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3D metal printing of mold inserts

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BACHELOR'S THESIS

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Abstract

Studied in this thesis work are the pros and cons of manufacturing the mold inserts in metal with 3D printing technique. Current molds used by ABB Oy are made with the traditional method, CNC-machining. The purpose of the research work is to clarify the manufacturing differences between CNC-machining and 3D printing the mold inserts. Highlighted research questions are the benefits of 3D printing the mold inserts. The goal is to use the 3D printed mold inserts in injection molding for mass-producing a plastic cover in polycarbonate, used in ABB's low voltage switches. The design freedom offered by 3D printing is studied for potential optimized mold design of cooling channels, which would shorten the injection molding cycle time.

The mold inserts are 3D printed with the additive manufacturing method, *selective laser melting* (*SLM*) by subcontractors of ABB. Post process methods such as electrical discharge machining and heat treatment are mandatory in order for the mold to be functional. Material options taken into consideration for the mold inserts are *aluminum*, *tool steel* and *stainless steel*.

Nearly all research questions got clarified for continued research in the future. The outcome indicates positive characteristics for both manufacturing methods. The distinction is mainly the different manufacturing process, even though the possibility to achieve same results.

Language: English Key words: 3D metal printing, mold, SLM, IM,

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Abstrakt

Forskat i denna avhandling är potentiella positiva och negativa aspekter för 3D-printning av formverktyg i metall. Nuvarande formverktyg i användning av ABB Oy är tillverkade med den traditionella tillverkningsmetoden CNC bearbetning. Syftet med forskningsarbetet är att klargöra tillverkningsskillnaderna mellan CNC-bearbetad och 3D printad formverktyg. Huvudsakliga undersökningsfrågor är fördelarna med att använda 3D printing för att tillverka formverktyg. Målet är att använda den 3D printade formen i formsprutning för massproduktion av ett plastlock i polykarbonat som används i ABB:s lågspänningsomkopplare. Även designfriheten som 3D printing erbjuder är undersökt för potentiell optimering av formens kylkanaler, som skulle förkorta formsprutnings cykeltiden.

Formen är framtagen av underleverantörer med additivtillverkningsmetoden, selektiv lasersmältning (SLM). Vissa efterbehandlings metoder som t.ex. gnistbearbetning och värmebehandling är obligatoriska för att formen skall kunna användas. Materialval som tas i beaktande för formen är aluminium, verktygsstål och rostfritt stål.

Nästan alla forskningsfrågor klargjordes för möjlighet till framtida fortsatt forskning. Resultatet tyder på positiva egenskaper för båda tillverkningsmetoderna. Skillnader är främst i tillverkningsprocessen, fastän samma resultat kan uppnås.

Språk**:** Engelska Nyckelord**:** 3D metal printing, mold, SLM, IM,

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Tiivistelmä

Tässä opinnäytetyössä on tutkittu mahdollisia positiivisia sekä negatiivisia näkökohtia muotti insertteistä jotka ovat 3D tulostettu metallista. ABB Oy: n nykyiset käyttämät muotit valmistetaan perinteisellä, CNC koneistus menetelmällä. Tutkimustyön tarkoituksena on selventää CNC koneistuksen ja 3D tulostettujen valmisteiden erot ja lopputulokset. Yksi tärkeimmistä tutkimuskysymyksistä oli selvittää mitä etuja muotti insertin 3D tulostuksessa on. Tavoitteena on käyttää 3D tulostettua muottia muovikotelon massatuotantoon polykarbonaatista, joka valmistetaan ruiskuvalu menetelmällä, jota käytetään ABB:n pienjännitekytkimissä. Myös 3D-tulostuksen tarjoamaa suunnitteluvapautta mahdollisten jäähdytyskanavien optimoimiseen tutkitaan ja että miten ruiskupuristuksen aikaa lyhennetäisiin.
Muotti on 3D tulostettu ABB: n alihankkijoiden tekemällä lisäaineen valmistusmenetelmällä, selektiivisellä laser sulatuksella (SLS). Jälkiprosessimenetelmiä, kuten sähköpurkauksen työstö ja lämpökäsittely ovat välttämättömiä, jotta muottia voidaan käyttää. Materiaalivaihtoehdot, jotka tutkittiin muotin käyttöön, ovat alumiini, työkaluteräs ja ruostumaton teräs.

Lähes kaikki tutkimuskysymykset selvitettiin tulevaisuuden jatko tutkimukselle. Tulos osoittautui positiiviseksi ominaisuudeksi molempiin menetelmiin. Erona pääasiassa on erilainen valmistusprosessi saman tuloksen saavuttamiseen.

Kieli: Englantia Avainsanat: 3D metal printing, mold, SLM, IM,

PREFACE

This bachelor’s thesis was made with collaboration between ABB Oy – Protection and Connection unit and Novia – University of Applied Science. I hope this survey can be of interest to anyone interested in subjects related to 3D metal printing of mold inserts. I want to thank my brother, Simon Renfors for the writing support along with my supervisors, Martti Taimisto, Jarmo Lehtimäki and Mika Vilkki from ABB, and Kenneth Ehrström from Novia.

Vasa, 2.4.2019

Edwin Renfors

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Glossary

2D	2 Dimensions
3D	3 Dimensions
ABB	ASEA Brown Boveri
BBC	Brown, Boveri & Cie
AM	Additive Manufacturing
CAD	Computer Aided Design
CNC	Computer Numerical Control
EDM	Electrical Discharge Machining
IM	Injection Molding
ISO	International Organization for Standardization
MEPC	Mitsubishi Engineering Plastics Corporation
PM	Project Manager
R_A	Roughness Average
R&D	Research & Development
SLM	Selective Laser Melting
STL	Stereolithographic

1 Introduction

This Bachelor's thesis is a collaboration with ABB Oy, Protection and Connection unit, and Novia – University of Applied Science in Vaasa.
3D printing in metal has developed greatly and is today a suitable additive manufacturing (AM) method to create tools and parts of complexed geometry with excellent material characteristics. In this thesis case mold inserts are 3D printed with the AM method, SLM. Mold inserts are used to produce plastic parts in the manufacturing method *injection molding*. The mold is designed to produce a small cover (figure 1) in polycarbonate for ABB's low voltage switches. Polycarbonate is used by ABB because of its good surface quality, mechanical properties and heat resistance. Materials investigated and taken into consideration for the mold are: aluminum, tool steel and stainless steel.

ABB already have several molds in use that produces the mentioned cover. The current molds are made with CNC-machining, that is a subtractive method – in contrast to 3D printing which is an additive manufacturing method. To simplify, CNC-machining removes material that can't be reused while 3D printing adds material with nearly no material wasted.

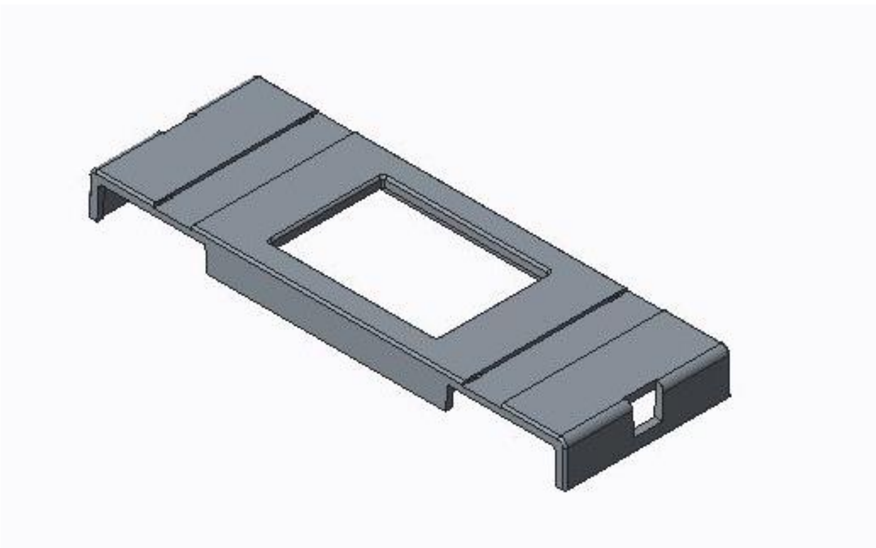

Figure 1 *Plastic cover*

1.1 Purpose of the thesis

The purpose of this thesis is to clarify the profitability and potential setbacks of using *selective laser melting* (SLM) to 3D print mold inserts in tool steel. The goal is to find potential benefits with the additive manufacturing (AM) method 3D printing compared to CNC-machining.

1.2 Structure

The structure of this thesis project is divided into two main sections. At first the essential theory scope is presented in chapter 1-4, after which the practical implementation along with related results are presented in chapter 5-7.

The theory section presented in chapter 2 are meant to give an understanding of 3D printing in metal, including process, available methods and material options. Chapter 3 presents the manufacturing method for the plastic cover, injection molding (IM). The theory scope covers the IM method, process and the mold inserts role. In chapter 4, the mold inserts are highlighted and explained along with the post process method, electrical discharge machining (EDM)

The 3D printed mold is presented in chapter 5. This chapter scope includes order requirements, material choices taken into consideration and the project course of action for 3D printing the mold inserts and fitting in the IM machine. The results of the 3D printed mold and produced cover are divided in chapter 6. Finally, a discussion along with future possibilities are held in chapter 7.

1.3 Methods

The methods consist of a theoretical survey of current literature on the topic and a practical investigation involving different analysis methods of mold and plastic cover. The analyzation includes visual inspection, comparing, measuring and testing.

The theoretical survey involved was mainly to get a profound understanding of 3D metal printing and injection molding. The survey was made during exact same boundary conditions.

1.4 ABB Oy, Protection and Connection unit

ABB was founded in 1988 after merging with the Swiss company, BBC, and the Swedish company, ASEA, making it a Swedish-Swiss multinational company. [1] ABB is and has for many years been a global leader in electrical equipment such as power grids, robotics and automation technology. ABB's headquarter is located in Switzerland, Zurich and the company operates in more than 100 countries having about 147,000 employees.

In ABB Finland there are nearly 5000 employees on nearly 40 different locations. The Finnish headquarter is in Helsinki and factories can be found in Vaasa, Porvoo and Helsinki. [2] The Finnish business unit Protection and Connection is located in Vaasa with about 250 employees. The unit is globally responsible for sales and marketing, product development, and manufacturing of different kind of low voltage switches. The factory manufactures load switches, change-over switches, safety switches, enclosed switches, switch disconnectors and cam switches. The switches are used worldwide in applications related to the generation and transmission of electrical energy. The switches allow, isolate or prevent the electricity flow in energy transfer and use. The products are used in engine startup and shutdown, as well in overload, short circuit protection and for switching energy supply. [3]

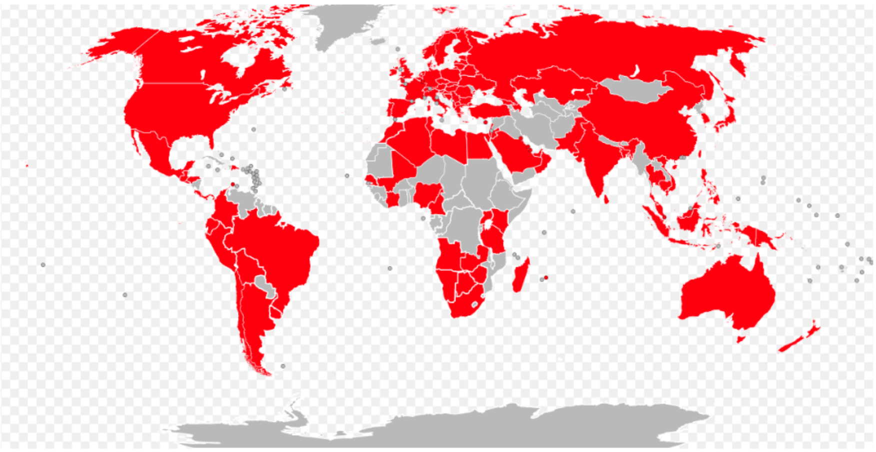

Figure 2 *ABB around the world* [4]

2 Basics of 3D metal printing

3D metal printing is an AM method that solidifies raw material, layer by layer into a three-dimensional object under computer control. The AM method first emerged in the early 1980s [5]. Originally the printers were large, expensive and highly limited in what they could produce. Through development the variation has expand greatly making 3D printers affordable even for hobby use by amateurs. [5]

Benefits with 3D metal printing are the abilities to easily create complex parts (see figure 3). Made possible is to merge assembly parts, and therefore potentially reduce material weight and related costs. Another benefit is that the 3D printers are self-automated and can therefore be left printing unobserved. 3D metal printing is also cost-efficient for prototyping and small batch orders. Due to the 3D printing benefits products can for example be found in aerospace technology where customized parts are required or medical field to fulfil the patient's anatomy. [5]

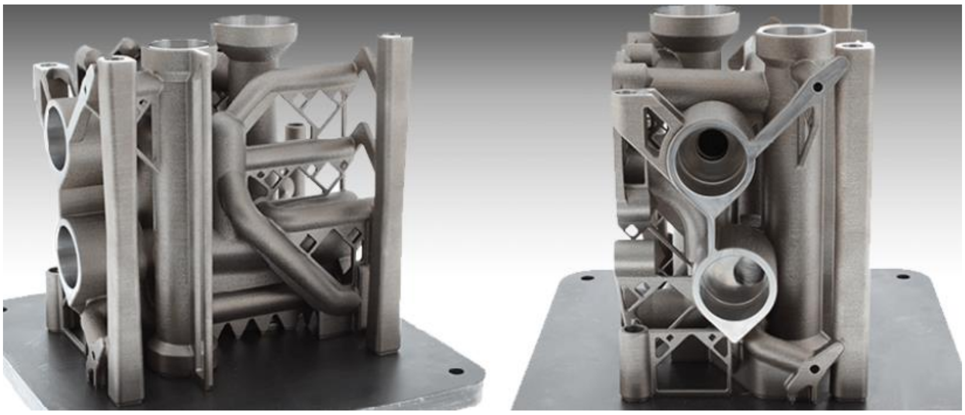

Figure 3 *Complexed 3D printed engine component by Renishaw* [6]

There are numerous methods to 3D print in metal. The main considerations when choosing a method are production speed, costs of the 3D printer, part requirements and material capabilities. The most common methods which melt or fuse the material to produce layers are for example, selective laser melting ((SLM), explained in chapter 3), selective laser sintering (SLS), or electron-beam melting (EBM). [7]

The high processing temperature of 3D metal printing needs to be taken into account to prevent faulty results. Parts are therefore most often printed at an oriented angle in order to minimize warping caused by thermal problems, such as bending or shrinking. Support structure are applied for anchoring the part to the building plate and complicated geometry such as overhang in the object. The support structures can be generated to the CAD design or added during the 3D printing process. [8]

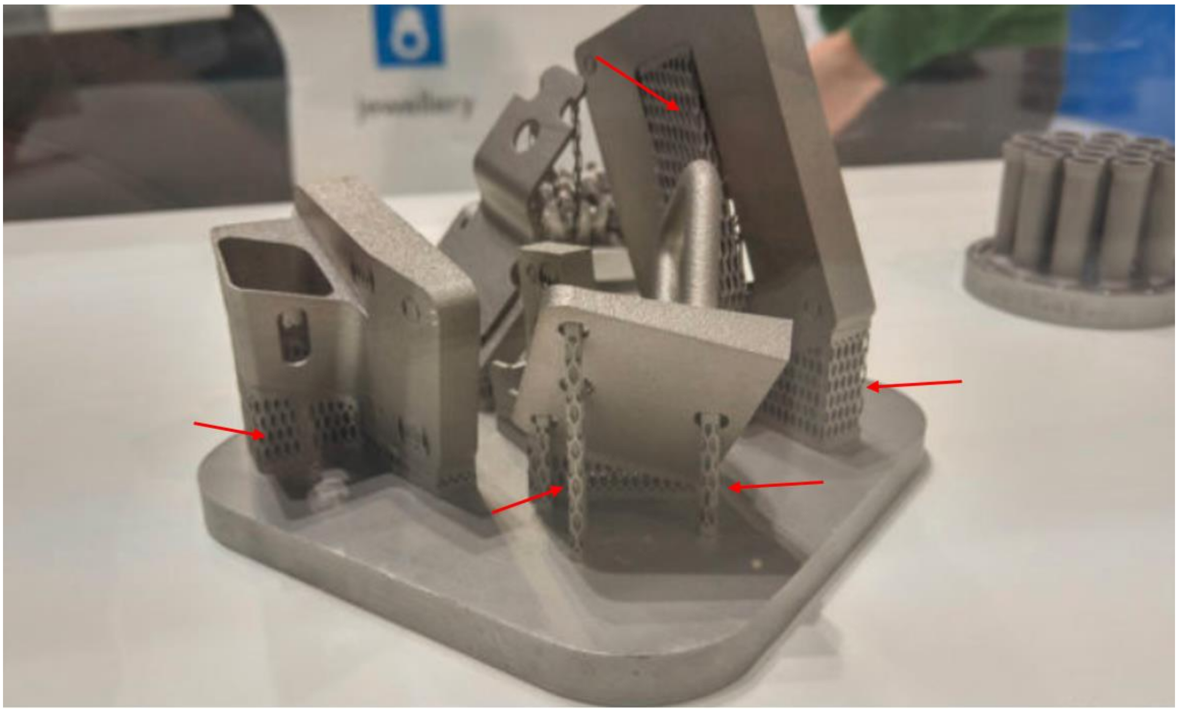

Figure 4 *Required support structure indicated with red arrows.* [9]

2.1 Additive manufacturing process

The AM process can be divided into three main stages (figure 5), part design, 3D printing, and finally, postprocess.

Figure 5 *Stages of 3D printing*

Step 1, Design:

The first step is to design a printable 3D object in a CAD software. If the designed object is of complex geometry, support structure needs to be added in this step, or alternatively in step two. [10] The design file is exported, usually to a .STL file, so that the 3D printer can recognize it. The design stage is of great impact of the final result and therefore, it’s essential to take advantage of the design freedom offered with 3D printing. It is wise to be in contact with the 3D printing manufacturer early in the design stage in order to avoid non-printable objects. Design changes can be edited in CAD software, if needed, and transferred directly from the designer to the 3D printing manufacturer, which eliminates for lost time and costs associated with shipping. [11]

Step 2, 3D printing:

This is the actual 3D printing process, so a material needs to be chosen at this point.
Support structure needs to be applied if not made earlier in the design step. As the printer recognizes the 3D model it cuts it into 2D layers, usually from 20 to 100 µm thick with assigned parameters, values and physical support. A thin layer of metal powder is spread over the build platform by the reciprocating recoater blade (figure 6). The high-power laser is used to melt the metal particles together to create layers. The build platform moves downwards by the created layer thickness, so the process can be repeated until the whole part is completely 3D printed. [10] The printing takes place inside a chamber containing a tightly controlled atmosphere of inert gas, either argon or nitrogen, this will minimize the oxidation of the metal powder. [12]

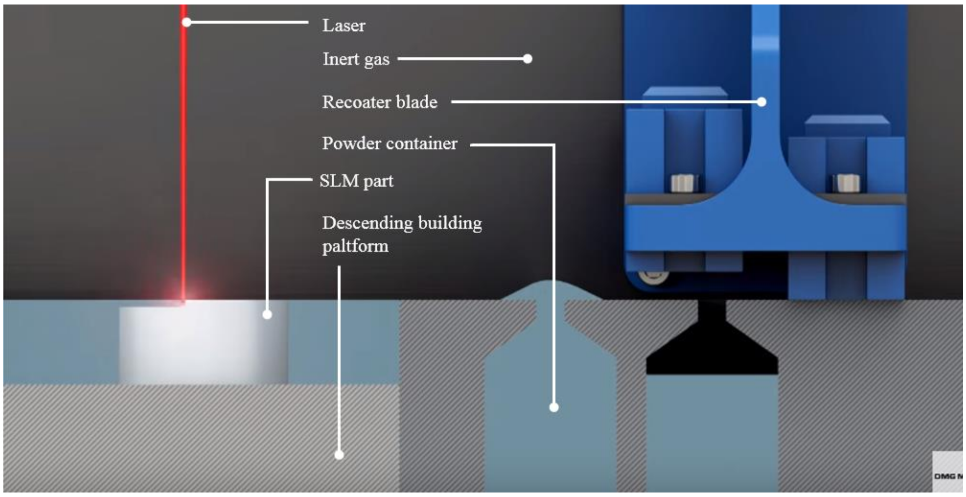

Figure 6 *3D metal printing* [13]

Step 3, Post process:

The unused metal powder that was sprayed on to the build platform is collected, sieved and topped to be reused. Normally (if done correctly), less than 5% of collected powder goes to waste. [10] The 3D printed object is removed by hand, cutting, machining or wire EDM. Necessary post process methods, including removal of support structure are performed to achieve the object's demands. The objects characteristics such as mechanical properties, accuracy and part appearance (figure 7) are improved with various post process methods. Machining is employed for dimensionally crucial features such as holes or threads, and removal of burrs and flanges. The high processing temperature of 3D printing followed by cooling causes inner stress for the material, leading to poor material hardness. The residual stresses are relieved by heat treatment, which is commonly used for improving the microstructure and mechanical properties. Heat treatment takes place in an oven big enough for the whole 3D printed object.

Figure 7 *3D printed object in Titanium, before and after postprocess which included support structure removal and surface texture finish* [14]

Once necessary post process methods are completed, inspection and testing can be performed so the object can be approved for use. There are numerous ways to inspect and analyze the object, but the most common methods are measuring, dye-penetrant testing, ultrasonic testing, computed tomography and scanning. [12]

2.2 Selective laser melting (SLM)

Selective laser melting is an additive manufacturing technique that allows complex metal parts to be printed in 3D. For example, thin walls, deep cavities, holes and channels in the object can easily be made. This German patented technology was discovered in 1995. [5]
The printable materials are namely steel, titanium, aluminum, cobalt-chromium and nickel alloys. [5] The method uses a laser beam (figure 8) to melt (thermal energy converted into

heat energy) metallic powder in specific places, indicated by the design made in CAD software. The metallic powder is deposited on to the bed of the build platform where the melting occurs. The machine will add beds of powder above the already created layer, until the object is completely printed in 3D. [5]

The powerful laser is a key component and yet at the same time the biggest constraint of SLM. Heat dissipation is made to the air, unused raw material powder, potential support structures, and most critical, the lower layers already printed. [8]

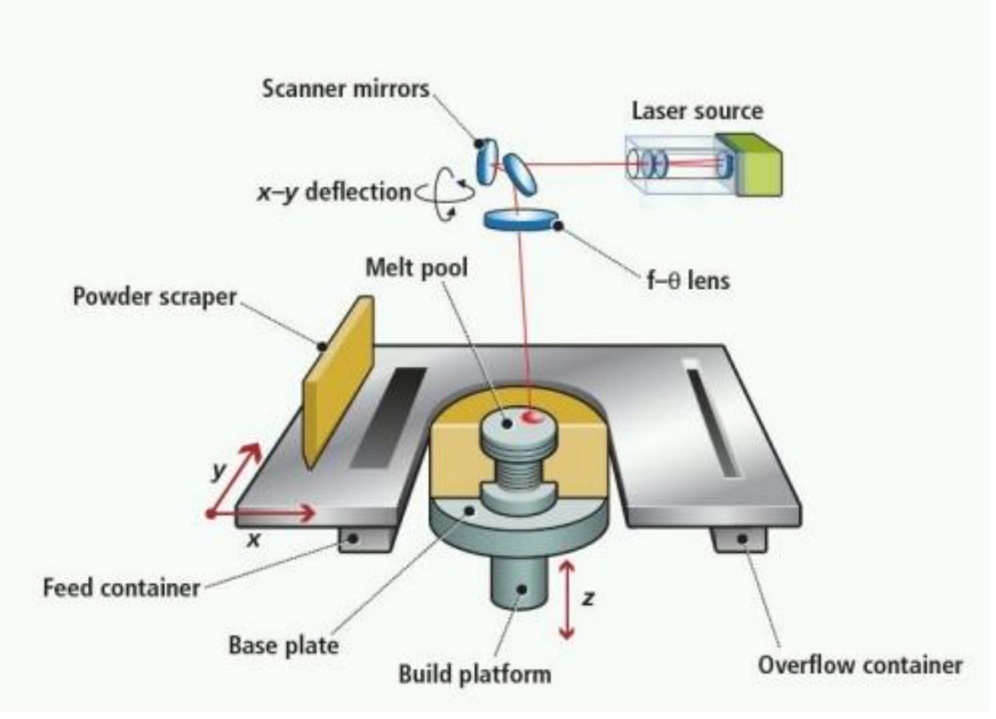

Figure 8 *Selective laser melting* [15]

Compared to other AM methods, no pressure is applied for SLM, which increases the mechanical properties such as higher density and material strength and therefore more durable object with fewer post process steps. [16] The improved molding accuracy results in less brittleness when subjected to stresses in material and. [17] The method produces low amount of noise, as there is no vibration during the process. [18]

3 Injection molding (IM)

The mold tool is used in the most common manufacturing method of plastic parts, *injection molding* (IM). The mold inserts are fitted into separate mold assembly frame, whereof one of the two frames are reciprocating in order for the mold tool to close and open. The most essential abilities with IM are: [19]

- Great variety of moldable materials
- Variety of products
- Automated process
- Fast and a-reliable method
- Scrap material can be recycled
- Most polymers can be used, including all thermoplastics, some thermosets, elastomers and glass fiber.
- Colorant may be added to control the color of the final part

A wide variety of products can be manufactured with IM. Variation in size, complexity, material and application is great. Parts made can be everything between a small lid to big car parts such as bumpers and instrument panels. The disadvantages are mainly high tooling and equipment costs. The IM tool lineup is illustrated in figure 9. [19]

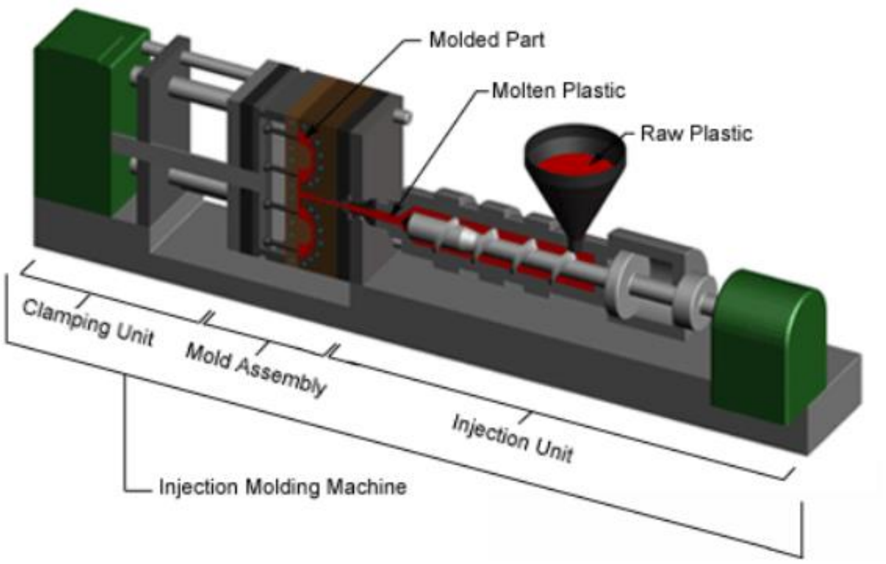

Figure 9 *IM tool line up* [19]

Essential parameters (listed in figure 10) taken into consideration when choosing a material for IM are mainly the melting temperature of the plastic raw material, mold temperature, drying, peripheral speed and emphasis. [20]

Parameters	Polycarbonate
Melting temperature	290 °C
Mold temperature	80-120 °C
Drying (max 0.02 % moisture content)	2-4 hours at 120 °C
Peripheral speed	0,4 m/s
Emphasis (after pressure)	60-80 [MPa]

Figure 10 *Essential parameters, values for polycarbonate*

3.1 IM process

The IM process can be divided into following four main stages:

Step 1: Melting/Clamping (Figure 11): During the first stage the mold halves are securely closed and pressed together by a clamping unit. Material granules from the hopper feed into the heated barrel & rotating screw. The injection material which is melted by heat, friction and shear force is forced through a check valve to the front by the rotating screw. [19]

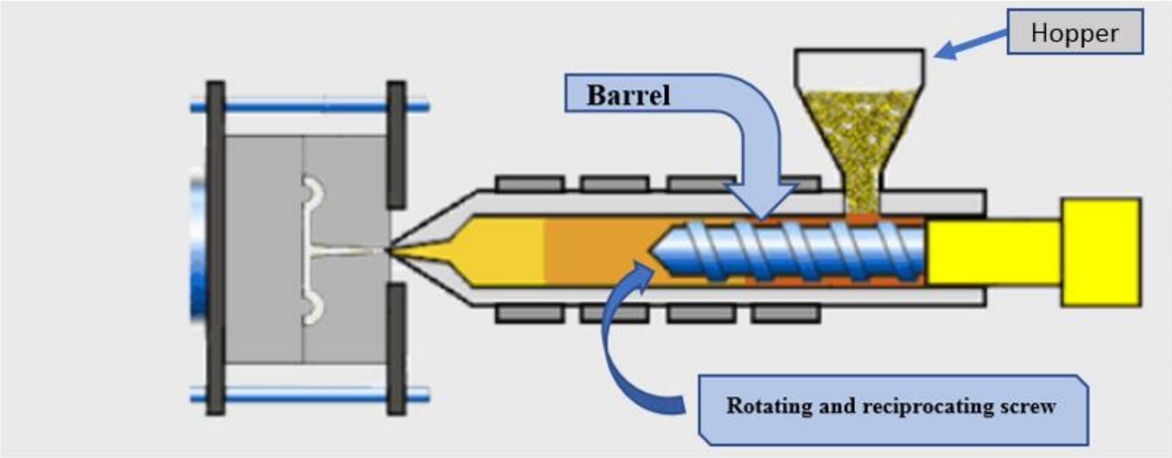

Figure 11 *Melting/clamping stage* [21]

Step 2: Injection (figure 12): The second stage is the injection phase of the molten raw material. At first about 95% of the material is quickly injected from the cylinder into the mold, followed by a hold, when the rest of the volume is filled with slower speed. The hold compensates for the shrinkage effect of the cooling material. [22]

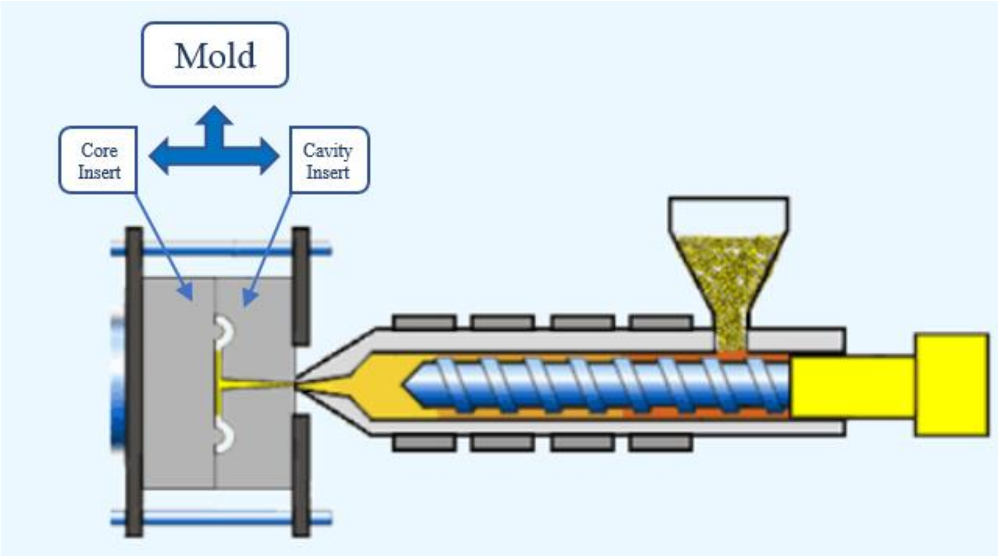

Figure 12 *Injection stage* [21]

Step 3: Cooling (figure 13): In the cooling stage the mold is held closed together under pressure until the plastic material cools & sets hard in the mold cavity, the cooling starts as soon as the material makes contact to the mold surface. Depending on material the melting temperatures vary between 150 – 450 °C when injected. To properly eject the component temperature has to decrease to 30 – 230 °C, depending on material. [22]

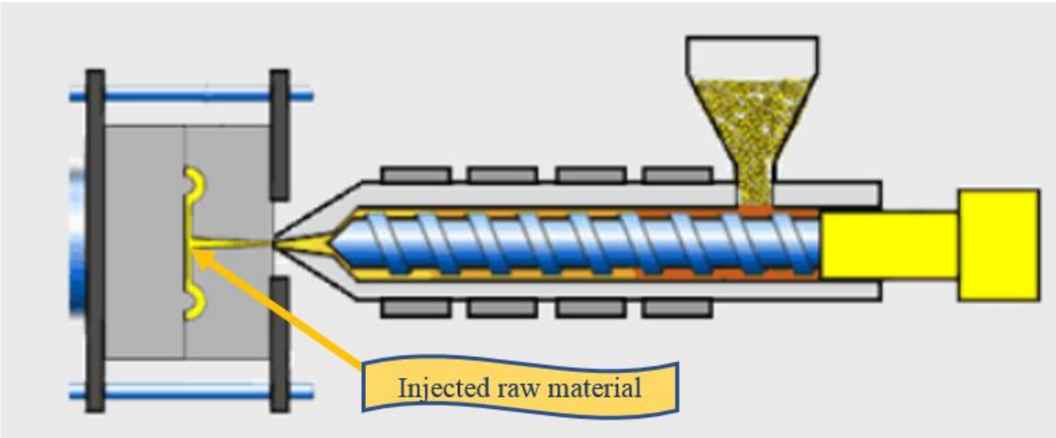

Figure 13 *Cooling stage* [21]

Step 4: Ejection: (Figure 14): The last step is the ejection phase.
The rotating screw starts moving backwards preparing for the process to start over from step 1 meanwhile the mold halves opens up allowing the molded part to be ejected.
In this phase the plastic has cooled enough to make it retract. Ejector pins are used to help the molded part to come of the mold core. The process can then start over again from stage 1. [22]

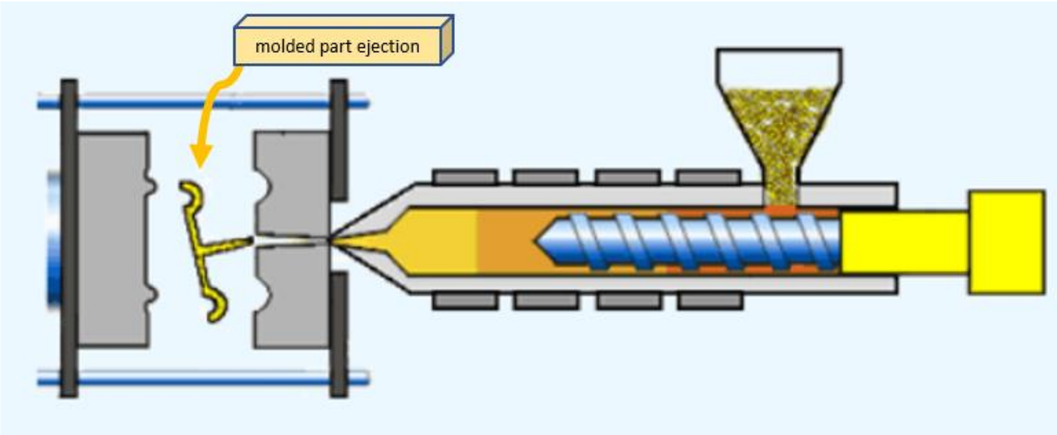

Figure 14 *Ejection stage* [21]

4 Overview of mold inserts

Mold inserts are composed of two parts called the *mold core* and the *mold cavity* (figure 15). The inserts are fitted to the assembly frame of the IM machine. The materials used for mold inserts are mainly hardened steel, aluminum and/or beryllium-copper alloy. The choice of material is primarily a question of economics and production volume.

When the mold halves are attached together it creates a hollowed-out shape between. The raw material is injected trough the sprue creating the desired plastic component. It is essential for the air to escape during the process, so the molded components don’t contain voids (air bubbles), that would result in poor surface finish. Once the injected raw material cools it hardens and adopts its shape. Cooling channels are built into the mold, where water flows in order for sufficient cooling of the raw material. Water is the most common and efficient coolant with thermal conductivity of 900 W/mK. [22] When the component is sufficiently cooled the mold opens allowing the created component to fall out. Ejector pins are used to ease the ejection phase. Several parts can be produced in each IM cycle depending on how many cavities the mold has. In mass production it is ideal to use a mold with as many cavities as possible to shorten the production time, normally used are molds with 1-4 cavities. [23]

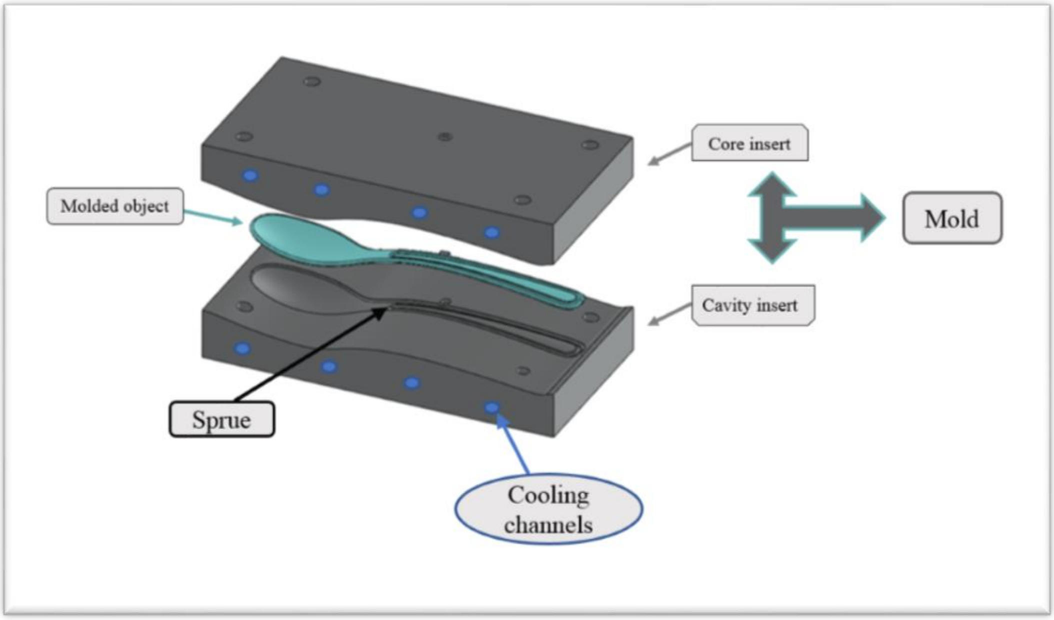

Figure 15 *A one-cavity mold used in IM to manufacture a plastic spoon* [24]

During the mold design phase, it is essential to take draft in consideration. The molded part will contract when cooling. Without applied *draft* (figure 16) the part would get pinned to the core insert. Draft needs to be applied during design of the plastic part and the mold.

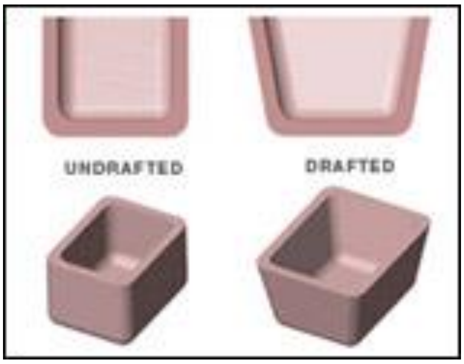

Figure 16 *Undrafted vs drafted explanation [23]*

The required draft (in degrees) depends on the geometry and surface texture requirements of the part. Normally 0,5 – 2 degrees are used.

4.1 Electrical discharge machining (EDM)

Electrical discharge machining (EDM), also known as *spark machining* or *sinker EDM* is a method which uses electrical discharge to achieve a desired shape, or surface texture. EDM is used for the mold because of the covers surface texture requirement, which is easiest achieved with EDM. There are two similar methods available, one being Wire EDM that uses a fine metal wire to cut the workpiece in any x-y direction, this method is suitable for any conductive material and can process demanding details such as narrow slots or dies that are difficult to machine with other methods. [25] The third method is called Hole Drilling EDM which is a fast and accurate method for producing holes with a rotating tube in any conductive material. [26]

With EDM minimal material will be removed from the object using thermal energy.
This method uses a high-frequency electrical current to flow (figure 17) between two electrodes and thereby creating a spark, one being the workpiece. The gap between is roughly about 100 µm. The spark can reach temperatures as high as 12 000 °C. [27]

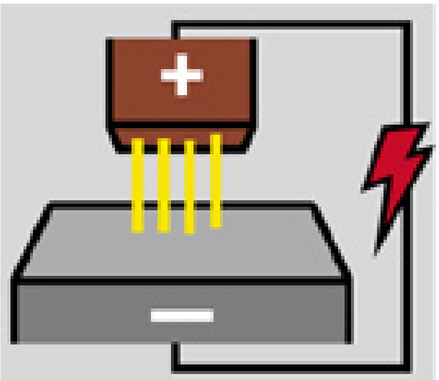

Figure 17 *Electrical current flow creating sparks.* [28]

Unless enough voltage is applied that would bring it to its ionization point, a dielectric fluid is needed as an electrical insulator. The fluid is also useful for cooling and controlling the sparks. After the process a "flush" is needed to remove the solid particles. Used is a conveyed dielectric liquid. [29] Also, the potential difference between the electrodes needs to be restored afterwards so a new dielectric breakdown can occur. [30] This accurate method allows tolerances as high as 0,012 mm and does not need any post process as it does not create burrs etc., therefor it is a very popular method in production stages. The disadvantages of EDM is the slow rate of material removal. [31]

5 SLM 3D printed mold

The mold inserts were 3D printed with SLM technique by subcontractors of ABB. The CNC-machined mold dimensions were useable for the 3D printed mold, despite the different manufacturing method. The hollow insert dimension, which is slightly larger than the cover, were set by the cover. Biggest design difference of the CNC-machined mold and the 3D printed mold are that the 3D printed mold contains four inserts which are one-cavity while the CNC-machined mold contains two inserts which are two-cavity. Theoretically both the CNC-machined mold and the 3D printed mold produce two covers each IM cycle, despite the different concepts (illustrated in chapter 6.1).

The project course of action includes all the operators required in the manufacturing chain to complete the project (figure 18). ABB ordered the mold through the manufacturing project manager (PM), whom was in charge of the manufacturing process and delivering of the mold. The mold *design* was operated by a subcontractor, followed by a *SLM mold manufacturer*, who 3D printed the mold in tool steel. The 3D printed mold was then used by the *plastic part supplier*, functioning as a third subcontractor using them for IM. My role in the project was to study and learn the process in order for reporting and analyzing the result.

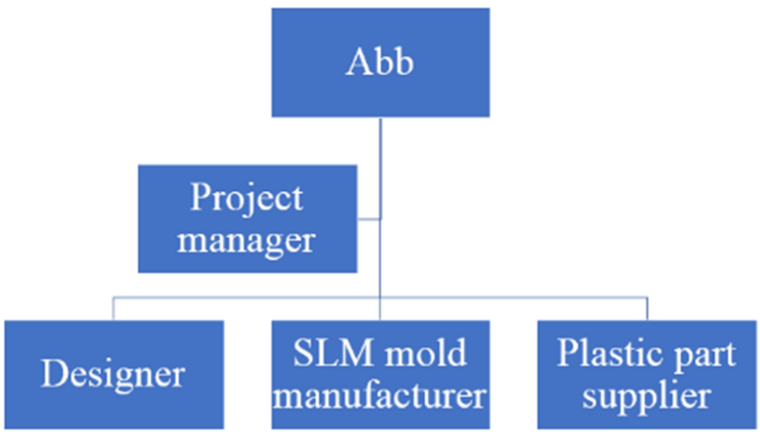

Figure 18 *Operators involved in the manufacturing stage from start to finish*

5.1 Choice of materials

The material choice for the mold is of great importance, especially when used in mass-production. Three different material options were studied for the 3D printed mold:

1. Aluminum (AlSi10Mg)
2. Stainless steel (316L)
3. Tool steel (1.2709)

All three materials meet the requirement as a precise material with close to 100% of the theoretical maximum density. As for the costs *Aluminum* is the cheapest followed by *stainless steel*. The most expensive one is *tool steel*. [32]

1. Aluminum

Aluminium is light, functional and durable, with low density of 2.7 g/cm^3. Hardness test measured at layer thickness 30 µm by Vickers Hardness is 117 [HV10]. [33] The hardness is not strong enough for the mold to be used in mass-production. Aluminium is however suitable for prototyping or small batch ordering. Possible post-process methods are for example heat treatment or hardening. See appendix 1 for full material specification.

2. Stainless steel

Stainless steel has a higher density and hardness, density being 7.95 g/cm^3 and hardness by Vickers Hardness 233 [HV10] (measured at layer thickness 30 µm). This makes Stainless steel a better choice than Aluminum. Also, Stainless steel (and Tool steel) are known for its low nitrogen and phosphor content of less than 0.025%. Stainless steel is widely used in the mold making industry today making it a possible choice. See appendix 2 for full material specification. [34]

3. Tool steel

Tool steel has the highest hardness and is the strongest one of the three material options. Its density is 8.042 g/cm^3 and hardness by Vickers Hardness 310 [HV10] (measured at layer thickness 30 µm). This makes tool steel the best choice of material for 3D printing the mold. [35] See appendix *3* for full material specification.

5.2 Requirements

Ordered for ABB's property consist a two-cavity mold, 3D printed in tool steel with SLM technique and post processed with EDM. The mold is to be movable for different IM machines in mass production, with mechanical life-span guarantee of 1 000 000 strokes. Design improvements related to material savings and cooling channels are highlighted.

As 3D printing in metal still is a relatively new and rising method, especially in mold manufacturing, a second requirement was to learn more about the steps along the process. The mold order requirements are altogether nine tasks (figure 19) which were clarified with the project manager before ordering.

Required task	Requirement (x)
A) Electrical discharge machining	x
B) Massproduction usage	x
C) Universal movable	x
D) Two cavitied	x
E) ABB's own property	x
F) Mechanical life-span guarantee 1 000 000 strokes	x
G) Optimized design	x
H) Tool steel	x
I) SLM technique	x

Figure 19 *List of required tasks*

5.3 Practical implementation

The core and cavity inserts were 3D printed in separate stages with layer thickness 30 µm. Two unsuccessful 3D printing attempts were made before succeeding the third attempt. The first two attempts failed because the suitable 3D printing angle for the mold needed to be practically tested. The two unsuccessful attempts failed because of incorrectly combined angles of different axis, illustrated in figure 20 are the simultaneously used angles for the two failed printing attempts, 30° angle seen from the front and 15° angle seen from the side.

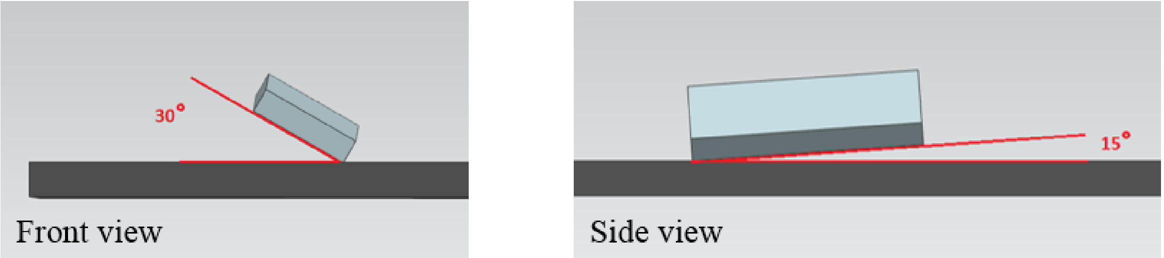

Figure 20 *The simultaneously used angles, 30° printing angle seen from the front and 15° angle seen from the side*

As explained in chapter 2, the printing angle is necessary for optimal heat dissipation, which maximize the hardness and minimize the likelihood of warping. The heat input from the laser is decreased per layer when the mold is oriented at an angle. The two unsuccessful attempts led to uneven heat dissipation that resulted in faulty surface texture, in form of “waves”, and wrong cross measurement of rectangle (figure 21) for the mold.

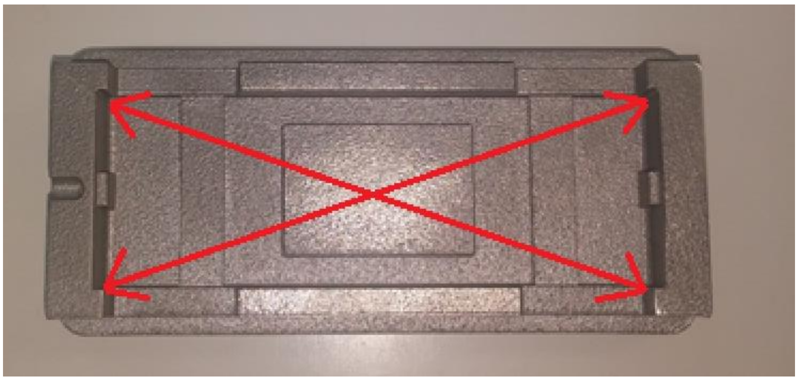

Figure 21 *The 3D printed cavity insert, wrong cross measurement (red arrows)*

The third 3D printing attempt excluded the 15° angle, so that only the 30° angle was used which resulted in better surface quality and right cross measurement (figure 22).

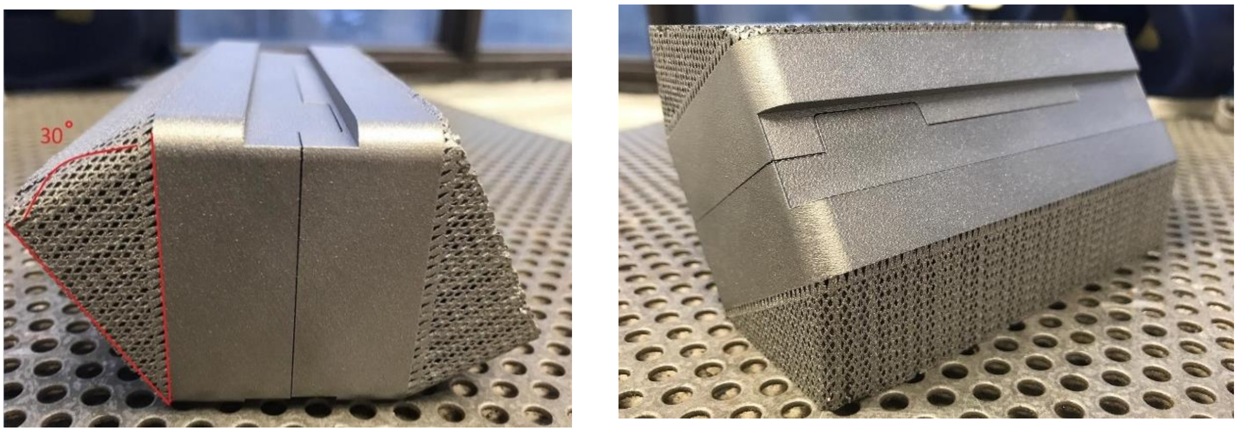

Figure 22 *The SLM 3D printed mold inserts clamped together, before removal of support structure. The support structure is seen within the red marked 30° angle.*

The mold post process involved removal of the support structure with sandblasting. Heat treatment was operated to relieve material stress, which took place in an oven at 490 °C for 6 hours.

The finished mold inserts were then fitted to Krauss Maffei IM machine (figure 23). Two (of the four) inserts were successfully fitted for use, mounting of all four inserts for simultaneously use failed because of orientation errors which was not successfully rectified in time before project interruption.

Figure 23 *Krauss Maffei IM machine*

Each insert is printed with a margin edge on the long sides of the insert (figure 24).

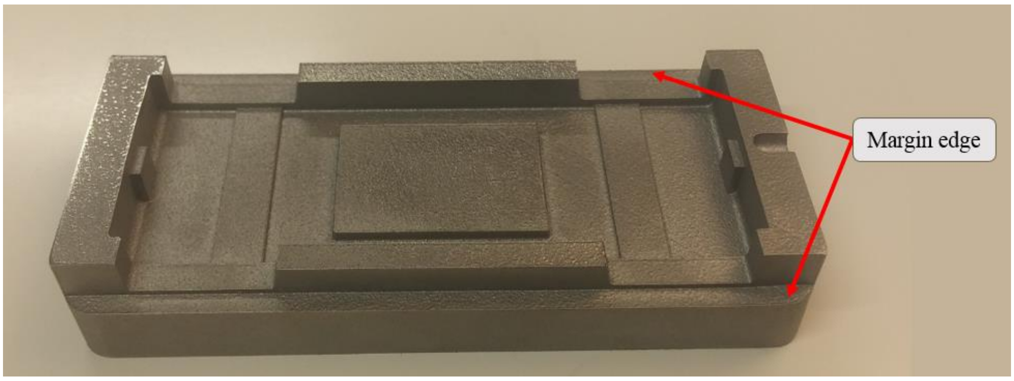

Figure 24 *The red arrows point out the two margin edges*

The edges are used for locking the insert into the IM machine frame (figure 25).

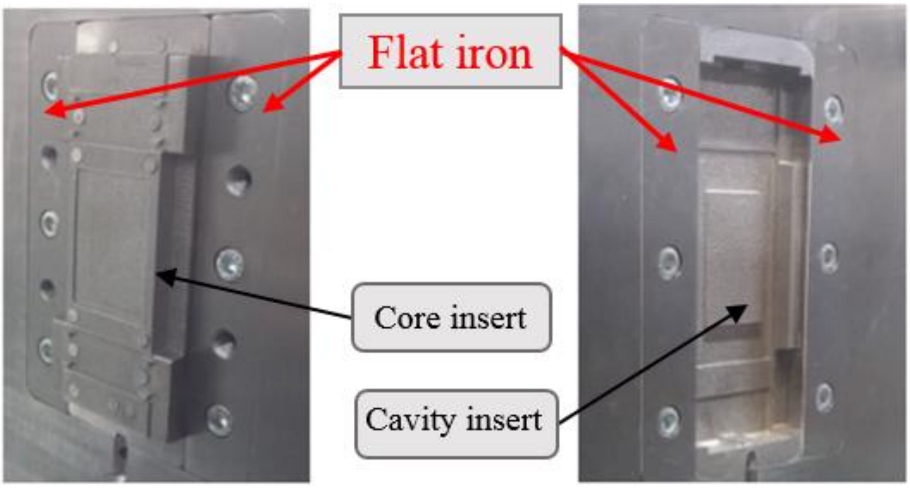

Figure 25 *The inserts assembled with screwed flat irons into the frame*

6 Results and analysis

Tens of covers were manufactured with the 3D printed mold, whereof two samples were received for analysis. The *3D printed mold* results are presented in chapter 6.1 and the *plastic cover* results in chapter 6.2. The manufacturing specifications of CNC-machined mold and 3D printed mold are compared in figure 26.

Manufacturing specifications	CNC-machined mold	Mold made with SLM
Mold cost	8900 Euro	10570 Euro
Material	Tool steel	Tool steel
Life cycle approximation	500 000 strokes	1 000 000 strokes (required)
Mold design time	1 week	1 week
Manufacturing time	10 weeks	12 weeks

Figure 26 *Manufacturing specifications for the CNC-machined mold and the 3D printed mold*

The manufacturing time for the 3D printed mold took 12 weeks (duration from order confirmed until installed in IM machine). The manufacturing time was promised by the project manager to be 3 weeks, which may be possible if done correctly without any setbacks. Main reason for the delayed manufacturing time is the fact that the mold was 3D printed three times.

6.1 3D printed mold

Problems in the communication chain between PM and supplier led to omitting some essential manufacturing specifications. This led to incomplete results that forced for the project to be interrupted. The main reason is that EDM was not taken into consideration during the mold design phase and can therefore not be performed. The consequences of omitted tasks are explained in same order as in figure 27.

Required task	Achieved (x)
A) Electrical discharge machining	
B) Massproduction usage	
C) Universal movable	
D) Two cavitied	
E) ABB's own property	x
F) Mechanical life-span guarantee 1 000 000 strokes	?
G) Optimized design	
H) Tool steel	x
I) SLM technique	x

Figure 27 *Achieved tasks*

A) Electrical discharge machining

EDM not made resulted in rougher surface finish for the cavity insert compared to old cavity, which was postprocessed with EDM. The cavity insert reflects its surface finish to the frontside of the plastic cover. For the new cover this resulted in a higher R_A (Roughness Average of a surfaces measured microscopic peaks and valleys) value compared to old cover. The EDM was not made because its required measurements were not taken in consideration during the mold design phase, making it too late for EDM to be performed. The new covers rough surface is not approved for use by ABB.

B) Two cavities

Illustrated in figure 28 are one cavity insert and one core insert fitted to the Krauss Maffei frame, mounting of all four inserts for simultaneously use failed because of orientation errors.

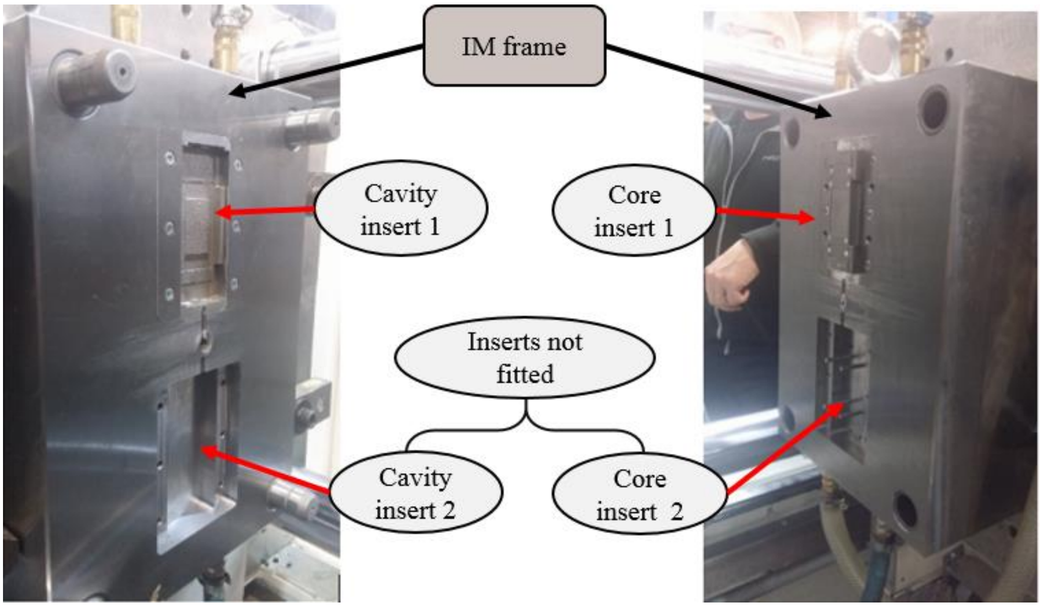

Figure 28 *The left (cavity) side is the stationary platen and the right (core) side is the movable platen*

The CNC-machined mold (figure 29) which is movable for use in different IM machine, consists of one core and one cavity insert.

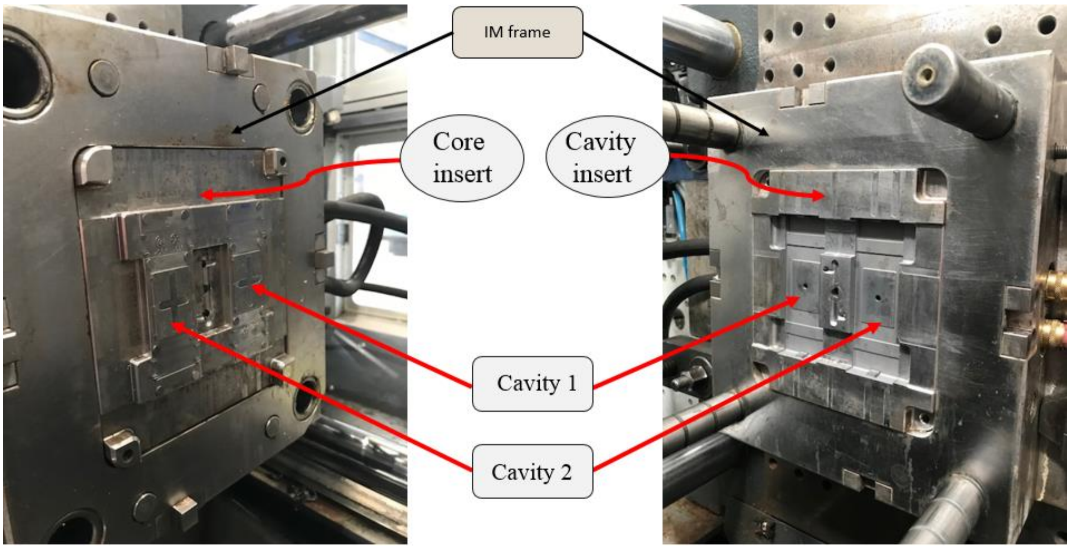

Figure 29 *CNC-machined mold*

C) Universal movable

The 3D printed mold is not movable for different IM machines because it was not printed with standard IM frame dimensions.

D) Mass production usage

The 3D printed mold is not approved for mass production use since the mold doesn't produce good enough quality covers. The reason for this is the omitted requirement tasks, for example omitted EDM which results in a too rough front surface texture of the cover.

E) ABB's own property (Achieved)

ABB is receiving the mold inserts for their own property as required. The mold will not be used in production.

F) Mechanical life-span guarantee 1 000 000 strokes

The required mechanical life-span for the mold is 1 000 000 strokes. This means the two-cavity mold would produce 2 000 000 covers before potential breakdown. No hardness test was made for the 3D printed mold before or after heat treatment, but the estimated values by the PM for Vickers scale are 332 HV before heat treatment and 746 HV after heat treatment. The life-span guarantee can't be stated as achieved nor failed since the mold has only been used for tens of strokes.

G) Optimized design

No optimized design was made for the cooling channels, instead, same cooling channel design as for the CNC-machined mold was used. With 3D printing benefits, the cooling channel design could have been improved. The cooling stage requires most time of all IM stages. Shorter cooling time reduces the covers production time. The IM stages and each stage duration are illustrated in figure 30.

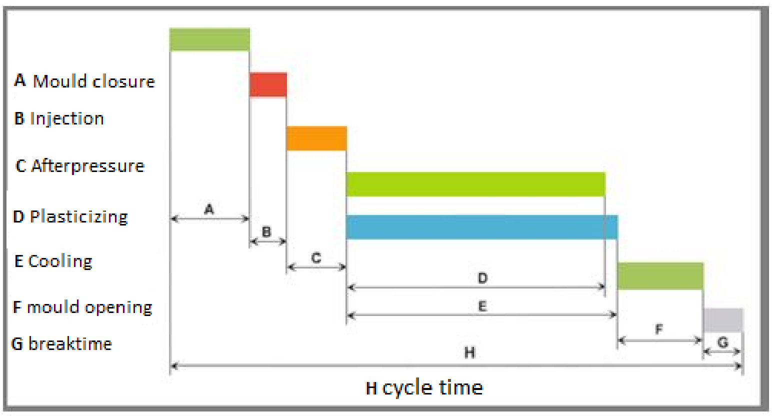

Figure 30 *IM process stages and cycle time* [36]

H) Tool steel (achieved)

The mold inserts were 3D printed in tool steel as it was the most suitable option due to mass production use were material hardness is of great impact.

I) SLM technique (achieved)

The mold was 3D printed with SLM technique. SLM was used because of its suitable properties for 3D printing the mold (explained in chapter 2.2).

6.2 Manufactured cover

The plastic covers produced by the CNC-machined mold and the 3D printed mold are compared and analyzed in this chapter. As explained in the previous chapter, EDM was not made for the 3D printed mold cavity leading to a higher R_A value for the new cover. The R_A value is not prioritized for measuring due to the omitted EDM process meaning the value has no reference value for comparing. Also, the rough surface texture does not meet the ABB requirements, and is therefore not approved for use. The backside design of the cover has a lower R_A value (finer surface). The fine surface ease the ejection from the mold. Listed in figure 31 are the cover dimensions, tolerance: SFS 3918-130 (appendix 4).

Dimensions	Theoretical Value
Volume	5,45 cm^3
Weight	6,54 gr
Length	100 mm
Width	34,8 mm
Height	9 mm
Front surface roughness (R_A)	3,15 µm

Figure 31 *Dimensions for the plastic cover*

Comparison of cover made by CNC-machined mold and 3D printed mold:

The visual cover comparison in figure 32 shows variation in color and surface roughness. The color difference is because of using different material specifications. Covers produced with CNC-machined mold are made in “basalt grey” colored polycarbonate, compared to the newer covers made in black colored polycarbonate. The different surface roughness is because no EDM was made for the 3D printed mold.

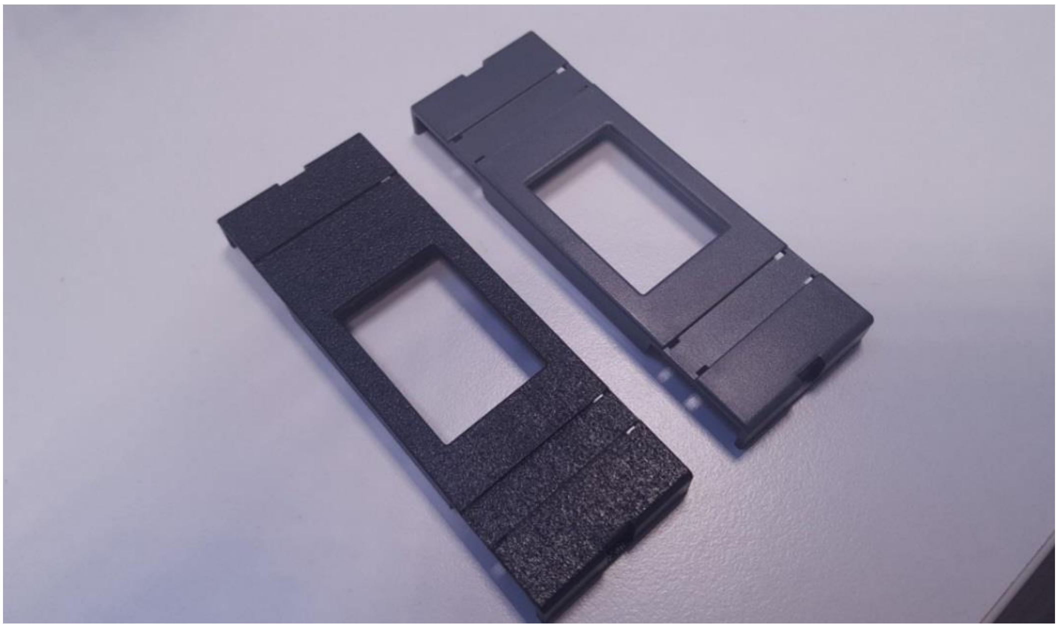

Figure 32 *Old cover (grey, right side) visually compared to the new cover (black, left side)*

It is common for minor errors for the first produced parts during startup since the IM machine settings needs to be rightly tuned along with correct orientation fitment for the mold inserts. The tuning is an enduring problem because of the material properties coupled with the IM machine specifications, such as pressure and temperature. [37] Orientation problems occurred in this project during fitting of all four mold insert, which explains the dimension errors for the new cover. The project was interrupted before optimal IM machine settings and orientation was reached. Unwanted flanges for the cover are seen in figure 33.

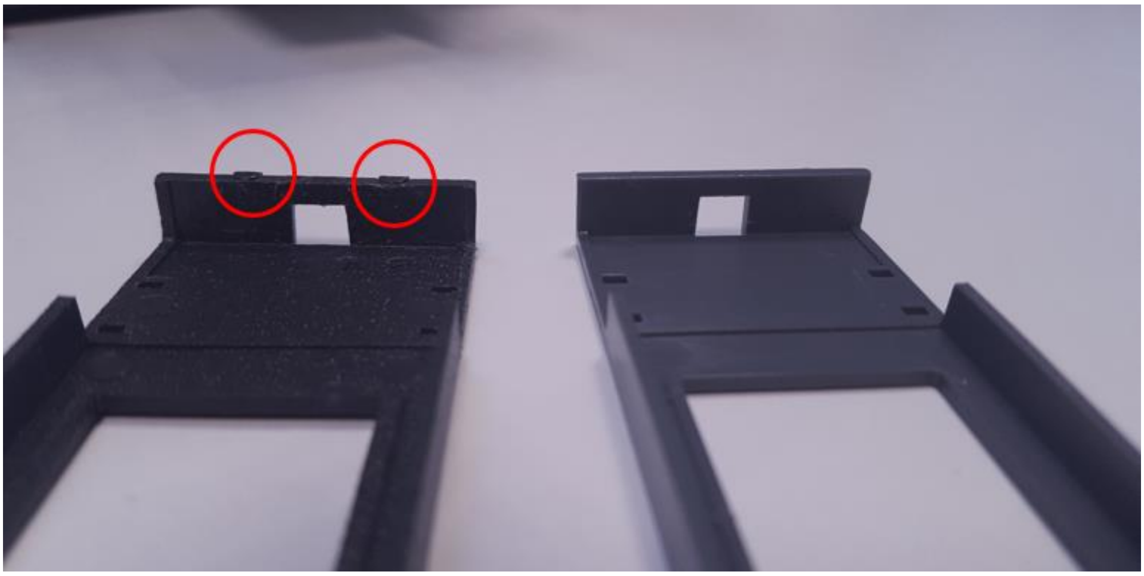

Figure 33 *New cover (left) has unwanted flanges of 0.2-0.3 mm*

The variation in ejector pins location, size and quantity are compared in figure 34.

Figure 34 *Circled are the marks from the ejector pins, (new cover to the right)*

Dimensions and mounting of cover:

The cover is commonly used for switches with multiple poles parallel between each other. When mounting the covers between each other it is essential for the combined cover walls to not exceed the theoretical max measurement, 3,13 mm, between the poles (figure 35). This means the theoretical max value for one wall is 1,565 mm (half of 3,13 mm). Although, if one of the two wall happens to be thinner than 1,565 mm, it allows for the other wall to be thicker and vice versa. The variation in cover wall thickness indicates that the new cover could cause problems in mounting stage. Digital calipers (± 0,02 mm) were used measuring the covers.

Figure 35 *Cover mounting to the switch pole*

All measured points for the new cover are thicker than the design dimensions. Illustrated in figure 36 are three different measured points of the cover, biggest variation was calculated to 0,27 mm.

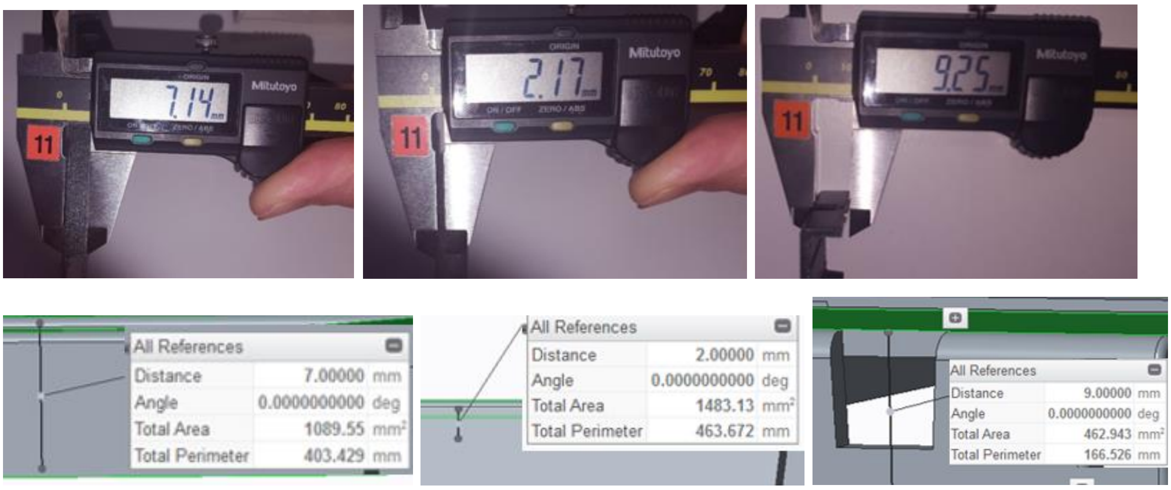

Figure 36 *Thicker dimensions at all three measuring points*

Another error related to the IM machine tuning is the covers curvature (figure 37), which can cause problems in mounting stage, i.e. if the curvature is too big. Common reasons for warpage are uneven mold temperature or inefficient shrink compensation. [20]

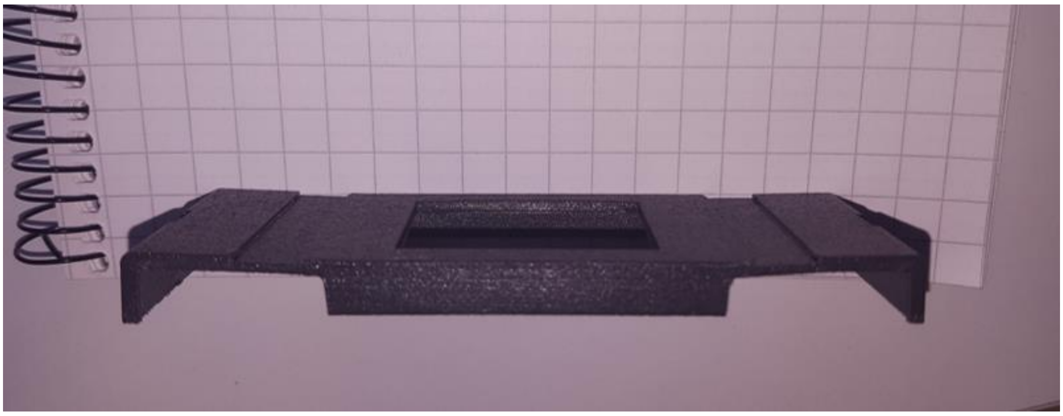

Figure 37 *Unwanted curvature of the cover*

The new covers injection point is relocated compared to old cover (figure 38). The hollow mold is equally filled when the injection point is located on the side of the cover, unlike if the injection point is on top of the cover. When on top, the injected melted plastic first fills the top, followed by the bottom, which leads to uneven cooling.

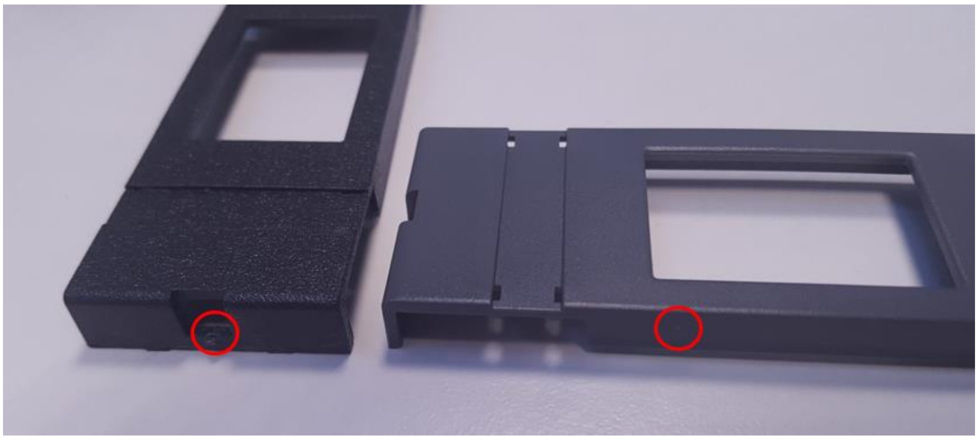

Figure 38 *The covers injection point are circled*

The cover has two identical area sections for ABB labels (figure 39). The sections dimensions are critical for labels to be mountable, especially in mass production were dimension changes (abrasion) may occur. The relocated injection point along with related IM machine tuning errors resulted in not completely filled mold.

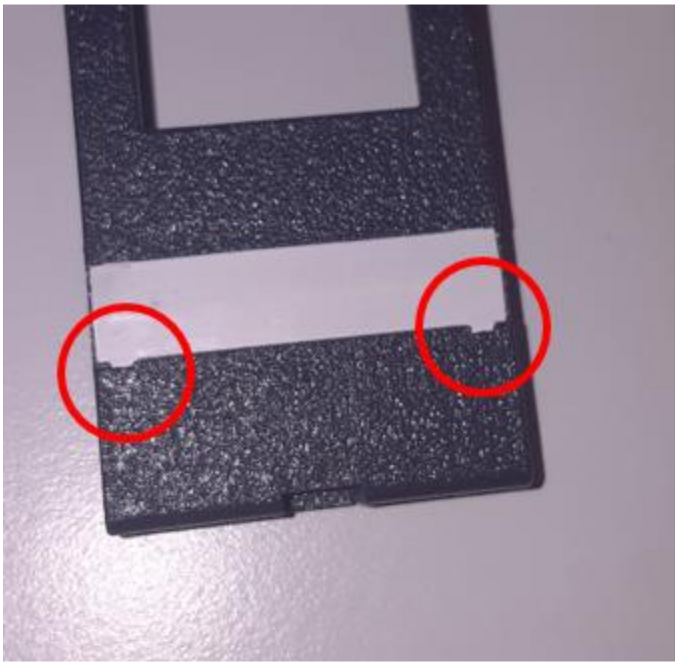

Figure 39 *The circled label flanges are not fitted correctly*

The cover made with the 3D printed mold do not achieve same quality as the old cover. The main reason is the omitted requirement tasks for the mold that led to poor cover results.

7 Discussion

Main purpose of the thesis was to find pros and cons of using SLM 3D printing instead of CNC-machining to manufacture a mold insert in tool steel. The study involved choosing an existing plastic part along with its CNC-machined mold to then compare them with the 3D printed mold along with its produced cover. The chosen cover has been manufactured with CNC-machined mold for over ten years by ABB, which indicates the liability of CNC-machined mold. Despite the setbacks, the 3D printed mold was successfully manufactured and used for producing tens of the plastic covers with IM, though the cover quality was not as good as the earlier made with the CNC-machined mold. To improve the cover quality, it would require starting over from the beginning and making sure that the communication flows so that all operators involved knows the order requirements for correct implementation.

7.1 Conclusion and improvements in the future

For 3D printing, the outcome is directly related to the design. One highlighted design requirement and significant research question was the design optimization for the mold inserts. The design requirement was highlighted because of the design freedom offered with 3D printing. Main focus was for the cooling channels to be optimized, which would result in shorter manufacturing time for the cover, which is significant in mass-production. The cooling stage requires most time of all the IM stages, but it can only be reduced to a certain level before deteriorated results such as poor surface texture. Too short cooling time causes the injected melt to solidify too rapidly so that subsequent liquid material flows over and forms a “orange peel” surface texture. Also, worth investigating are potential material savings offered by the 3D printing design freedom. The highlighted design requirement was left omitted due to the communication problem between PM and supplier. Yet it is still worth for future research as production time always are of great importance since it reduces the costs. During the mold design it is also necessary to take EDM into consideration, since EDM removes material from the hollow mold insert which results in larger dimensions of the cover. With that said, EDM could maybe have been performed if the hollow insert dimensions instead would have been too small.

It can’t really be stated which method is more suitable for mold manufacturing since both methods has their own characteristics. Although when it comes to mold manufacturing, both methods are and can be used. 3D printing is likely to be the better choice if complex geometry or design improvements are required, which are more restricted to perform with CNC-machining. Complete measuring and analysis of the mold inserts should be provided in order to clarify which method provides better material hardness along with longer life-span. Unfortunately, the mold inserts were not available for analyze during this thesis implement.

3D printing in metal with SLM or similar AM methods are worth further investigation in the future as the methods still develops. Other research topics could be the possibility to merge a complex assembly, for example, NASA managed to reduce the assembly parts for a component from 115 pcs down to only two pcs. [38] With less assembly parts it is possible to save material, abolish potential tolerances and shorten the total manufacturing duration that includes the assembly station.

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Appendix 1 *Aluminum data sheet*

Materialdatenblatt
Material Data Sheet
AlSi10Mg/3.2381/A03600[1]

Mechanische Kennwerte
Mechanical Data

Zugversuch[2][3] *Tensile Test[2][3]*		Schichtdicke 50 µm[4] *Layer thickness 50 µm[4]*
Zugfestigkeit *Tensile Strength*	R_m [MPa]	397 ± 11
Dehngrenze *Yield Strength*	$R_{p0,2}$ [MPa]	227 ± 11
Bruchdehnung *Elongation Break*	A [%]	6 ± 1
Brucheinschnürung *Contraction at Fracture*	Z [%]	8 ± 2
E-Modul *Young's modulus*	E [GPa]	64 ± 10
Härteprüfung[3][5] *Hardness Test[3][5]*		
Härte nach Vickers *Vickers Hardness*	[HV10]	117 ± 1

Physikalische und chemische Eigenschaften
Physical and Chemical Properties

Materialdichte *Material Density*	2,7 g/cm³	
Bauteildichte[3][6] *Build Part Density[3][6]*	**Schichtdicke 50 µm[4][6]** *Layer thickness 50 µm[4][6]*	> 99 %

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Appendix 2 *Stainless steel data sheet*

Materialdatenblatt
Material Data Sheet
316L/1.4404/F138 [1]

SLM SOLUTIONS

Mechanische Kennwerte
Mechanical Data

Zugprüfung[2][10] *Tensile Test[2][10]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Zugfestigkeit *Tensile Strength*	R_m [MPa]	654 ± 49	633 ± 28
Dehngrenze *Yield Strength*	$R_{p0,2}$ [MPa]	550 ± 39	519 ± 25
Bruchdehnung *Elongation Break*	A [%]	35 ± 4	30 ± 5
Brucheinschnürung *Contraction at Fracture*	Z [%]	59 ± 3	49 ± 11
Elastizitätsmodul *Young's modulus*	E [GPa]	170 ± 31	184 ± 20

Härteprüfung[4] [10] *Hardness Test[4][10]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Härte nach Vickers *Vickers Hardness*	[HV10]	233 ± 2	209 ± 2

Rauheitsmessung [10] *Roughness Measurement[10]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Mittenrauwert *Mean Roughness Index*	R_a [µm]	9 ± 3	10 ± 2
Gemittelte Rautiefe *Average Surface Roughness*	R_z [µm]	48 ± 14	53 ± 10

Physikalische und chemische Eigenschaften
Physical and Chemical Properties

Materialdichte *Material Density*	7,95 g/cm³	
Bauteildichte[6] *Build Part Density[6]*	30µm[3] > 99,5 %	50µm[5] > 98 %

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Appendix 3 *Tool steel data sheet*

Materialdatenblatt
Material Data Sheet
1.2709/M300-3

Mechanische Kennwerte
Mechanical Data

Zugprüfung[1][2] *Tensile Test[1][2]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Zugfestigkeit *Tensile Strength*	R_m [MPa]	1016 ± 34	1011 ± 39
Dehngrenze *Yield Strength*	$R_{p0,2}$ [MPa]	854 ± 50	837 ± 76
Bruchdehnung *Elongation Break*	A [%]	10 ± 1	7 ± 2
Brucheinschnürung *Contraction at Fracture*	Z [%]	26 ± 9	20 ± 6
Elastizitätsmodul *Young's modulus*	E [GPa]	142 ± 43	167 ± 24

Härteprüfung[1] [4] *Hardness Test[1][4]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Härte nach Vickers *Vickers Hardness*	[HV10]	310 ± 4	321 ± 7

Rauheitsmessung [1] *Roughness Measurement[1]*		Schichtdicke 30 µm[3] *Layer thickness 30 µm[3]*	Schichtdicke 50 µm[5] *Layer thickness 50 µm[5]*
Mittenrauwert *Mean Roughness Index*	R_a [µm]	7 ± 2	8 ± 2
Gemittelte Rautiefe *Average Surface Roughness*	R_z [µm]	41 ± 10	42 ± 11

Physikalische und chemische Eigenschaften
Physical and Chemical Properties

Materialdichte *Material Density*	8,042 g/cm³
Bauteildichte[1][6] *Build Part Density[1][6]*	30µm[3] > 99 %

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Release 01/15

Appendix 4 *Tolerance SFS 3918-130*

Taulukko 2

Toleranssi-ryhmä taulukosta 1	Tunnus [1)]	Perusmitta 0 1	1 3	3 6	6 10	10 15	15 22	22 30	30 40	40 53	53 70	70 90	90 120	120 160	160 200	200 250	250 315	315 400	400 500	500 630	630 800	800 1000
Toleranssialue toleroimattomille mitoille (yleistoleranssit)																						
160	A	±0,28	±0,30	±0,33	±0,37	±0,42	±0,49	±0,57	±0,66	±0,78	±0,94	±1,15	±1.40	±1,80	±2,20	±2,70	±3,30	±4,10	±5,10	±6,30	±7,90	±10,00
	B	±0,18	±0,20	±0,23	±0,27	±0,32	±0,39	±0,47	±0,56	±0,68	±0,84	±1,05	±1,30	±1,70	±2,10	±2,60	±3,20	±4,00	±5,00	±6,20	±7,80	± 9,90
150	A	±0,23	±0,25	±0,27	±0,30	±0,34	±0,38	±0,43	±0,49	±0,57	±0,68	±0,81	±0,97	±1,20	±1,50	±1,80	±2,20	±2,80	±3,40	±4,30	±5,30	± 6,60
	B	±0,13	±0,15	±0,17	±0,20	±0,24	±0,28	±0,33	±0,39	±0,47	±0.58	±0,71	±0,87	±1,10	±1,40	±1,70	±2,10	±2,70	±3,30	±4,20	±5,20	± 6,50
140	A	±0,20	±0,21	±0,22	±0,24	±0,27	±0,30	±0,34	±0,38	±0,43	±0,50	±0,60	±0,70	±0,85	±1,05	±1,25	±1,55	±1,90	±2,30	±2,90	±3,60	± 4,50
	B	±0,10	±0,11	±0,12	±0,14	±0,17	±0,20	±0,24	±0,28	±0,33	±0,40	±0,50	±0,60	±0,75	±0,95	±1,15	±1,45	±1,80	±2,20	±2,80	±3,50	± 4,40
130	A	±0,18	±0,19	±0,20	±0,21	±0,23	±0,25	±0,27	±0,30	±0,34	±0,38	±0,44	±0,51	±0,60	±0,70	±0,90	±1,10	±1,30	±1,60	±2,00	±2,50	± 3,00
	B	±0,08	±0,09	±0,10	±0,11	±0,13	±0,15	±0,17	±0.20	±0,24	±0,28	±0,34	±0,41	±0,50	±0,60	±0,80	±1,00	±1,20	±1,50	±1,90	±2,40	± 2,90
Toleranssit toleroiduille mitoille																						
160	A	0,56	0,60	0,66	0,74	0,84	0,98	1,14	1,32	1,56	1,88	2,30	2,80	3,60	4,40	5,40	6,60	8,20	10,20	12,50	15,80	20,00
	B	0,36	0,40	0,46	0,54	0,64	0,78	0,94	1,12	1,36	1,68	2,10	2.60	3,40	4,20	5,20	6,40	8,00	10,00	12,30	15,60	19,80
150	A	0,46	0,50	0,54	0,60	0,68	0,76	0,86	0,98	1,14	1,36	1,62	1,94	2,40	3,00	3,60	4,40	5,60	6,80	8,60	10,60	13,20
	B	0,26	0,30	0,34	0,40	0,48	0,56	0,66	0,78	0,94	1,16	1,42	1,74	2,20	2,80	3,40	4,20	5,40	6,60	8,40	10,40	13,00
140	A	0,40	0,42	0,44	0,48	0,54	0,60	0,68	0,76	0,86	1,00	1,20	1,40	1,70	2,10	2,50	3,10	3,80	4,60	5,80	7,20	9,00
	B	0,20	0,22	0,24	0,28	0,34	0,40	0,48	0,56	0,66	0,80	1,00	1.20	1,50	1,90	2,30	2,90	3,60	4,40	5,60	7,00	8,80
130	A	0,36	0,38	0,40	0,42	0,46	0,50	0,54	0,60	0,68	0,76	0,88	1,02	1,20	1,50	1,80	2,20	2,60	3,20	3,90	4,90	6,00
	B	0,16	0,18	0,20	0,22	0,26	0,30	0,34	0,40	0,48	0,56	0,68	0,82	1,00	1,30	1,60	2,00	2,40	3,00	3,70	4,70	5,80
120	A	0,32	0,34	0,36	0,38	0,40	0,42	0,46	0,50	0,54	0,60	0,68	0,78	0,90	1,06	1,24	1,50	1,80	2,20	2,60	3,20	4,00
	B	0,12	0,14	0,16	0,18	0,20	0,22	0,26	0,30	0,34	0,40	0,48	0,58	0,70	0,86	1,04	1,30	1,60	2,00	2,40	3,00	3,80
110	A	0,18	0,20	0,22	0,24	0,26	0,28	0,30	0,32	0,36	0,40	0,44	0,50	0,58	0,68	0,80	0,96	1,16	1,40	1,70	2,10	2,60
	B	0,08	0,10	0,12	0,14	0,16	0,18	0,20	0,22	0,26	0,30	0,34	0,40	0,48	0,58	0,70	0,86	1,06	1,30	1,60	2,00	2.50
Hienome-kaniikka	A	0,10	0,12	0,14	0,16	0,20	0,22	0,24	0,26	0,28	0,31	0,35	0,40	0,50								
	B	0,05	0,06	0,07	0,08	0,10	0,12	0,14	0,16	0,18	0,21	0,25	0,30	0,40								

1) A Mitat, joita muotti ei sido.
B Muotin sitomat mitat.