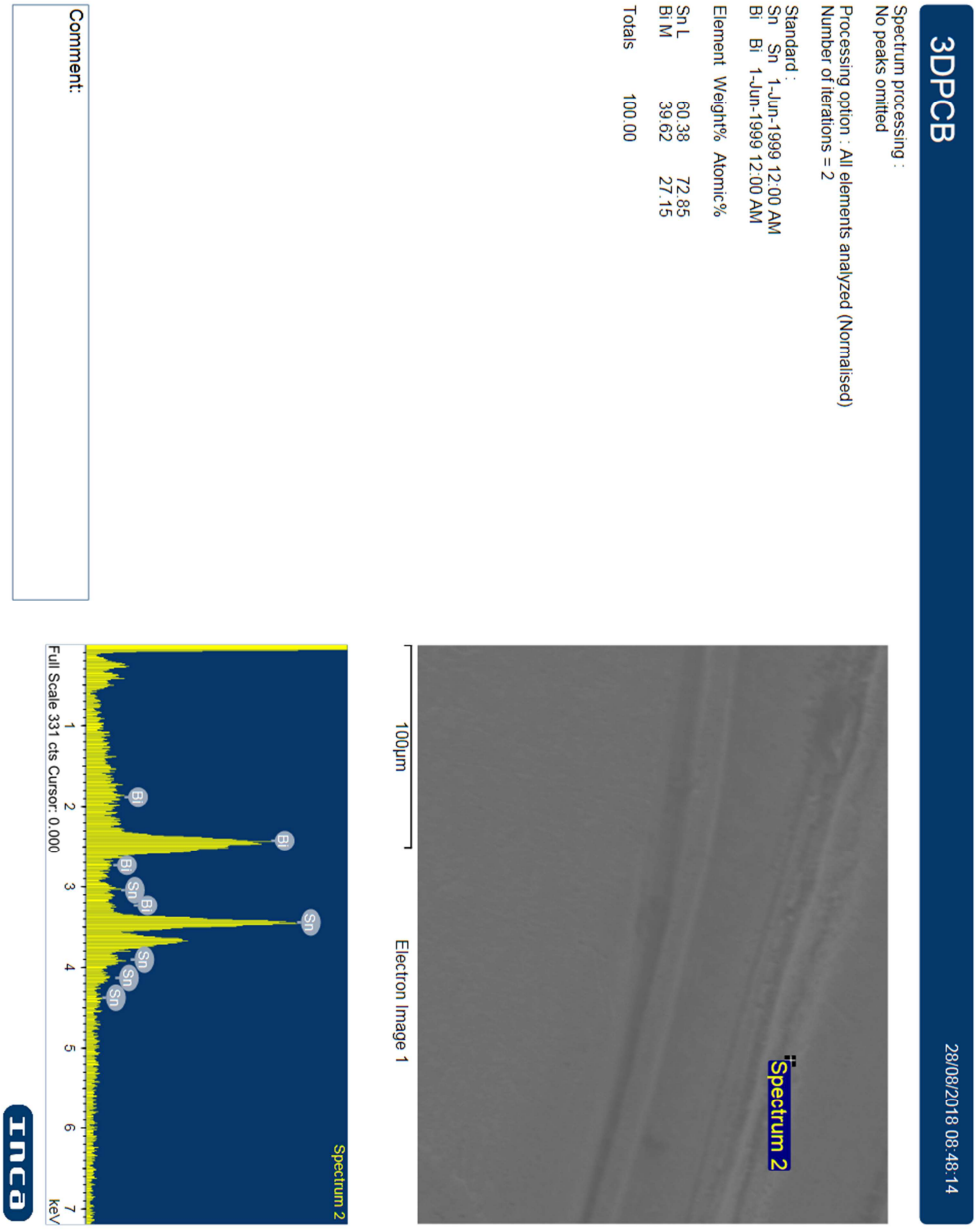


MOUNTING DRAWING

SAAB	Prepared (also subject responsible if other) OELDHK Åsa Rystedt
Classification Export Control: NOT EXPORT CONTROLLED	Document responsible/Approved: OELDHK (Andreas Berntsson) | Date: 2018-05-28 | Rev: A
Classification Company Confidentiality: COMPANY UNCLASSIFIED	Product name: PRINTED BOARD ASSEMBLY 3D-printing testboard
Classification Defence Secrecy: OPPEN/UNCLASSIFIED	Document No.: 1078-TEST1804001/1 en | Sheet: 1(2)

Appendix F: SEM+EDX analysis- Solder surface 10 kV

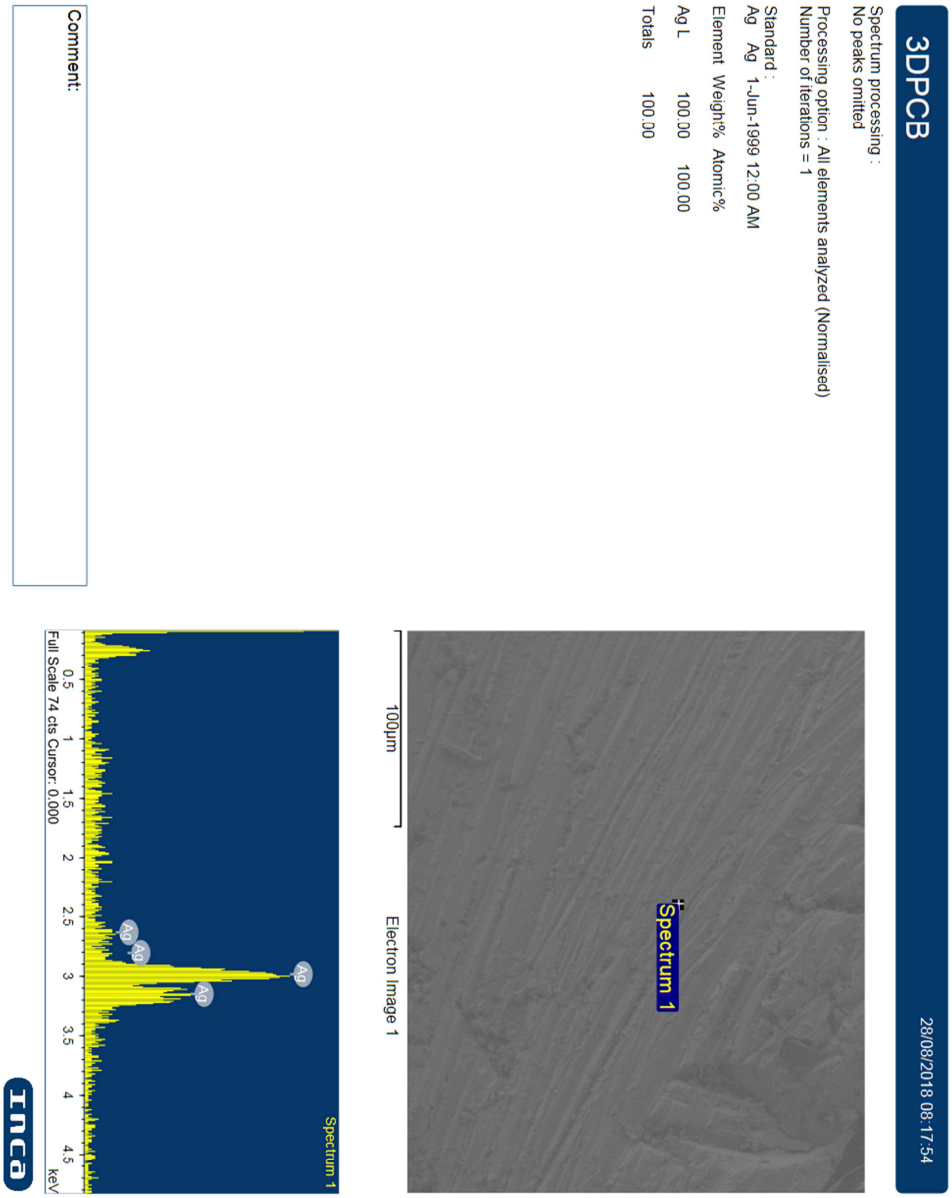
Appendix G: SEM+EDX analysis- Solder scratch 10 kV



Appendix H: SEM+EDX analysis- Solder scratch 20 kV

Appendix I: SEM+EDX analysis- Solder surface 20 kV

Appendix J: SEM+EDX analysis- Polished VIA -10 kV



Appendix K: SEM+EDX analysis VIA - 10 kV