Faculdade de Engenharia da Universidade do Porto

Feasibility of Producing Additively Manufactured High-feed Milling Tools

Henrique Jorge Santiago e Couto Coelho

Master's dissertation in Mechanical Engineering

Supervisor: Dr. Rui Ricardo Loureiro Amaral

Co-Supervisor: Dr. Omid Emadinia

September 2023

Resumo

O surgimento do fabrico aditivo, mais conhecida como impressão 3D, introduziu uma mudança de paradigma em vários sectores, prometendo inovação e redução de custos. Esta dissertação, conduzida em colaboração com o INEGI e a Palbit explora o potencial do fabrico aditivo no domínio dos metais, com foco específico na incorporação de canais conformais (internos) em ferramentas de corte de alto avanço. O objectivo principal é investigar a viabilidade e os benefícios da integração de canais de internos, para o arrefecimento da própria ferramenta, como também para facilitar a remoção da apara durante o processo de maquinagem. Para tal, fez uso da tecnologia de fabrico aditivo de pó metálico, mais concretamente do processo de LPBF. A definição e estratégia de construção dos protótipos teve em conta a obtenção vários factores: qualidade superficial dos canais, rigor dimensional, e rendimento da matéria-prima (uma vez que é necessária a utilização de suportes). Com base nas recomendações sugeridas na literatura, optou-se por maximizar o número de canais cuja direcção de construção é vertical, uma vez que apresentam uma melhor qualidade de superfície, dado que o efeito de escada é evitado ou, pelo menos, reduzido, e também evitando curvas muito fechadas. Por fim, foram produzidos protótipos com base em diferentes iterações geométricas e posteriormente analisados recorrendo a cortes de secções transversais, com o intuito de medir os canais internos e respectiva comparação com o CAD original. Esta análise revelou uma boa correlação entre as dimensões dos canais nas secções avaliadas, concluindo-se que é possível a produção de canais internos com dimensões compreendidas entre os 0,6 mm e 1,7 mm, através do processo de LPBF, no entanto canais de maior diâmetro têm maior rigor dimensional.

Palavras-Chave

Fabrico Aditivo; LPBF; Ferramenta de Corte; Maquinagem; Alto Avanço; Canais Internos.

Abstract

The emergence of additive manufacturing (AM), better known as 3D printing, has introduced a paradigm shift in several sectors, promising innovation and cost reduction. This dissertation, conducted in collaboration with INEGI and Palbit explores the potential of additive manufacturing in the metals domain, with a specific focus on the incorporation of conformal (internal) channels in high-feed cutting tools. The main objective is to investigate the feasibility and benefits of integrating internal channels, to cool the tool itself, as well as to facilitate chip removal during the machining process. To this end, it used metal powder AM technology, more specifically the LPBF process. The definition and construction strategy of the prototypes took into account several factors: surface quality of the channels, dimensional accuracy, and raw material yield (since the use of supports is necessary). Based on recommendations suggested in the literature, it was decided to maximize the number of channels whose construction direction is vertical, as they present a better surface quality, given that the staircase effect is avoided or, at least, reduced, and also avoiding very sharp curves. Finally, prototypes were produced based on different geometric iterations and subsequently analysed using cross-sectional cuts, with the aim of measuring the internal channels and comparing them with the original CAD. This analysis revealed a good correlation between the dimensions of the channels in the evaluated sections, concluding that it is possible to produce internal channels with dimensions between 0,6 mm and 1,7 mm, through the LPBF process, however larger diameter channels have greater dimensional accuracy.

Key Words

Additive Manufacturing; LPBF; Cutting Tool; Machining; High-feed; Internal Channels.

Acknowledgements

I would like to express appreciation to my supervisors, Dr. Rui Ricardo Loureiro Amaral and Dr. Omid Emadinia, for their guidance over the course of this work, as well as to Eng. Francisco Matos, Dr. Tiago Emanuel Silva, and Eng. Rui Daniel Madureira, for their assistance during this period, and to Palbit, for the opportunity.

I would also like to thank my parents for subsidising me during my studies, my grandmother for giving me a bed, and above all I want to thank Daniela, to whom I dedicate this dissertation, for her unstoppable and unwavering support and affection throughout all these years.

Institutional Acknowledgements

Author gratefully acknowledges the funding of Hi-rEV – Recuperação do Setor de Componentes Automóveis (02-C05-i01.02-2022.PC644864375-00000002), co-financed by Plano de Recuperação e Resiliência (PRR), through the financial support of the Portuguese Republic and NextGenerationEU from European Union.

PRR Plano de Recuperação e Resiliência

REPÚBLICA PORTUGUESA

Financiado pela União Europeia NextGenerationEU

Contents

List of Figures

List of Tables

Symbols and Acronyms

3D	Three Dimensional
AM	Additive Manufacturing
BJ	Binder Jetting
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DED	Direct Energy Deposition
EPBF	Electron Beam Powder Bed Fusion
GE	General Electric
HFM	High-feed Milling
INEGI	Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
Laser	Light Amplification by Stimulated Emission of Radiation
LPBF	Laser Powder Bed Fusion
MAM	Metal Additive Manufacturing
MEX	Material Extrusion
MJT	Material Jetting
M_f	Martensite Finish
M_s	Martensite Start
PBF	Powder Bed Fusion
PCD	Polycrystalline Diamond
SLM	Selective Laser Melting
STL	Standard Tessellation Language
%wt	Percentage by Weight

1. Introduction

1.1. Project's framework and motivation

In recent decades, additive manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology with the potential to revolutionise various industries, including aerospace, automotive, healthcare, and consumer goods. This revolutionary approach to manufacturing allows for the creation of complex and customised geometries, offering unparalleled design freedom and cost-efficiency. Among the numerous applications of AM, the fabrication of metal components has garnered significant attention due to its potential to overcome traditional manufacturing limitations and open up new possibilities in engineering design.

One particular area of interest within AM of metals is the incorporation of internal channels within the manufactured parts. These internal channels have shown tremendous promise in enhancing the performance and functionality of metal components. The integration of such channels has been found to optimise heat dissipation, fluid flow, structural integrity, and overall efficiency in various industrial applications.

The purpose of this dissertation is to investigate the advancements and challenges in AM of metals and to assess the feasibility and benefits of incorporating internal channels within metal components, more specifically within high-feed milling tools. This research aims to shed light on the potential advantages, limitations, and implications of using AM for creating intricate internal geometries, which can significantly influence the future landscape of metal fabrication. This dissertation was conducted at INEGI, in a partnership with Palbit.

1.2. Objectives

The objective of this dissertation is to study the feasibility of the production of additively manufactured internal channels for machining tools. As such, the following tasks are intended to be completed:

- Literature review on the state of the art of metal additive manufacturing technology focusing on LPBF, the characteristics of additively manufactured maraging steels, the CAD process, and machining cutting tools, specifically those intended for high-feed use and the integration of internal cooling channels in these;
- Development of the design of internal cooling channels for a milling cutting tool;
- Manufacture and dimensional study of the additively manufactured parts;
- Evaluation of dimensional accuracy achieved through this process.

1.3. Structure

The structure of this dissertation is divided into several chapters, organised as follows:

- Introduction – Summary of the project's framework and motivations and this dissertation's goals;
- Literature Review – Literature review about additive manufacturing, focusing on the solid laser melting process of maraging steel powders, on the CAD process and aspects relevant to internal cooling channels, and about machining processes, specifically high-feed face milling tools;
- Experimental Procedure – Material characterization and description of the preparatory stages for the design stage, accompanied by part drawings and equipment used;
- Results and Discussion – Analysis of the results from the manufacturing process, specifically the channels' dimensional accuracy;
- Conclusion and Future Work – Summary of the main conclusions derived from this investigation and complimentary list of proposed future works.

2. Literature Review

2.1. Metal Additive Manufacturing

2.1.1. Introduction to Additive Manufacturing

Additive manufacturing (AM) is a manufacturing technology that builds parts layer by layer using a digital 3D model. This is achieved through a process of deposition, melting, or sintering, resulting in the consolidation of physical slices to form the final product. AM has the potential to revolutionise manufacturing by offering rapid prototyping and enabling the fabrication of final products. It can shift the manufacturing paradigm from centralised mass production with high costs and dedicated tooling to distributed manufacture and mass customization, where parts can be produced on demand [1].

One of the key advantages of AM is its versatility and adaptability, allowing for highly customised designs, geometries, and materials, almost without impacting cost. This technology can be used throughout the product life cycle, from prototyping to full-scale production, for tooling applications or post-production repair. The process enables innovative structural design and the manufacture of highly complex shapes in a single step [2, 3]. However, AM still faces challenges related to design, process modelling, simulation and control, materials, processes and machines, qualification, and certification [4].

Despite these challenges, AM is a fast-growing industry, with a focus on metal additive manufacturing (MAM). MAM poses unique challenges due to the specific solidification conditions and thermal processing cycles involved. A better understanding of the relationship between processing, microstructure, and properties is required to overcome these challenges. Additionally, achieving process repeatability and part reproducibility across different machines and materials is a major hurdle that must be overcome for MAM to become widely implemented [1].

2.1.2. MAM Categories

Within AM technologies, specifically MAM technologies, there are a few categories, namely, powder bed fusion (PBF), direct energy deposition (DED) processing, binder jetting (BJ), material extrusion (MEX), and material jetting (MJT) of which PBF will be the main focus, with some light also shed on DED. PBF can be further differentiated through their type of primary heat source as PBF systems can be equipped with either a laser (LPBF), or with an electron beam (EPBF) operating in high vacuum [5]. For the purposes of this work, LPBF will be the focus. LPBF is a metal-exclusive form of AM, feasible when using a metal powder which can range from steel, aluminium, or titanium alloys [1].

PBF in general, and LPBF in specific, helps reduce material waste when compared with subtractive methods of manufacturing, as it is a process that hangs on the principle of minimal material waste, and provides efficient reusing of un-melted powder. It can also improve production development times, enabling rapid prototyping and low volume production, and allows for the creation of fully customised parts on a batch-by-batch basis, eliminating fixed designs and allowing for greater optimization and experimentation [6]. LPBF also provides a better resolution when compared to some other AM processes, thus reducing the need for post-processing treatments, such as surface finishing, and even reduces the need for heat treatments, though these are still valuable to improves mechanical properties and reduces residual stress [7]. Despite this, high costs, due to high power usage and poor energy efficiency, of around 10% to 20%, and low speed of process, can be dissuasive, as can the severe size limitations [8].

DED systems can utilise all of the aforementioned heat sources, and may also use powder-feed systems and/or wire-feed systems, the latter delivered through nozzles in the moving heat source-feeding integrated head [9]. And, opposite to LPBF systems, DED has been shown to be a process up to ten times faster and five times less expensive than PBF, when creating mid-size metal parts, as material use, cooling, and build times were all greatly reduced when comparing both AM processes, although with DED there is an increased need for post processing [10].

2.1.3. LPBF Process

The LPBF process starts with a comprehensive 3D digital representation of the geometry of the part generated through CAD software modelling. The CAD file is converted to a STL file describing the external closed surfaces of the CAD model, which is the basis for the calculation of the slices. The STL file is then transferred to a pre-processing software, where the scale, layout, position, and orientation of the parts is set by the operator, and then finally that is transferred to the AM machine [1].

Machine manufacturers provide the default setups for each material developed and provided by them, with optimised settings that can prioritise processing speed or surface finish, or a compromise between the two. The build is a completely automated sequence of layer deposition, selective laser melting, and consequent consolidation, of which Figure 1 is a useful schematic [1].

The process occurs inside a chamber filled with an inert gas, such as nitrogen or argon. The temperature is usually kept at around 200 °C, and the building base can be pre-heated as well. The building platform is lowered corresponding to the layer thickness, which is around in-between 25 µm and 100 µm, so that the powder layer may be spread across the build area using a counter-rotating powder levelling roller, which will evenly distribute the material powder. Any excess powder is pushed into a recovery vat. The laser beam focuses on the powder bed, directed by galvanometers, tracing the scanning pattern, often a raster pattern, and selectively melting the material to form the first slice. The surrounding powder remains loose and can serve as support for subsequent powder layers. After the melting and consolidation of each layer, the build platform is again lowered by one-layer thickness and a new layer of powder is laid so that the laser may draw the subsequent slice, repeating the process until all layers are formed and the complete part is built [8]. A cooldown period is typically required to allow the parts to uniformly cool to an appropriate temperature for handling and exposure to ambient temperature and atmosphere. Post-processing requires the cleaning of excess powder and the removal of the finished part from the build plate, and of any support structures that may exist. The final application of the produced parts may require further consolidation, finishing, heat treatments, coating, or assembly operations [1].

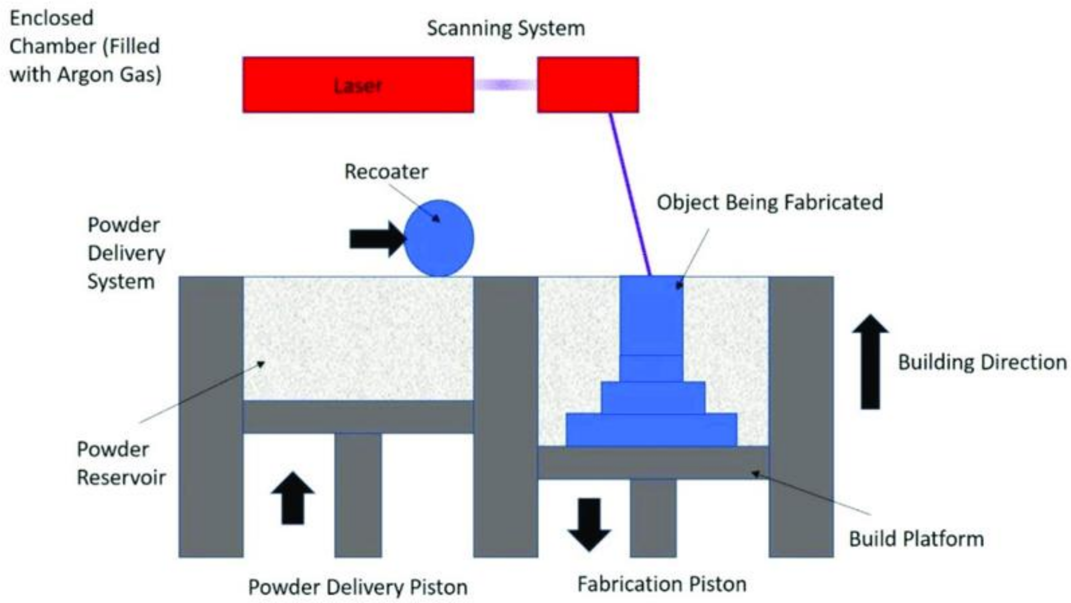


Figure 1 - Diagram of the LPBF process [11]

2.1.4. LPBF Process Parameters

In the LPBF process, several parameters influence the quality of the final product. These parameters can be categorised into four major areas, being laser-related, scan-related, powder-related, and temperature-related, represented in Figure 2:

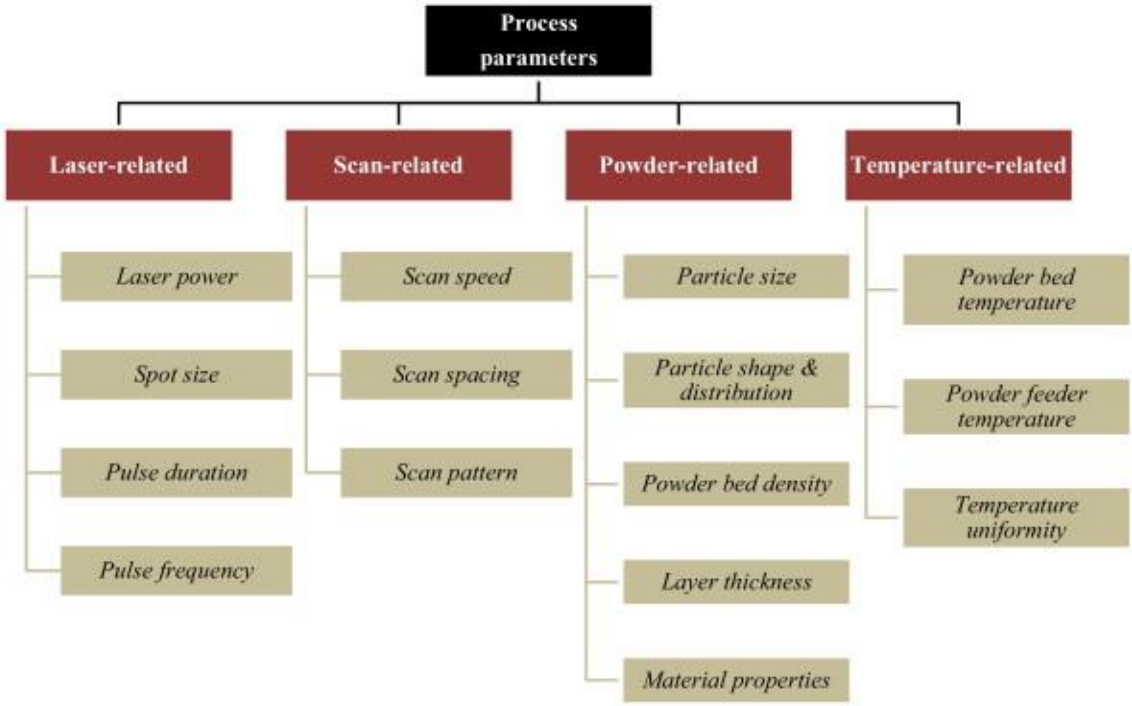


Figure 2 - Process parameters of LPBF [12]

The first parameter, laser-related, needs to be adjusted along with other parameters to ensure complete melting of the powder. If the power is too low, incomplete melting may occur, leading to a decrease in density and mechanical properties. On the other hand, if the power is too high, heat transfer may occur, resulting in inconsistencies in the final structure of the part. Spot size, pulse duration, and frequency will also affect the melting of the powder, and may cause irregularities if not properly calibrated [13].

In the second parameter, scan-related, speed, spacing, and pattern (of which several strategies can be seen represented in Figure 3), are all important sub parameters to take into attention. High scan speeds lead to incomplete melting, whereas slow speeds lead to excessive heat input, large spacing may lead to adjacent melt lines not fusing together, and the pattern creation is important in order to achieve minimal internal stresses, as well as possibly cutting down on material usage [13].

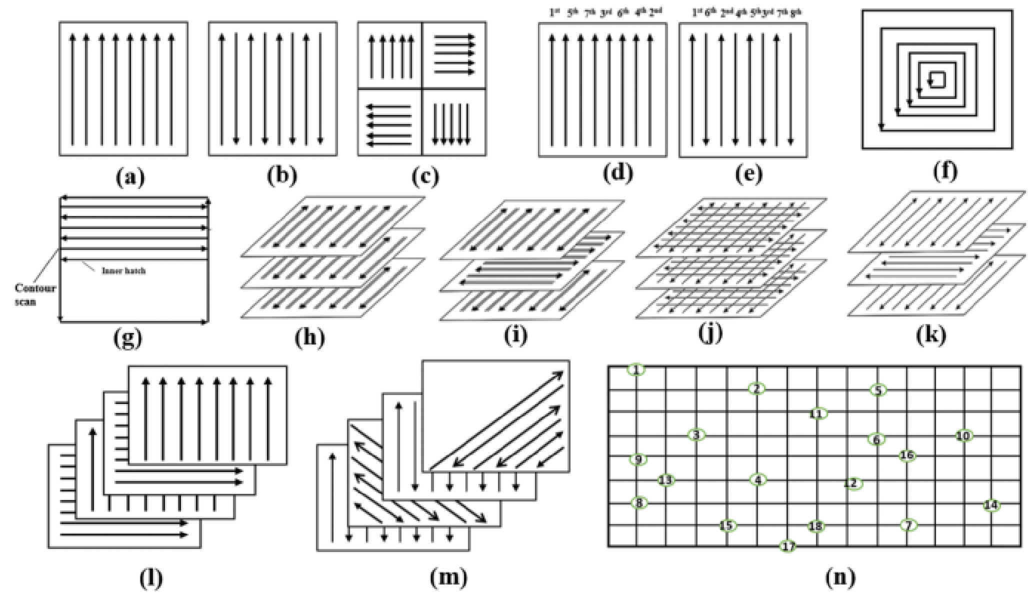


Figure 3 - Examples of scanning strategies [14]

In this figure the represented scanning strategies are:

a) uni-directional scan;
b) bi-directional/zigzag scan;
c) island scan;
d) variation of scanning sequences based on uni-directional scan;
e) variation of scanning sequences based on bi-directional scan;
f) helix scan;
g) contour scan;
h) bi-directional, double pass of laser beam;
i) bi-directional, double pass of laser beam, 90° rotation scan vector between layers
j) cross scan;
k) bi-directional, single pass of laser beam, 90° rotation of scan vector between layers;
l) 90° rotation of uni-directional scan between successive layers;
m) 45° rotation of scan vector;
n) point melting scan.

For the third parameter, powder-related, these categories mainly concern flowability of the melt and final strength of the material, and will be further discussed in chapter 2.1.8. Lower layer thicknesses and a well-balanced mixture of large and small particles will aid to this effect [13].

For the final parameter, temperature-related, these parameters can affect the thermal behaviour of the material during the building process and can influence the quality and properties of the final product. In addition, as previously stated, the preheating of the powder bed before the melting process is also an important temperature-related parameter that can affect the quality of the final part [13].

2.1.5. Structural Supports

Supports structures play a crucial role in ensuring the success of fabrication processes and achieving high and efficient production yields. They serve to minimise contact area and facilitate part removal, to secure part position and counter external forces, reducing warping, and to achieve thermal and microstructural consistency, which will be important in matters of surface roughness and porosity. To achieve this, two key steps must be taken: build orientation optimization and suitable support type selection, as the supports should possess the strength needed to support the fabrication process while remaining easy to remove and using minimal material [15, 16].

A support structure comprises two functional components, the main support, the larger part of the support structure, that should be robust enough to withstand vertical loads, recoating forces, and thermal stresses, and the teeth, that will serve as connections between the main support and the part, thus leading to a reduction in contact area, and ease of removal. Teeth design parameters like top length, spacing, and height require fine-tuning for optimal performance, as too many teeth may cause degradation of the surface quality, while too few will do for a weak support [15, 16]. Figure 4 provides a diagram of the connection between the support structure and the part being manufactured.

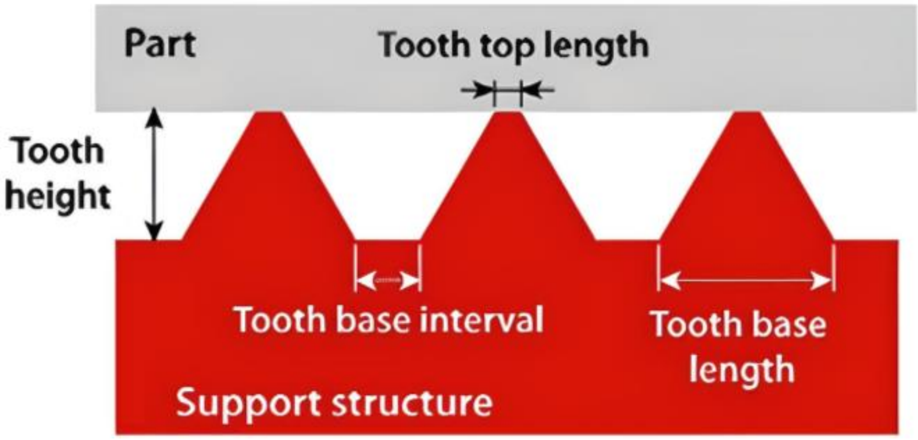


Figure 4 - Diagram of a support structure [16]

Various geometries are available for the main support, such as block, point, web, contour, and line structures, pictured in Figure 5. Block supports, which consist of a grid pattern in which the distance is set by the hatching distance, and can be adjusted, are the more commonly type of support structure [15, 16].

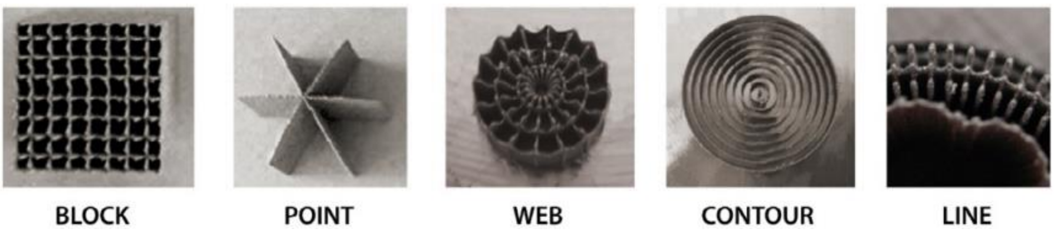


Figure 5 - Different types of main structure geometries [16]

However, these support structures aren't without their disadvantages. The introduction of support structures can hinder machine productivity by increasing build time and material consumption, elevating the overall part cost. Supports can impose constraints on part geometry due to AM design rules, requiring meticulous consideration. Additionally, supported surfaces may demand extra post-processing efforts to eliminate roughness and sharp edges, affecting both aesthetics and functionality, which can also pose as a safety hazard. These post-processing concerns will also serve to increase costs, both in manual labour and in time spent. Because of these concerns, minimizing or eliminating supports requires careful consideration of part design, build orientation, build time adjustments, parameter optimization, and machine type. While some software, such as Materialise Magics, automates support generation, it might be better to add so called "sacrificial geometries" in certain cases, reducing the need for extensive support structures, especially for tall block supports that are prone to distortion. Other solutions encompass modifying part orientation and layout, adjusting machine parameters like laser power or scan strategies may further reduce support requirements, or even innovative design approaches that incorporate supports into the part's functionality, such as by integrating cooling channels. Evaluating the impact of support elimination on overall part cost is essential, with the benefits being highly dependent on part geometry. Additionally, reduced supports provide greater design freedom and fewer inspection steps, enhancing the overall AM process [15, 16].

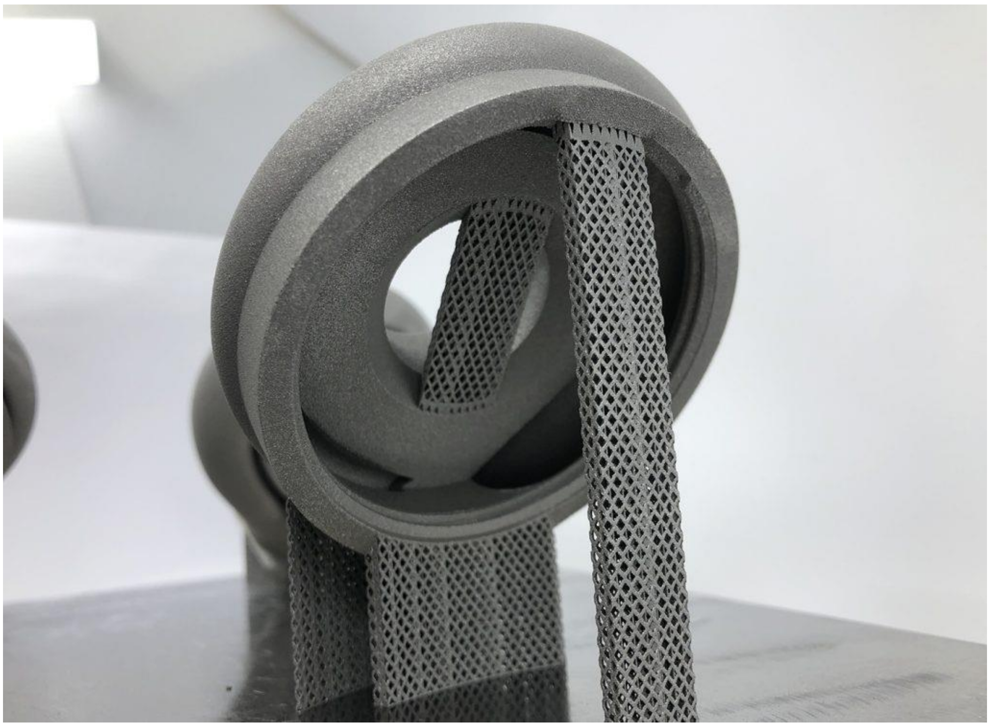


Figure 6 - Example of a support structure, with a "sacrificial geometry" [15]

2.2. Powder Feedstock for LPBF

2.2.1. Powders for LPBF

As the field of industrial AM continues to grow, the quality of metal powders used in LPBF will become increasingly important. Particle size, shape, and size distribution all play significant roles in achieving high-quality components with good repeatability and efficiency. Given the costs associated with metal powders, it is crucial to consider the impact of these factors on the overall success of the process [17].

Research has shown that particle shape plays a crucial role in the quality of finished components produced using LPBF. The shape of the particles, for instance, can affect the amount of oxidation each particle picks up, which can lead to non-uniform particle melting and the development of pores. Spherically shaped particles, on the other hand, result in a homogeneous and dense layer, making them ideal for LPBF processing. Particle shape is also linked to layer density, with spherical particles exhibiting low interparticle friction and high mobility, facilitating high layer packing density [17].

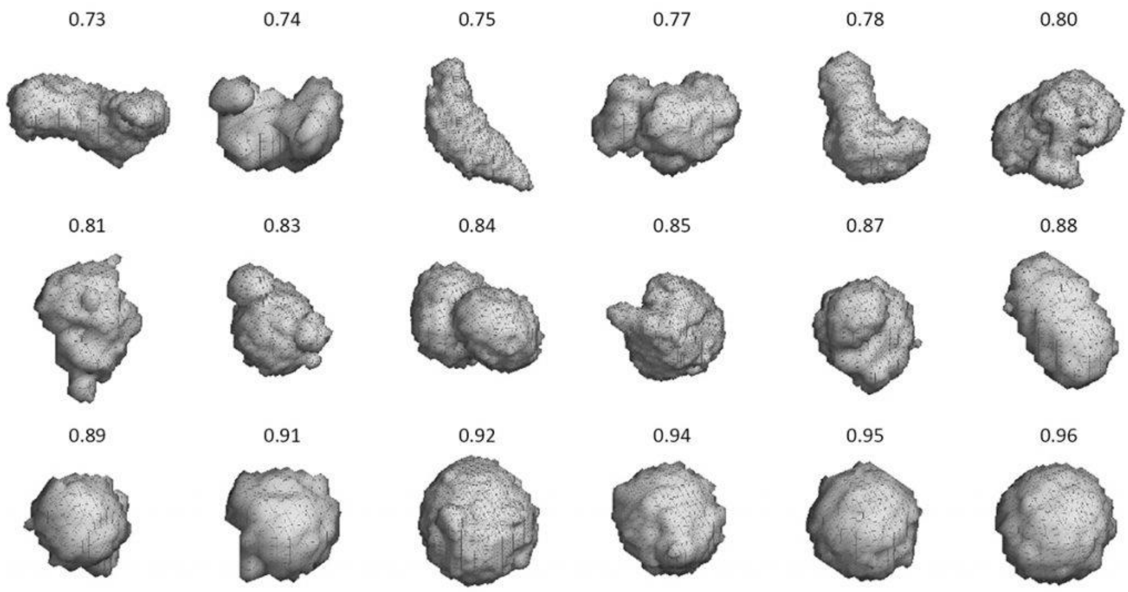


Figure 7 - Measurements of particle sphericity [18]

Particle size and size distribution are other important criteria. Both are critical factors in powder flowability, and their impact is significant in LPBF. Fine particles tend to cluster, preventing uniform recoating during LPBF, while large particles reduce the maximum layer packing density available. A mix of small and larger particles is best suited for LPBF, where the smaller particles percolate through the larger particles, filling the voids and achieving higher density [17].

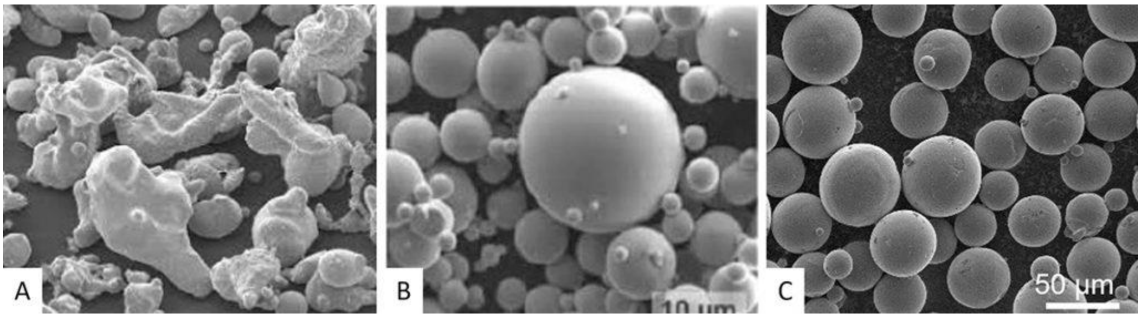


Figure 8 - Representative morphologies obtained from water atomisation (A), gas atomisation (B), and plasma atomisation (C) [18]

Bi-modal mixtures of powders have been shown to increase powder density by about 30%, but only if the amount of fine particles is around 30%, with higher amounts leading to agglomeration of particles, eliminating their positive effects [17].

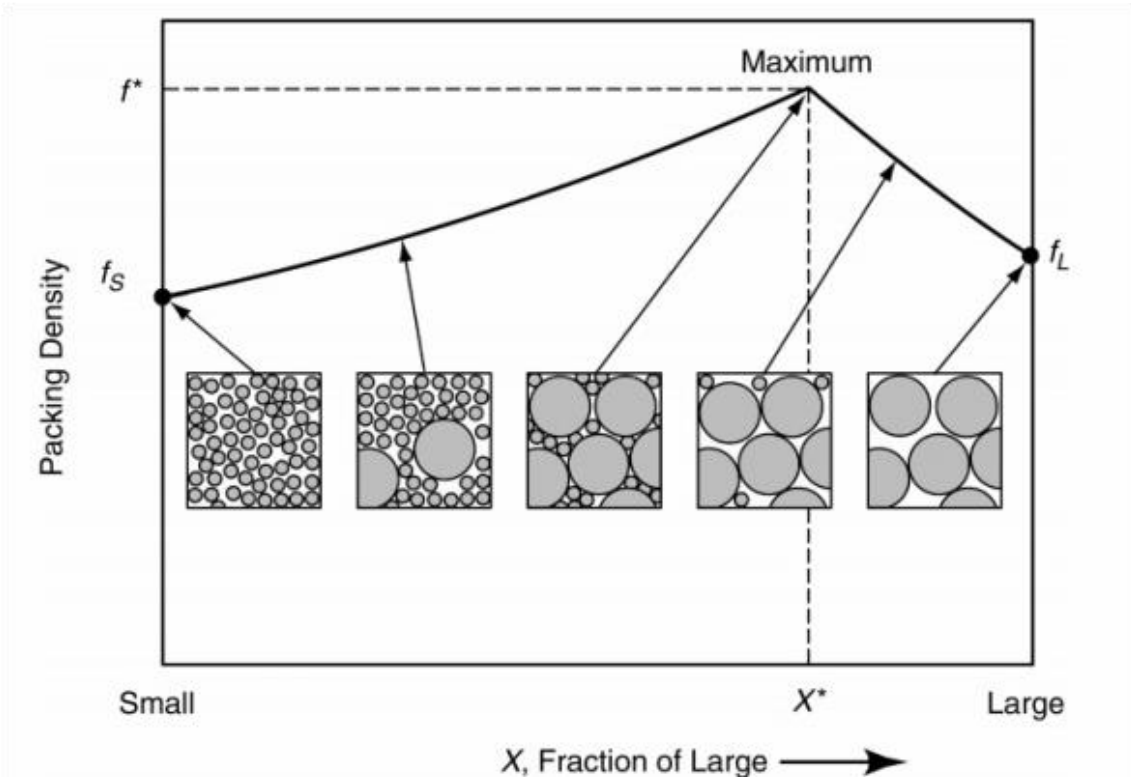


Figure 9 - Relation between particle packing density and particle size distribution [17]

Research further discovered that the critical criteria are D10, D50, and D90, with the following criteria being also identified for a maximum recoated thin layer density of 60%:

- D10 < layer thickness: 10% of particles are smaller than the layer thickness;
- D90 < layer thickness: 90% of particles are smaller than the layer thickness;
- D50 ≥ 10×D10: 50% of particles are 10 times coarser than the 10% finer grains;
- D90 ≤ 19×D10: the coarsest particles are in a 1:19 ratio with finer particles.

Combined with the recoating systems, particle size and size distribution affect recoating homogeneity, real layer thickness, and layer packing density, ultimately influencing surface roughness, LPBF efficiency, and repeatability [17].

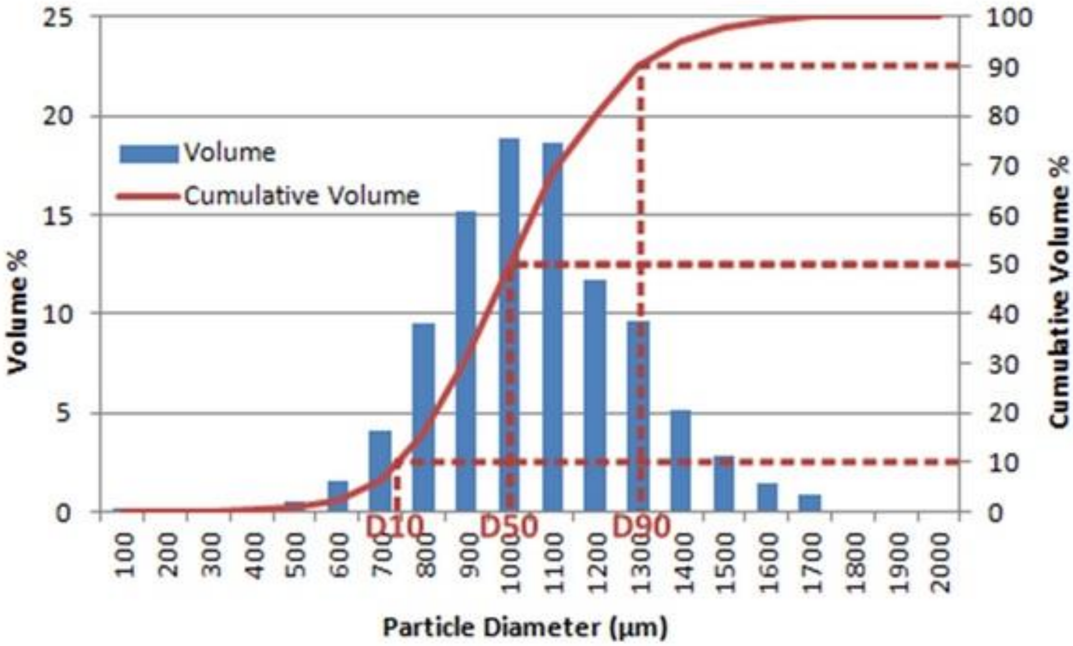


Figure 10 - Relation between particle diameter and volume [17]

2.2.2. Maraging M300 Steel

Maraging M300 steel, also known as 18Ni300 or EN 1.2709 steel, is part of the class of high-strength precipitation hardened steels. Maraging steels form a class of iron alloys, which has a martensitic crystal structure and is strengthened via aging at approximately 500 °C, hence the name "maraging". Maraging steels are ultra-low carbon alloys, and distinctive by combining high strength with relatively good ductility, good hardenability, and weldability, requiring a simple aging heat treatment. These properties are derived from precipitation of intermetallic compounds rather than carbon content, and makes this material of great importance, for example, in the automotive and nuclear industries, but even more so in the aerospace and tooling industries, as materials combining these properties with the geometrical optimization granted by AM, which partially compensates for the relatively high density of iron alloys, are key to the future development of lightweight engineering design strategies [19, 20, 21].

In maraging steels, nickel is the main alloying component, with cobalt, molybdenum, and titanium as secondary intermetallic alloying metals. Maraging steels are hardened by precipitation, during ageing, of finely dispersed Ni_3Mo, Ni_3Ti, Ni_3Al and Fe_2Mo. Unlike most types of steel, the carbon content is kept very low to avoid the formation of titanium carbide precipitates, which severely reduce the impact strength, ductility and toughness when present in high concentration. Because of this carbide precipitation is practically eliminated [19, 20].

These types of steels are produced by austenitising the steel, followed by slow cooling in air to form a martensitic microstructure. The slow cooling of hypoeutectic steel from the austenite phase usually results in the formation of ferrite and pearlite; rapid cooling by quenching in water or oil is often necessary to form martensite. However, martensite forms in maraging steel upon slow cooling owing to the high nickel content which suppresses the formation of ferrite and pearlite. The martensitic microstructure in as-cooled maraging steel is soft compared with the martensite formed in plain carbon steels by quenching. However, this softness is an advantage because it results in high ductility and toughness without the need for tempering. The softness also allows maraging steel to be machined into structural components, unlike hard martensitic steels that must be tempered before machining to avoid cracking. After quenching, maraging steel undergoes a final stage of strengthening involving thermal ageing before being used in aircraft components. Maraging steel is heat-treated at 480-500 °C for several hours to form a fine dispersion of hard precipitates within the soft martensite matrix [19, 20].

During PBF processes, a melt pool is created by melting a small amount of powdered metal, which quickly cools and solidifies. When the laser melts the material, it heats it above the M_s temperature and rapidly cools it below the M_f temperature. As a result, the material undergoes a quenching transformation from austenitic to soft martensitic structures. This is represented in the schematics in Figure 11, showing the formation process of microstructure in the maraging steel during the LPBF process in (a), (b), and (c), as well as together with a schematic thermal history of the sample by local laser heating in (d). So, as part of the LPBF process, the aforementioned heat treatments are applied to the part, resulting in the formation of intermetallic precipitation phases. These phases provide maraging steel with its characteristic strength and hardness while maintaining its ductility. This makes maraging steel a prime material for used in AM, and more specifically in LPBF [22].

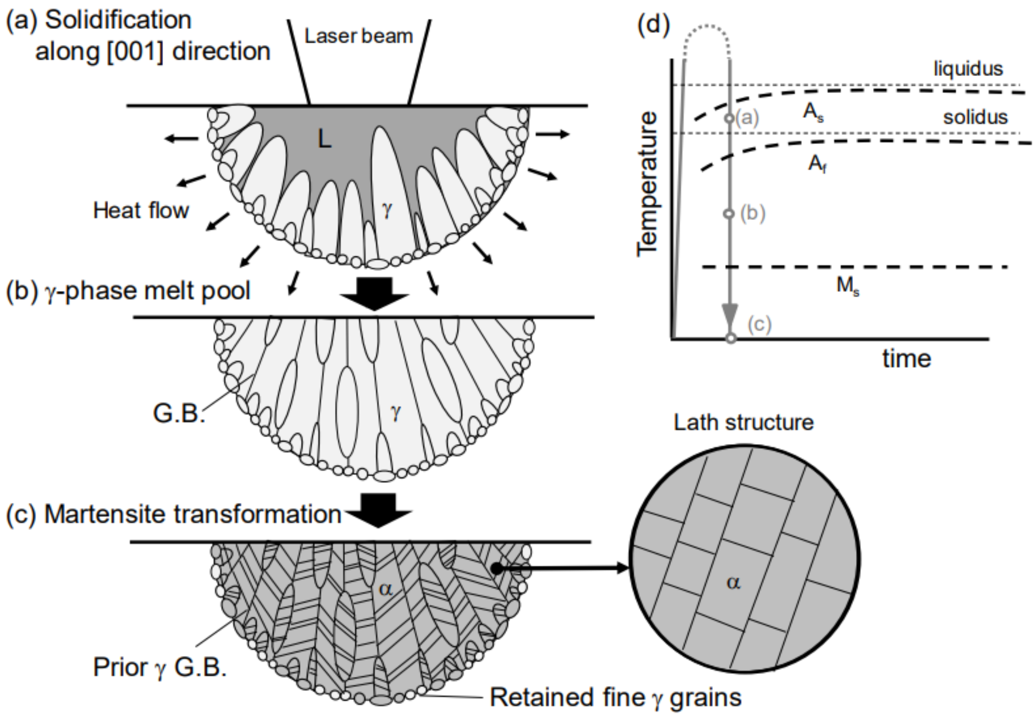


Figure 11 - Schematics of the formation process of microstructure in maraging steel during LPBF [22]

2.2.3. 316L Stainless Steel

Even though the maraging M300 steel is the chosen and preferred material in the long term for the development of this tool, due to various constraints, not least of all availability of the materials, for the purposes of this work 316L stainless steel will be used instead, so it's also important to give proper context for this material.

316L stainless steel, or stainless steel type 1.4404, is an austenitic stainless steel, renowned for its high versatility, exceptional corrosion resistance, and durability. The "L" in its designation indicates its low carbon content, under 0,03%, a key attribute that enhances its resistance to sensitization, or to carbide precipitation, as this ensures the alloy's ability to maintain its structural integrity even in high-temperature environments. Its main alloying elements are chromium, nickel, and molybdenum, which above all lead to an increased corrosion resistance [23, 24].

As stated, one of the most remarkable features of 316L stainless steel is its impressive corrosion resistance. Thanks to the combination of chromium and nickel, this alloy is exceptionally resistant to pitting, crevice corrosion, and chloride-induced stress corrosion cracking, making it a preferred choice for applications exposed to harsh or corrosive environments. Furthermore, the presence of molybdenum enhances its resistance to sulfuric acid and other acidic compounds, contributing to its widespread use in chemical processing equipment and industrial settings where corrosive substances are present. This characteristic gives the material a wide range of applications, from medical implants to the marine sector [23, 24].

Another aspect that reflects its versatility is its ease of fabrication, and excellent formability and weldability. It can be readily shaped into various, and intricate forms and structures, making it suitable for a wide array of manufacturing processes, such as for use in machining processes. Its combination of mechanical properties, corrosion resistance, and aesthetic appeal has also led to an increase in popularity in architectural applications, such as decorative components and structural elements in both indoor and outdoor environments, further widening its range of applicabilities [24].

It's these characteristics, of high corrosion resistance and excellent formability and weldability that make 316L such a prime material for implementation in LPBF. In fact, when employed in LPBF, 316L stainless steel exhibits promising characteristics, such as reduced porosity and improved microstructural homogeneity, meaning it's harder and more resistant than conventionally manufactured stainless steel [23].

2.2.4. Powder Production

Maraging steel powder production for LPBF processing involves a complex series of steps that are designed to produce a high-quality powder suitable for use in 3D printing applications. Maraging steel powder for LPBF is typically produced using gas atomization, a process in which a molten metal stream is atomised with a high-pressure gas, such as nitrogen or argon [25, 26].

The first step in the production process is to prepare the maraging steel alloy by melting it in a vacuum induction furnace. The molten alloy is then poured into a crucible and fed into the gas atomization chamber, where it is atomised into fine droplets. These droplets are then rapidly solidified into spherical particles by the high-pressure gas, resulting in a powder with a controlled particle size distribution. After this process, the maraging steel powder is screened and classified to remove any oversize or undersize particles. The resulting powder is then processed using a series of heat treatments to enhance its properties and ensure that it meets the specific requirements of the application [25, 26].

One of the critical aspects of maraging steel powder production for LPBF processing is ensuring that the powder has a consistent chemical composition and microstructure. This is achieved by carefully controlling the atomization process and subsequent heat treatments to ensure that the powder has the desired properties, such as high strength and toughness, and is free from defects. However, the choice of powder production process can depend on the specific requirements of the application and the desired properties of the powder. To this effect, other processes exist as well, albeit being less common than gas atomization. Among them are included electrolysis, a process where an electric current is passed through a molten salt containing the metal ions which are reduced and deposited on a cathode as metal powder; solid-state reduction, a process that involves reducing metal oxide powders to metal powders by heating them in a reducing gas atmosphere; and mechanical alloying, which consists of milling metal powders together with a milling media to produce alloy powders with a fine, homogeneous microstructure, with the resulting powders being typically used for LPBF of complex alloys [25, 26].

There are other forms of atomization as well, which may offer fulfil different requirements than that of gas atomization, in which are included water atomization, the cheapest option, in which an high-pressure water jet is utilised to break up molten metal into small droplets, which are then collected and dried to form metal powder; plasma atomization, where the same occurs, but with a plasma jet instead of an high-pressure water jet; induction melted bar atomization, which consists of melting metal bars using induction heating and then atomising the molten metal using a high-pressure gas to produce metal powder; and plasma rotating electrode process, a process where a rotating electrode made of the desired metal is melted using a plasma arc and then atomising the molten metal using a high-pressure gas to produce metal powder with a uniform composition and high degree of spherical shape [25, 26].

These different processes can be used to achieve different results, in regards of the powder size, shape, and composition, as well as the specific requirements of the application, and some of its advantages and disadvantages are listed in Table 1.

Table 1 - Advantages and disadvantages of the leading metal powder manufacturing methods for metal AM [25]

Process	Advantages	Disadvantages
Gas Atomisation (GA)	• Excellent metallurgical quality • High powder flow rates • Wide selection of alloys • New and modified alloys can easily be made • Scalable technology: very high volumes available and can easily support AM growth • Large supply base • Relatively low cost, especially when AM increases quantities	• Variability in powder properties between suppliers • Large number of suppliers and atomising technologies can be confusing • Reactive and high melting point alloys not available • Few companies currently atomising titanium
Induction Melted Atomisation (EIGA)	• Excellent metallurgical quality • High flow rates • Reactive and high melting point alloys can be made • Titanium alloys available • High production rates, but restricted by yield considerations	• Limited supply base - but growing • Only alloys available as bar can be made • High cost
Plasma Atomised Wire Process (PAW)	• Excellent metallurgical quality • Very high flow rates - near perfect spheres • Reactive and high melting point alloys can be made • Titanium alloys available	• Limited supply base: only a few suppliers, and new patents may lock out additional • Only alloys available as wire can be made • High cost
Plasma Rotating Electrode Process (PREP)	• Excellent metallurgical quality • Very high flow rates - perfect spheres • Reactive and high melting point alloys can be made • Titanium alloys available	• Limited supply base - but growing • High quality bar needed as starting material • High cost
Water Atomisation (WA)	• Low cost • Scalable atomising technology	• Metallurgical quality lower than gas atomisation • Powder not natively spherical • Not yet established for powder bed applications

2.3. Design

2.3.1. CAD

Computer-Aided Design (CAD) has transformed the approach of engineers, architects, and designers in the creation and development of products, structures, and systems. The CAD process is a systematic method for producing digital representations of physical objects or systems, encompassing a series of steps that facilitate efficient design, analysis, and documentation of ideas [27, 28].

Typically, the CAD process commences with conceptualisation, during which designers brainstorm and outline their concepts for a product, component, or system. Subsequently, in the initial design phase, they employ CAD software to generate a fundamental digital model, defining the shape, dimensions, and key features. As the design advances, further particulars are incorporated into the model, specifying materials, tolerances, and other parameters. CAD software allows for iterative design, empowering designers to implement modifications and refinements based on analysis outcomes, feedback, or evolving requirements. This adaptability is a defining characteristic of CAD, streamlining the design process by automatically updating the entire model when adjustments are made [27, 28].

Furthermore, CAD software facilitates diverse analyses and simulations, including stress testing, motion analysis, and fluid dynamics, ensuring alignment with functional and structural prerequisites. Upon finalisation of the design, CAD tools generate comprehensive documentation, encompassing 2D drawings and assembly instructions, which prove indispensable for manufacturing or construction. The CAD process fosters collaboration, visualisation, and data management, cementing its status as an integral component of contemporary product design and engineering workflows [28, 29]. Figure 12 represents a schematic of the AM process, and how the CAD process features in it.

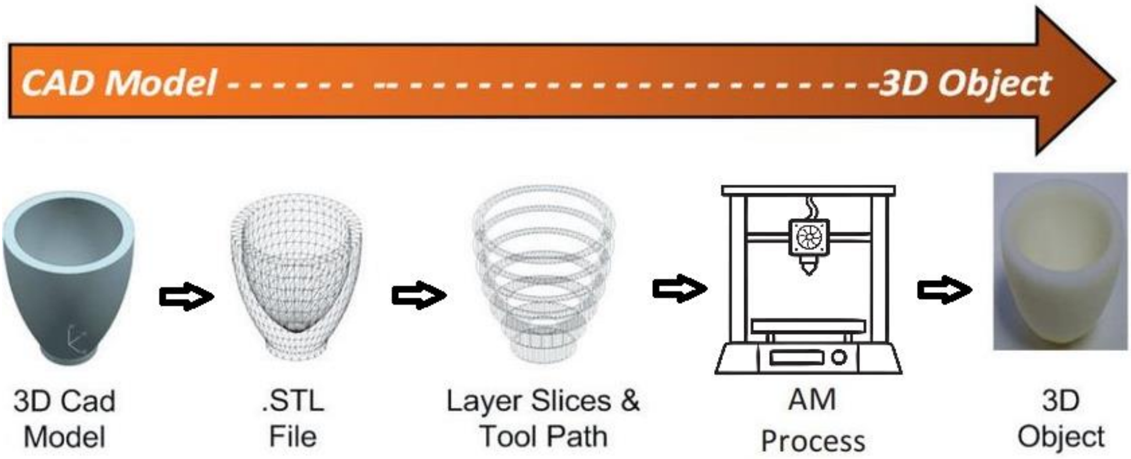


Figure 12 - Schematic of the AM process, from CAD through to part completion [30]

Notable CAD tools, that are relevant to the objectives of this dissertation, are SolidWorks, developed by Dassault Systems, and Magics, from Materialise.

2.3.2. SolidWorks

SolidWorks is a CAD software package widely used in engineering and product design across various industries, as it offers an extensive set of tools and capabilities to support the entire product development process. At its core, SolidWorks is known for its robust 3D modelling capabilities, allowing users to create intricate and precise 3D models of mechanical and electronic components, assemblies, and products. What sets SolidWorks apart is the software's user-friendly interface and intuitive features, which make it accessible to both novice designers and experienced engineers, and its parametric modelling approach, where changes made to a design are automatically propagated throughout the model, by enabling users to define dimensions and relationships between parts, making it easy to modify and update designs as needed, and also ensuring consistency, and reducing errors. This feature proves invaluable during the iterative design process, where modifications can be swiftly implemented to refine and optimise the final product [31].

2.3.3. Materialise Magics

Materialise Magics is a versatile and powerful software solution designed specifically for the AM industry. It serves as a comprehensive toolkit for every stage of the AM process, as it allows its users to import 3D CAD models in various formats, and then to prepare and optimise these models. The software offers an array of functions, including geometry repair, mesh editing, lattice structure generation, part nesting, and support structure creation within the models. These tools help ensure that 3D models are print-ready and can be produced with high quality and efficiency. Furthermore, Materialise Magics excels in streamlining the AM workflow, making it an invaluable asset across various industries. It facilitates precision in part orientation, offers quality control checks to identify potential issues, and supports custom build plate generation. The software's ability to integrate with other AM software and hardware systems enhances its usability, as it enables the conversion of the initial file into the appropriate format for the AM machine in question, makes it an even more invaluable tool in the AM process [32].

2.4. Machining

2.4.1. Introduction to Machining

Machining is an essential subtractive process in the manufacturing industry that involves using cutting tools to remove small chips of material from a workpiece. It plays a crucial role in modern manufacturing by facilitating the production of highly precise and intricate components with excellent surface finish, and which can be used in a wide range of applications, both broad and specific. This diverse field encompasses various processes and techniques, such as turning, drilling, boring, and milling, that shape and manipulate materials to create desired components [33, 34].

In machining operations, a relative motion between the tool and the work is necessary, which consists of a primary motion known as "cutting speed", and a secondary motion called "feed." By combining these motions with the tool's shape and penetration into the work surface, the desired shape of the resulting work surface is achieved [33, 34].

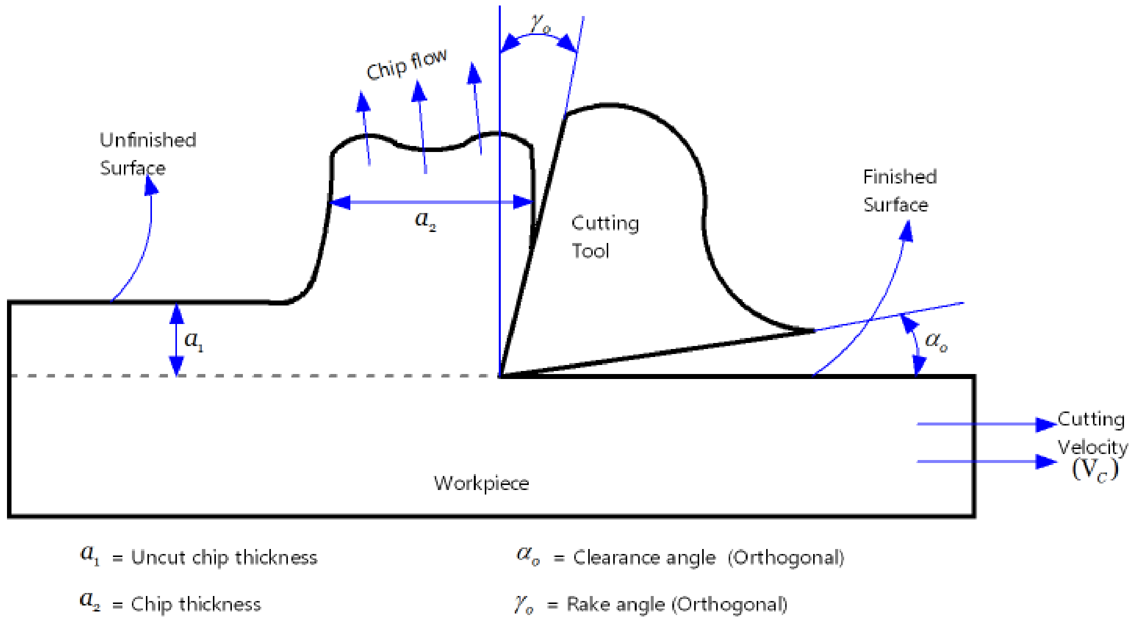


Figure 13 - Machining process diagram [35]

2.4.2. Conventional machining operations

There are many kinds of machining operations, such as the ones mentioned above, each of which is capable of generating a certain part geometry and surface texture, but in this work focus will be on milling, as the part to be created will be used in these types of operations. But firstly, a brief explanation on each of these operations, some of which can be seen represented in Figure 14, will be given [33, 34].

Turning involves using a cutting tool with a solitary cutting edge to eliminate material from a revolving workpiece, resulting in the creation of a cylindrical shape. The primary motion is achieved by rotating the workpiece, while the feed motion is attained by gradually moving the cutting tool parallel to the workpiece's axis of rotation. Drilling is employed to produce a circular hole by utilising a rotating tool typically equipped with two or four helical cutting edges. The tool is fed into the workpiece in a direction parallel to its axis of rotation, resulting in the formation of the round hole. Boring entails advancing a tool with a single angled pointed tip into a roughly formed hole in a rotating workpiece to slightly enlarge the hole and enhance its precision. This operation serves as a meticulous finishing process employed during the final stages of product manufacturing [33, 34].

Finally, milling is a versatile machining operation that uses rotating multi-toothed cutting tools to remove material from a workpiece. The milling cutting tool, or cutter, moves in various directions to create complex shapes. This process involves moving the cutter perpendicular to its axis. As the milling cutter enters the workpiece, its cutting edges repeatedly cut into and exit the material, removing chips. The cutting action is shear deformation, which occurs when an object changes shape because forces are applied to it and does not just become longer or shorter. To accomplish material removal, milling performs many separate small cuts. This is achieved by using a cutter with multiple teeth, rotating at high speed, and advancing the material slowly through the cutter. The combination of these approaches allows for efficient milling. The feed rate can also be adjusted to better suit the imposed requirements [33, 34].

There are two main types of milling processes, face milling and peripheral milling. In the former, the cutting action occurs primarily at the end corners of the milling cutter, and is primarily used to create flat surfaces or flat-bottomed cavities, while in the latter the cutting action occurs primarily along the circumference of the cutter, shaping the milled surface to match the cutter's form, and making it more suitable for cutting deep slots, threads, and gear teeth. Face milling specifically should be given a greater emphasis for the purposes of this work, has the part to be created is a face milling cutter [33, 34].

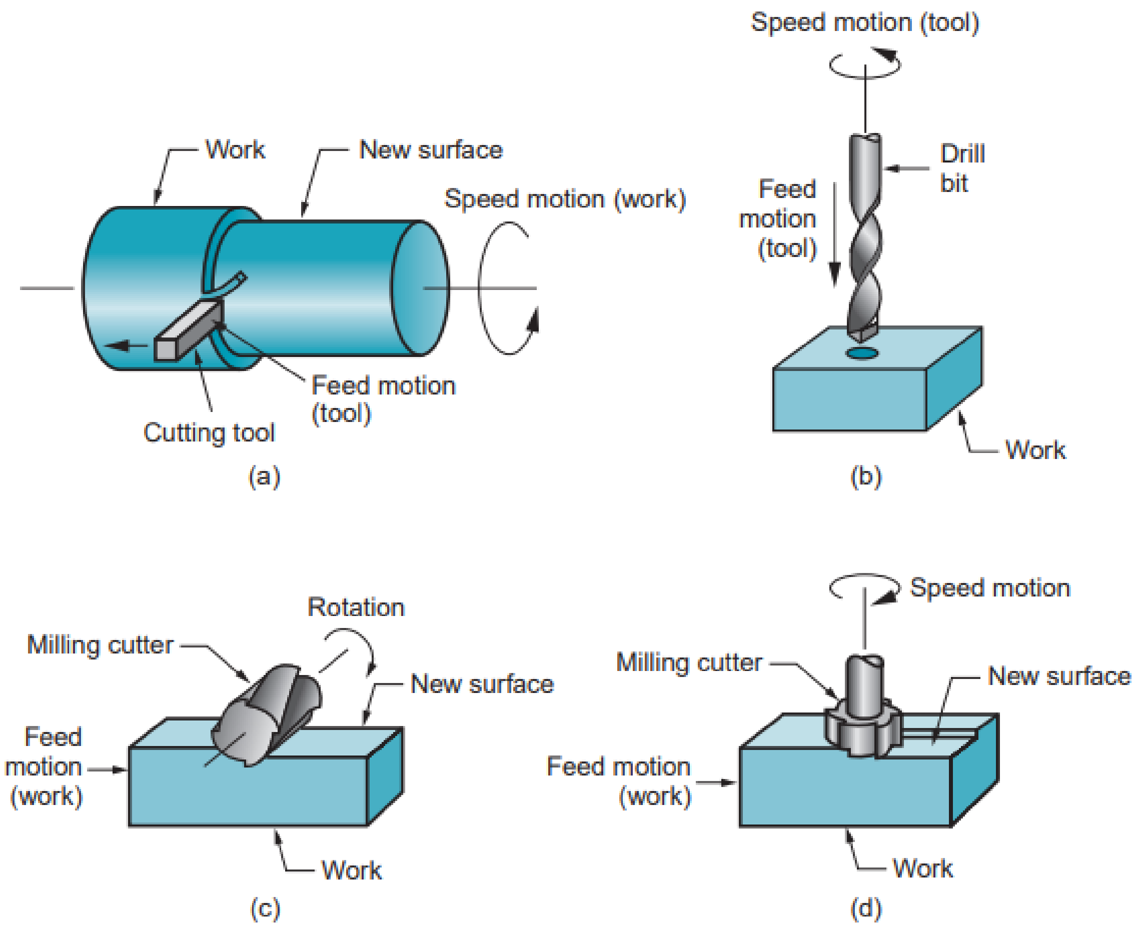


Figure 14 - Examples of some types of machining processes: turning (a), drilling (b), peripheral milling (c), and face milling (d) [33]

There is also gang milling, in which multiple milling cutters are mounted on the same arbour in a horizontal setup. This allows for efficient production of duplicate parts, as each cutter can perform a specific type of operation. Gang milling was particularly important before the era of computer numerical control (CNC) machines, as it improved efficiency compared to manual milling. With the advent of CNC mills and automatic tool change capabilities, gang milling has become less necessary for duplicate part production [33]. Modern CNC mills with 4 or 5-axis control can handle multiple operations without the need for changing machines or setups, and the advent of AM has further decreased the need for gang milling, as milling cutters could then be produced with more intricate shapes, with more cutting edges, allowing for increases in production with single cutters [36].

2.4.3. High-feed Milling

High-feed milling (HFM) is an advanced method of machining that falls under the category of progressive machining techniques, three times as fast as conventional methods. This process uses shallow depths of cut and, as the name indicates, higher feed rates per tooth, thus maximising feed utilization, in order to maximise the amount of metal being removed from a part in a shorter amount of time, as well as assuring greater surface finish and reducing cutting forces. By employing this method, a greater volume of material can be efficiently removed during the machining process [37].

The primary advantages of this process are its ease of automation, as it can easily be coupled with CNC systems, and the reduction and distribution of cutting forces, primarily in the direction of the spindle, and reduction of machining vibrations, which lead to an improved tool life and more stable machining process. This also lessens the need for post-processing like semi-finishing, as this process often already achieves low roughness [37]. However, it proves to be a higher cost machining process, as HFM tools are specialised tools, often requiring novel manners of production, such as AM, and are therefore more expensive, specially design inserts, usually with shallow lead angle, are also needed to best utilise this process to its fullest potential, and due to its requirement for higher feeds, and often higher spindle speeds, not every machine has the capability to use this method [38, 39]. HFM also leads to increased chip accumulation, further enhancing the requirement for efficient chip evacuation.

HFM has been shown to achieve better results in dimensional accuracy, surface quality, and productivity than conventional machining, making it more suitable for roughing operations, and even finishing operation, and for face milling especially [40, 41]. This makes it an ideal milling process for several industries, namely the automotive and aircraft industries [37].

2.4.4. Face Milling

Face milling is a machining method employed to flatten and refine the surface of workpieces. This technique utilises either a machining centre or a milling machine, differing from traditional milling methods in that the machine is positioned perpendicular to the workpiece. Consequently, the top of the machine engages with the workpiece, as opposed to the side used in other milling approaches [42].

The process can be executed manually or automatically, with the primary distinction being the feed rate. Manual face milling necessitates frequent machine stops to move the workpiece across the table, while automatic face milling maintains a more consistent feed rate. As a result, the automatic method is less prone to errors or incorrect cuts [42].

Regarding the process itself, it is divided the process into four stages [42]:

- Workpiece Positioning – Before initiating the process, it is crucial to securely attach the workpiece to the machine table to prevent slippage.
- Milling Machine Placement – The milling machine must be positioned correctly, perpendicular to the workpiece, enabling the cutter's top to operate on the material effectively.
- Adjusting Feed Rate and Spindle Speed – The next step involves fine-tuning the feed rate and spindle speed. Proper adjustment of these parameters ensures accurate cutting by the machine.
- Machining – Once the machine is set up, the machining process commences. For CNC machining, where the computer is provided with the necessary code, it takes charge of executing the machining operation, shaping, and forming the workpiece according to the desired specifications.

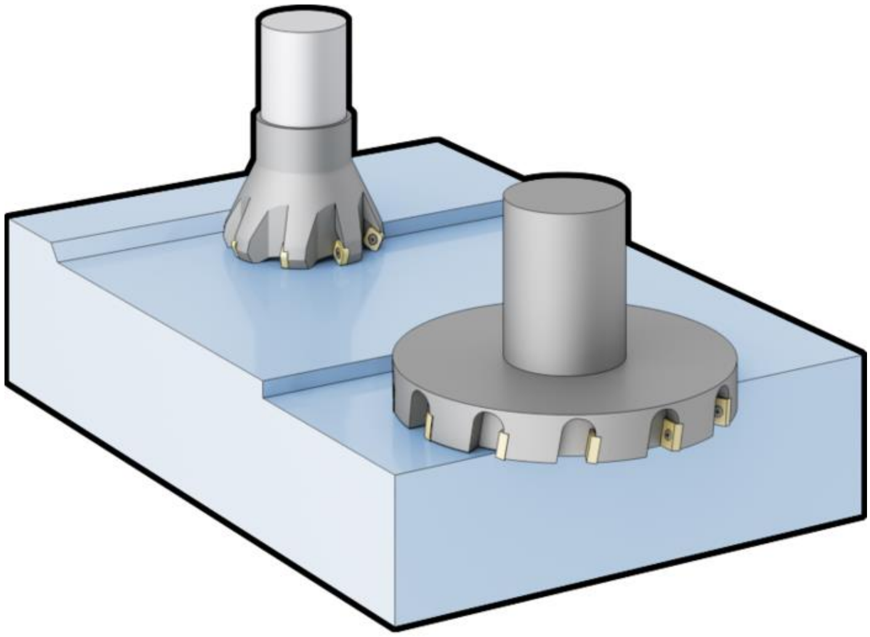


Figure 15 - Example of face milling [43]

2.4.5. Cutting Tools

When it comes to cutting tools, they are vital components in machining processes. They are designed to withstand high forces, temperatures, and cutting speeds that would cause severe tool wear. These cutting edges function to remove material from the parent work material, in the form of chips, and are comprised of two surfaces: the rake face and the flank [33].

The rake face is the surface that directs the flow of the newly formed chip and is positioned at a specific angle, known as the rake angle. The rake angle is measured in relation to the plane perpendicular to the work surface. It can be either positive or negative. The flank of the tool creates clearance between the tool and the newly formed work surface. This clearance protects the surface from abrasion, which would diminish the quality of the finish. The angle between the work surface and the flank surface is referred to as the relief angle [33].

Furthermore, cutting tools can be divided into two fundamental types, single-point tools, which possess a solitary cutting, and multiple-cutting-edge tool, which feature more than one cutting edge and generally achieve their motion relative to the workpiece through rotation. These latter ones are the ones used for milling operations, and specifically have a circular shape, with the cutting edges located along the radius. They often function to cut with the cutter's ends rather than their sides [33].

Commonly used materials for cutting tool inserts include high-speed steel, carbide, and ceramic, providing different properties such as hardness, wear resistance, and toughness [33, 44]. These can be attached to the cutting edges through soldering or with screws.

Figure 16 - Face milling cutter [45]

2.4.6. Internal cooling channels

In recent years, the inclusion of internal cooling channels has brought about a significant transformation in the domain of cutting tools, assuming a pivotal role in enhancing their performance and durability. By directing coolant or lubricants directly to the cutting edge, internal channels disperse heat more effectively, averting excessive temperatures that can lead to tool wear and damage [46]. This precise cooling not only sustains the tool's integrity but also ensures consistent cutting performance, thereby ultimately bolstering efficiency in machining procedures. Additionally, the effective application of lubricants within these channels diminishes friction between the tool and the workpiece, further augmenting the efficacy of the cutting tool [47, 48].

Furthermore, the introduction of internal channels in cutting tools has streamlined the process of chip removal, a fundamental facet of machining operations. Efficient evacuation of chips is pivotal in preventing blockages or re-cutting of chips, both of which can jeopardise the quality of the workpiece and accelerate tool wear. The integration of internal channels facilitates the timely removal of chips from the cutting zone, thus maintaining an uninterrupted cutting process. Consequently, the extended lifespan of cutting tools becomes evident, reducing the frequency of tool replacements and the accompanying costs [48]. This proves especially important in HFM operations, as previously stated, as cutting performance and tool maintenance are important factors in it, and, with the growing development and application of AM techniques, the importance of these internal channels has become increasingly pronounced, as these channels serve as a critical means to improve the cooling of cutting tools during machining processes, and through AM these channels can attain more complex shapes, can be more evenly distributed, and can be designed for optimal lubricant flow.

Figure 17 - Examples of HFM tools with internal channels' exits visible [49]

3. Experimental Procedure

The experimental procedure of this dissertation focusses on the design stages of a milling tool cutter to be manufactured via LPBF, and with said manufacturing process. It is then followed by a series of measurements and tests, to not only check the feasibility of the designs selected, but to also understand the viability of the methods of production.

This chapter will shed some light into these steps of the dissertations, providing some in-depth observations regarding the material used, the design process, the manufacturing process, and the equipment utilised.

3.1. GE Concept Laser M2

To achieve the objectives of this work, the GE Concept Laser M2 was the LPBF machine of choice. This is a cutting-edge AM machine that revolutionises the production of complex metal parts. Built by GE Additive, a division of General Electric, the M2 was designed for industrial applications where precision, speed, and efficiency are paramount. This advanced 3D printing system utilises LPBF technology to create fully functional metal components with exceptional accuracy [50, 51].

One of the key features of the GE Concept Laser M2 is its large build envelope, which enables the fabrication of relatively large parts or multiple smaller components in a single print job. This capability allows for efficient batch production and reduces the need for post-processing and assembly. With its high-powered laser and optimised scanning system, the M2 delivers excellent resolution and surface finish, ensuring the manufactured parts meet the most demanding quality standards [50, 51].

The GE Concept Laser M2, pictured in Figure 18, incorporates advanced control and monitoring systems that ensure process reliability and repeatability. It employs real-time monitoring and feedback mechanisms to detect any deviations or anomalies during the printing process, enabling immediate adjustments and minimising the risk of defects. Additionally, the M2 features an intuitive user interface and software ecosystem that simplifies job setup, parameter optimization, and workflow management, making it accessible to both experienced operators and newcomers to additive manufacturing [50, 51].

Figure 18 - GE Concept Laser M2 [50]

3.1.1. Machine Parameters

This GE Concept Laser M2 machine's specifications reveal it possesses a build volume of 245 x 245 x 350 mm, and a fibre laser system, with two 400 W lasers, with a variable focus diameter of 70 µm to 500 µm. The machine is capable of scanning speeds of up to 4,5 m/s, and producing layer thicknesses of between 20 µm and 80 µm, leading to production speeds of 2 cm^3/h to 35 cm^3/h. The inert gas used is nitrogen, consumed at a rate of up to 1,5 m^3/h [51].

The manufacturing parameters were determined as follows:

Table 2 - Manufacturing parameters [51]

	Advances Lattice Support	Advanced Surface Area Contour	Downside Contour	Advanced Surface Area
Power (W)	330	160	140	300
Speed (mm/s)	1400	300	200	700
Offset to Original Contour (mm)	0,1	0,09	0,08	0,1
Spot size (µm)	100	85	75	130
Trace Spacing	-	-	-	0,13

Figure 19 below serves as a visual illustration of the parameters:

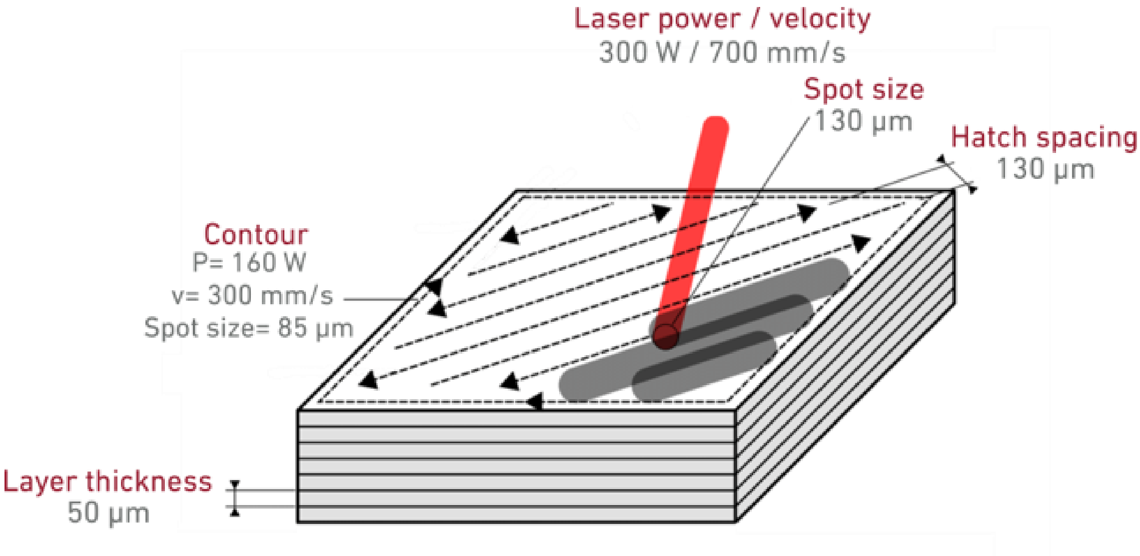


Figure 19 - Printing parameters

3.2. Material

While a maraging M300 steel will be the part's ultimate material, for the purposes of this work the 316L stainless steel powder, provided by GE, will be used, due to matters of availability and cost of material. 316L is an appropriate substitute for M300, as it is also useful in matters of prototyping and for industries such as the automotive [52]. In Table 3 its chemical composition is displayed, while the technical data can be viewed in Table 4:

Table 3 - 316L stainless steel powder chemical composition [52]

Element	Standard wt%
Fe	Balance
Cr	16,5 – 18,5
Ni	10,0 – 13,0
Mo	2,0 – 2,5
Mn	≤ 2,0
Si	≤ 1,0
P	≤ 0,045
C	≤ 0,03
S	≤ 0,03

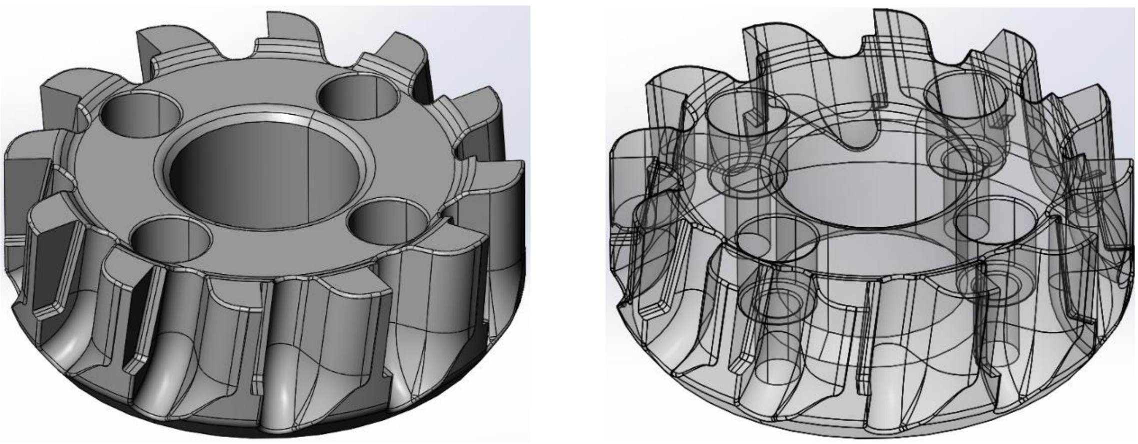
Table 4 - 316L stainless steel powder technical data [52]

	90°	45°	0°
Yield strength - $R_{p0,2}$ (N/mm²)	374 ± 5	385 ± 6	330 ± 8
Tensile Strength - R_m (N/mm²)	650 ± 5	640 ± 7	529 ± 8
Elongation - A (%)	65 ± 4	63 ± 5	63 ± 5
Young's modulus - (N/mm²)	ca. 200 · 10^3	ca. 200 · 10^3	ca. 200 · 10^3
Thermal conductivity - λ (W/mK)	ca. 15	ca. 15	ca. 15
Hardness - (HRC)	20	20	20

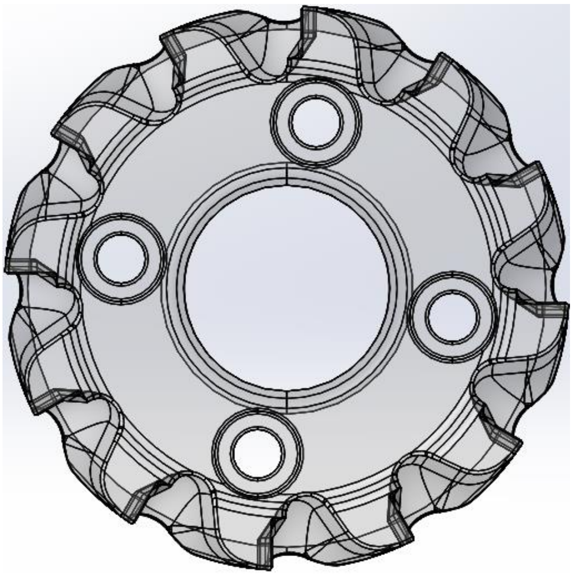
To enable the verification of the material standards for each alloying element, the chemical composition is to be evaluated by optical emission spectrometry using a spark emission spectroscopy, the SPECTROMAXX metal analyser equipment, in order to compare its values with the maximum and minimum quantities for each alloying element.

3.3. Design and Manufacture

The part is a milling cutting tool, especially designed for additive manufacturing production by Palbit. It measures 13,8 mm in height and 39,3 mm in diameter. The design stage of this work thus begins with a sample drawing provided by Palbit, pictured in Figure 20.



(a) (b)



(c)

Figure 20 - Different views of the initial design provided by Palbit (standard (a), transparent (b), transparent from above (c))

The initial iteration of the design was intended to feature 7 channels per teeth, with 3 aiming at the attack face, and 4 aiming the exit face, being that 3 were on the side and 1 on the contact surface of the cutter. The channels were designed in such a way to allow for the fluid to exit in directions perpendicular to the cutting zone (attack face) and parallel to the cutting zone (exit face). This was done to not only ensure lubrication of the cutting process, but also to facilitate the removal of chips from the cutting zone, thus allowing for a smoother cutting process [48].

Another element in their design was to minimise any sharp curves that would cause increased tear and decrease durability inside the channels [53, 54], and it was tried whenever possible to not have channels whose axis was less than 45° when compared with the base, in order to achieve minimal roughness, as this reduces the staircase effect and helps maintain the intended channel shape [55, 56].

The channels were made circular, as although teardrop profiles have been shown self-supporting and less susceptible to deformation, they were deemed unnecessary due to small size channels dimensions, as channel diameters should be between 0,5 mm and 3mm are considered self-supporting on their own [54, 56]. The channels and their exit holes had therefore diameters of 0,6 mm for the ones aiming at exit face and 0,8 mm for those aiming at the attack face.

In Figure 21 are pictured different views from the first iteration of design, showing the overall design of the part, as well as details of the internal channels, for better viewing comprehension.

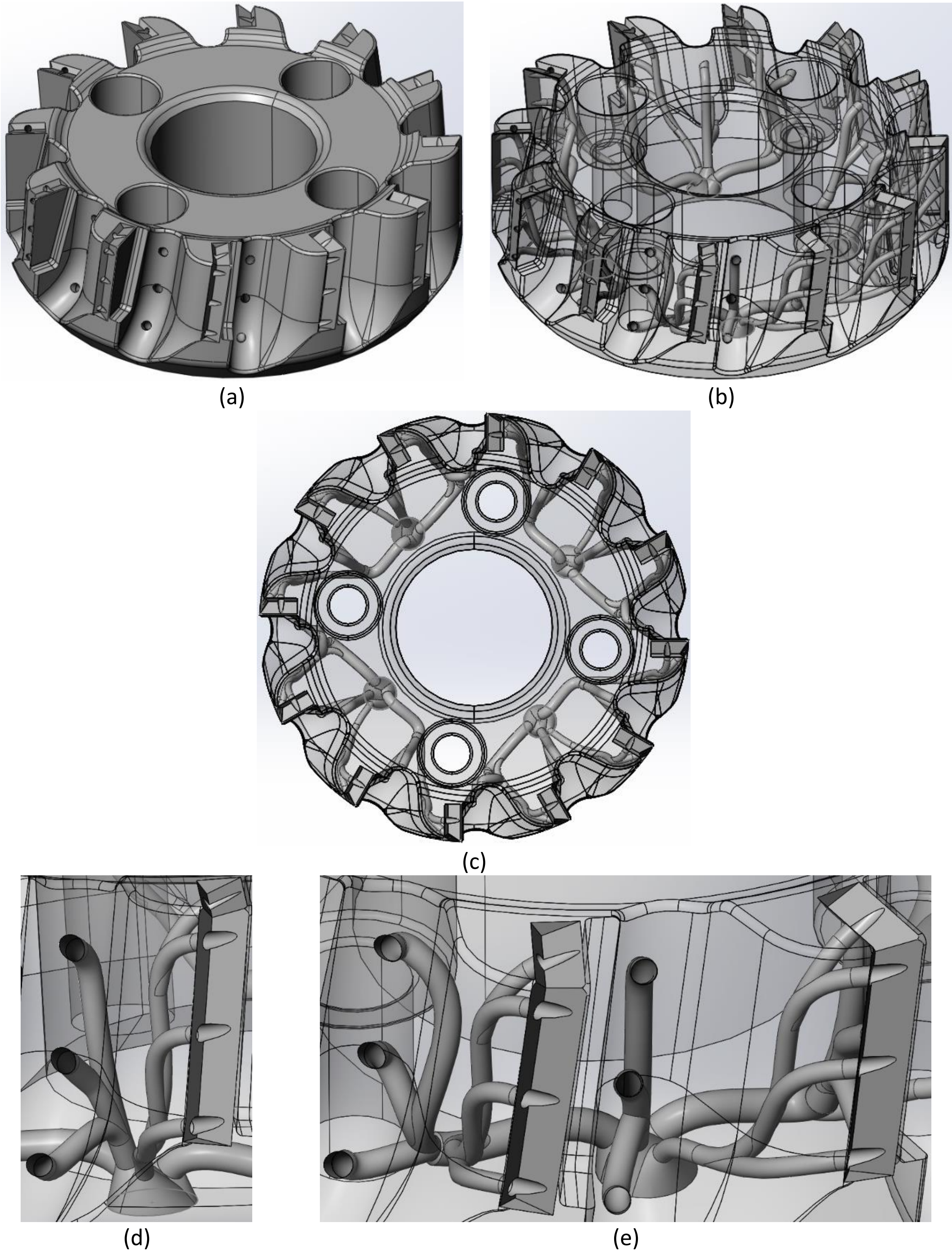


Figure 21 - Different views of the first iteration design (standard (a), transparent (b), transparent from above (c), channel details (d) and (e))

The part design was then processed via the Materialise Magics software, fitting it with supports and altering the orientation for a better printing process, such as to avoid horizontal channels [57] or to minimise thermal stresses [54], and subsequently additively manufactured through LPBF technology in the GE Concept Laser M2, as pictured in Figures 22 and 23, respectively.

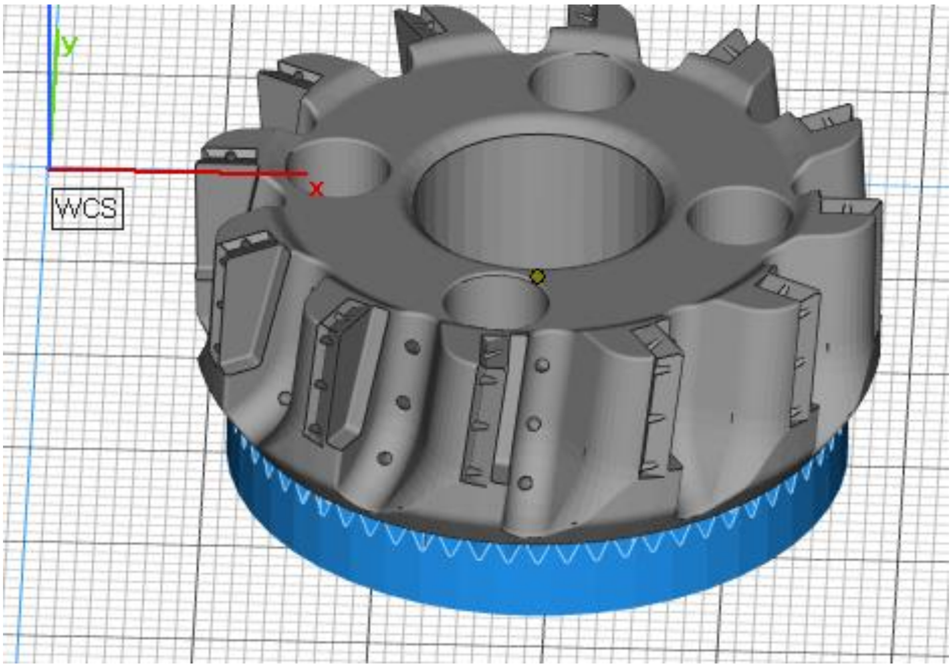


Figure 22 - Design processing in the Materialise Magics software

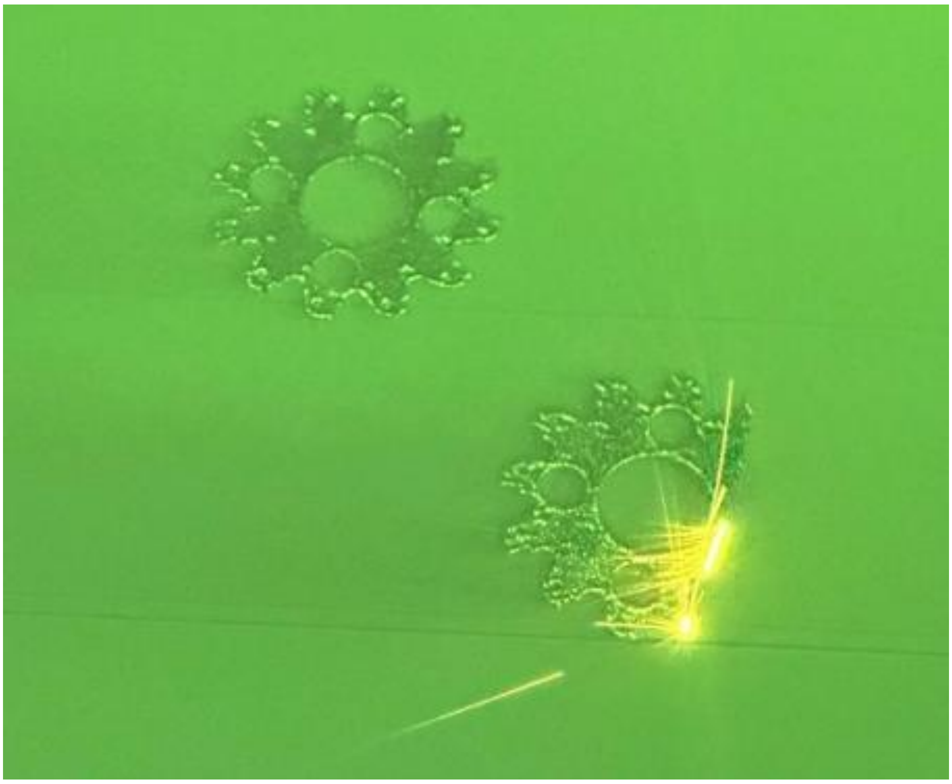
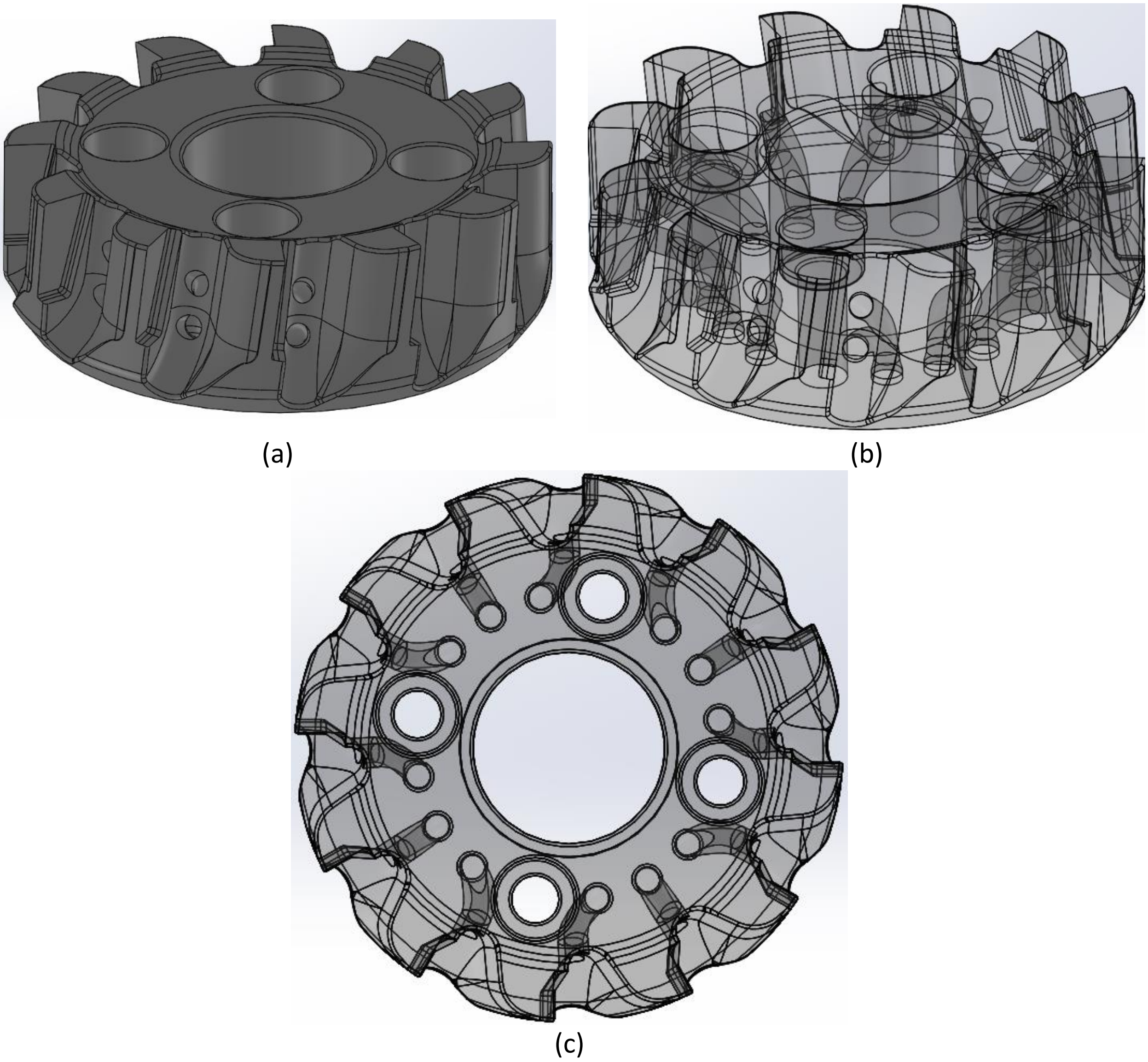


Figure 23 - Part manufacturing in the GE Concept Laser M2

Manufacturing the part revealed the channel dimensions to be too small and, since the proportional error becomes smaller for bigger channels, a second iteration, with larger channel dimensions, proves necessary [55, 57]. Given this fact, further iterations of the design were created, with larger channel diameters, of at least 1 mm. This new iteration began with an updated design provided by Palbit, featuring two circular channels, of 1,7 mm in diameter, aiming at the attack faces, as seen here in Figure 24.



(a) (b)

(c)

Figure 24 - Different views of the second iteration design provided by Palbit (standard (a), transparent (b), transparent from above (c))

This design, in which the "attack face" channels and exit holes measured 1,7 mm in diameter, was then further altered to also feature 1 circular channel aiming at each exit face, measuring 1,5 mm in diameter, and with an oval exit hole, measuring 1,2 mm in the short axis, and 2,82 mm in the long axis. Figure 25 further shows this alteration to the design, along with a close up of a detail, for better viewing comprehension.

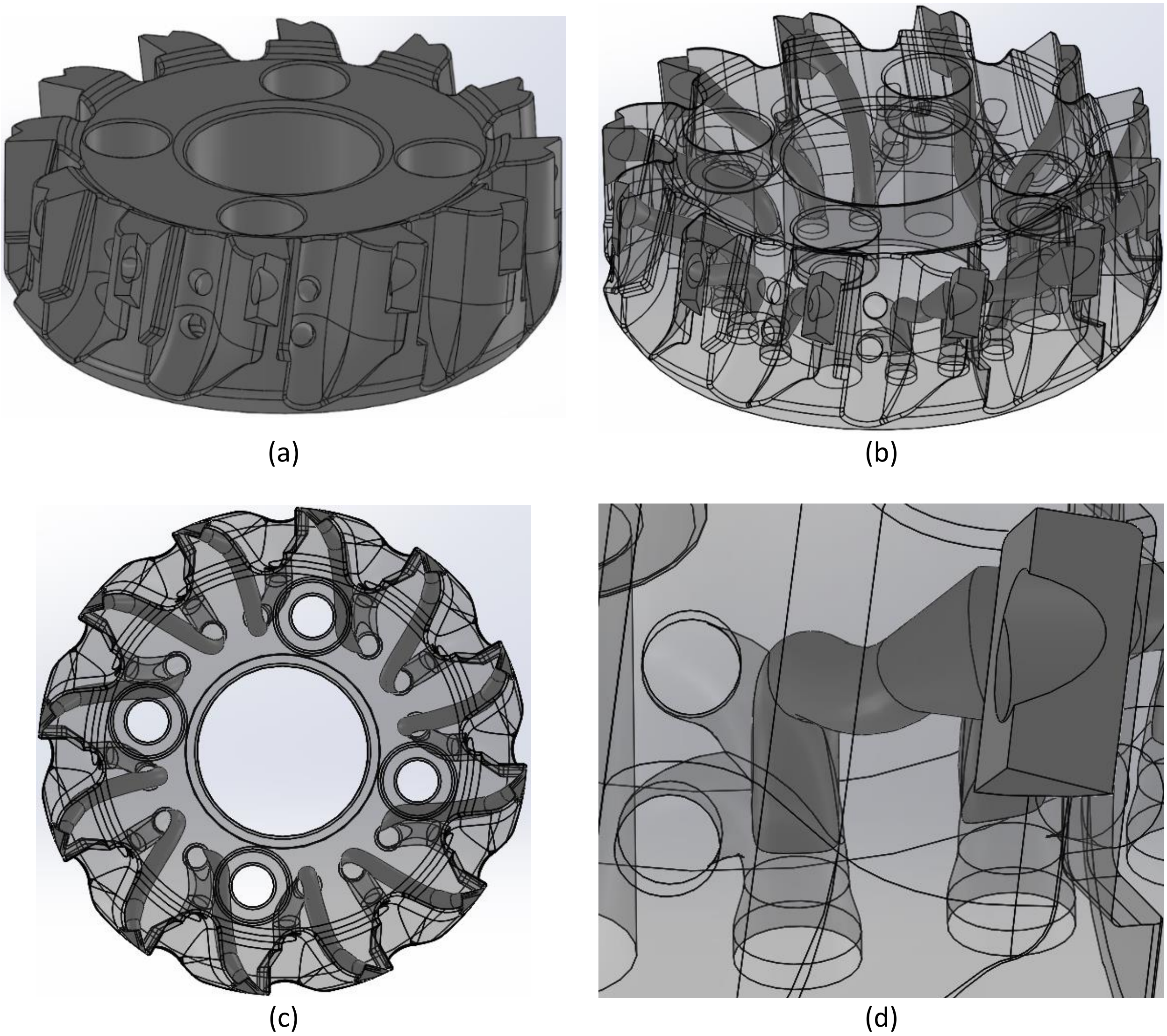


Figure 25 - Different views of the second iteration design (standard (a), transparent (b), transparent from above (c), channel details (d))

For this iteration the same design principles were applied, and then the part went through the same processing and additive manufacturing steps as the first iteration.

3.4. Experimental Apparatus

Following the manufacture of the part, measurements are to be conducted on it. These were all conducted at INEGI's facilities. Firstly, it is necessary to cut the parts, as to measure its internal dimensions, as well as to perform roughness and eventual material characterization tests. To achieve this, a wet abrasive cutting machine fitted with a zirconium oxide wheel, the Metkon Metacut 302, pictured in Figure 26, is used.

Figure 26 - Metkon Metacut 302 cutting machine

The dimensional measurements themselves were conducted using a Dino-Lite Digital Microscope, pictured in Figure 27, connected to a computer running the company specific software DinoCapture, on which the pictures are saved, and measurements can be made.

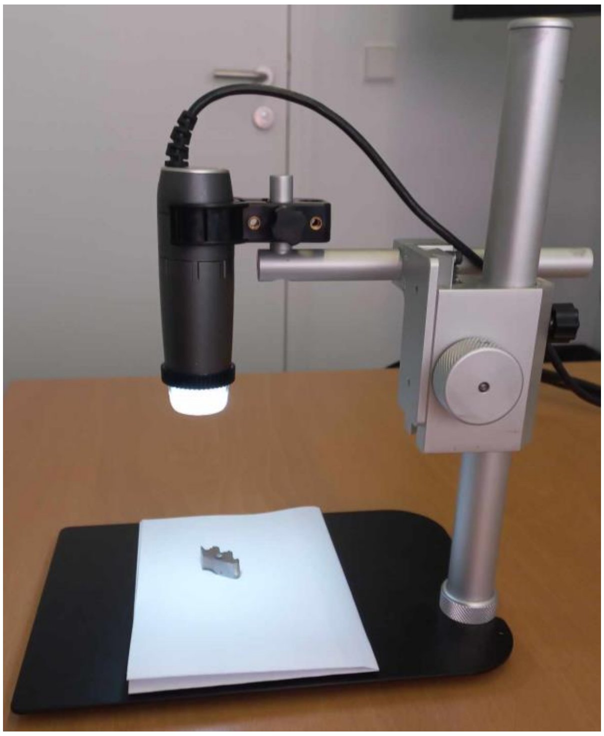


Figure 27 - Dino-Lite Digital Microscope

The roughness tests were conducted with a Mitutoyo SJ-210 measuring instrument, seen in Figure 28.

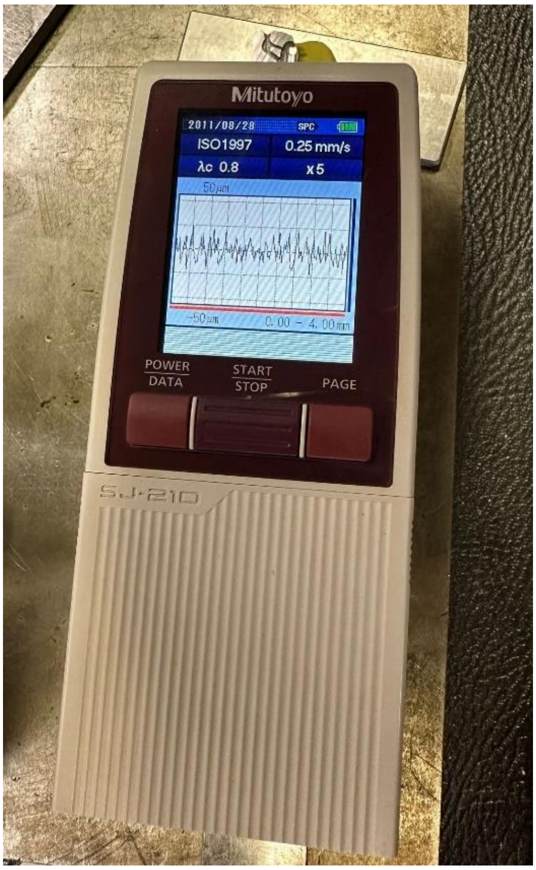


Figure 28 - Mitutoyo SJ-210 measuring instrument

4. Results and Discussion

In this chapter of the dissertation, an observation and explanation of the results from the previous section will be presented. Firstly, an in-depth look at the results of the LPBF process for the first iteration of the design will occur, followed by an examination of the same results for second iteration. Finally, an exploration of the material characterization tests, them being the chemical composition analysis, hardness test, and microstructure analysis, will be conducted. These steps will help lead to the conclusion on the viability of the objectives of the dissertation.

4.1. First Iteration

After the first iteration design was manufactured, one part was selected to have its internal channels measured.

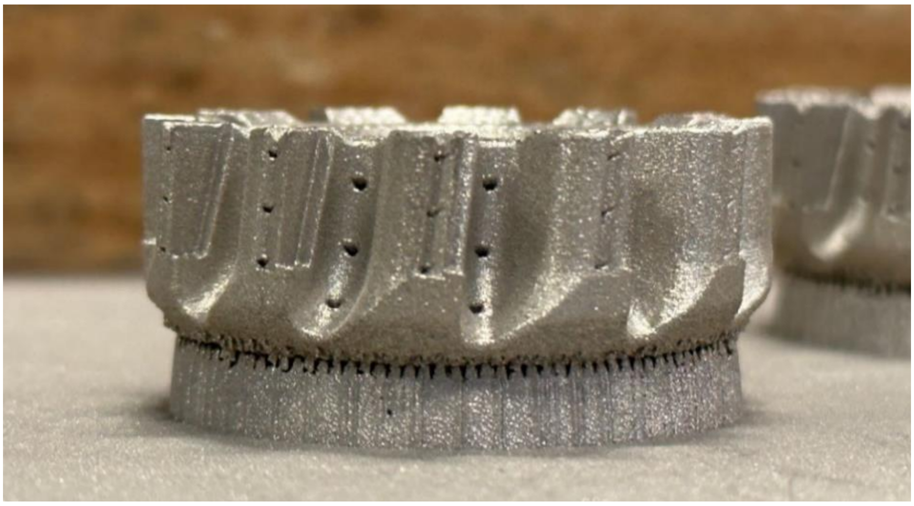


Figure 29 - Result of additively manufacturing the first iteration design

To achieve this, the part was firstly cut in several places of interest, and had its surfaces polished to allow for better imaging. It is important to remember that the cutting and polishing were both made by hand and therefore are subject to human error, which, due to the small nature of these channels, means that all deviations will be significant, as, for example, the cutting wheel is 2 mm in thickness. Ideally these cuts should be located in the central section of the channels, for those vertically cut, such as cut (a). Nevertheless, the cuts made can be compared with the following design sections merely in an illustrative manner, as shown in Figure 30, in order to show in which section of the design they were roughly made.

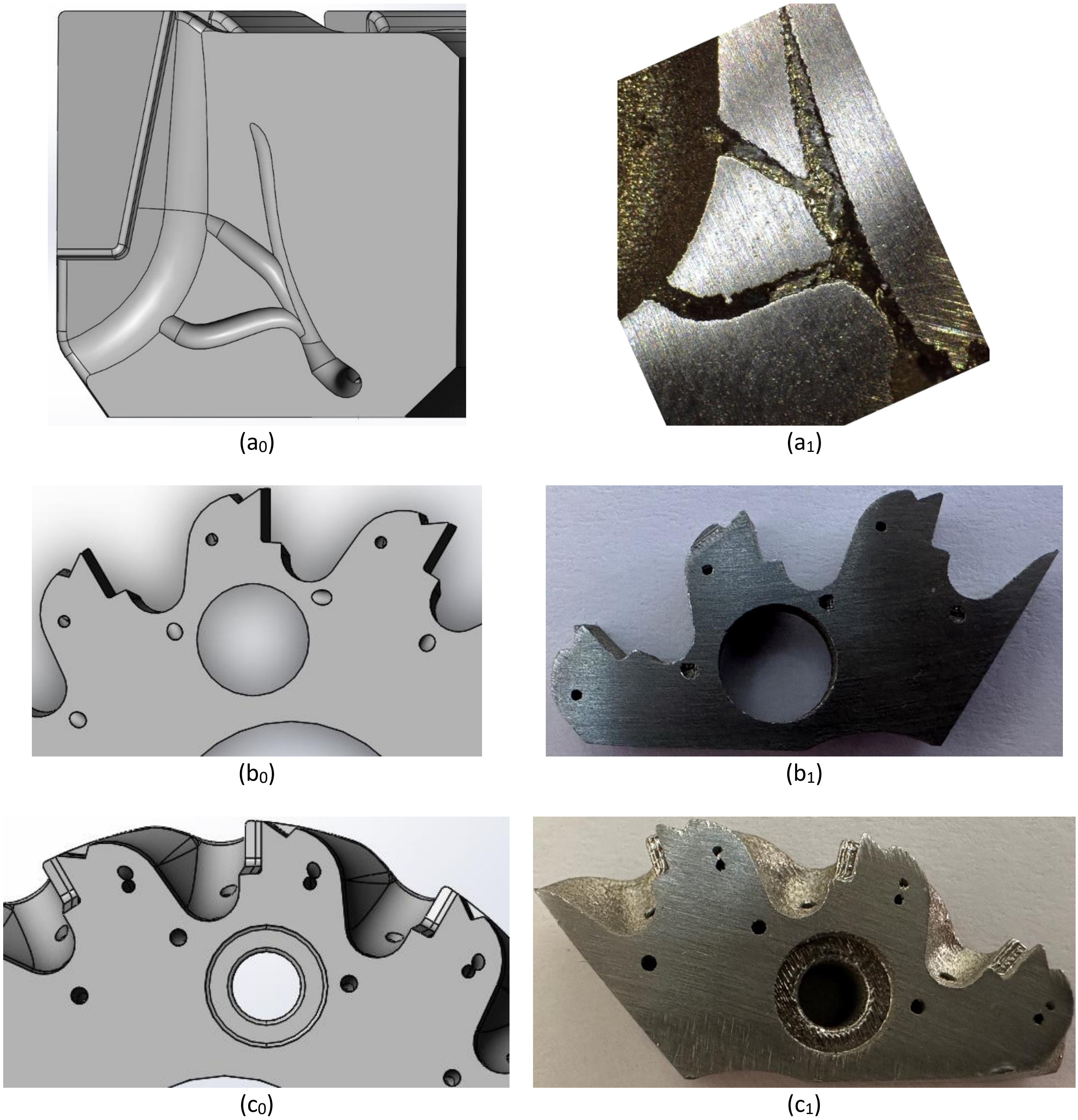
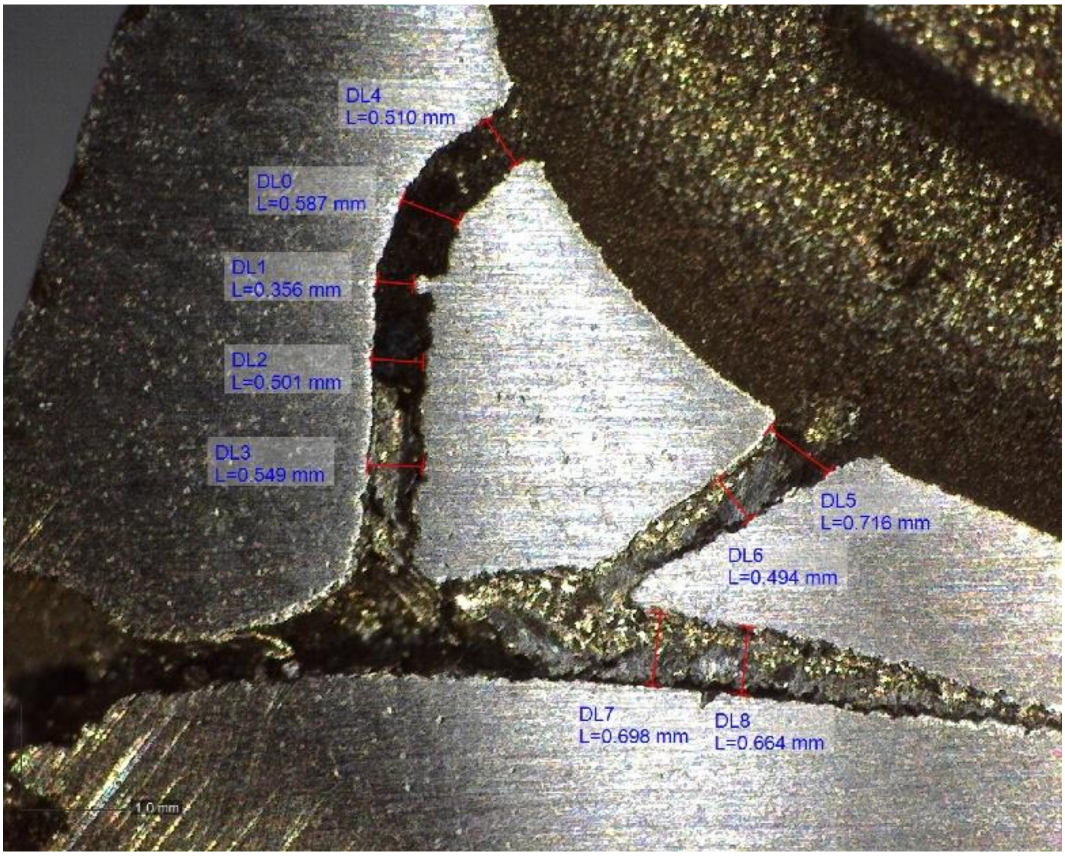
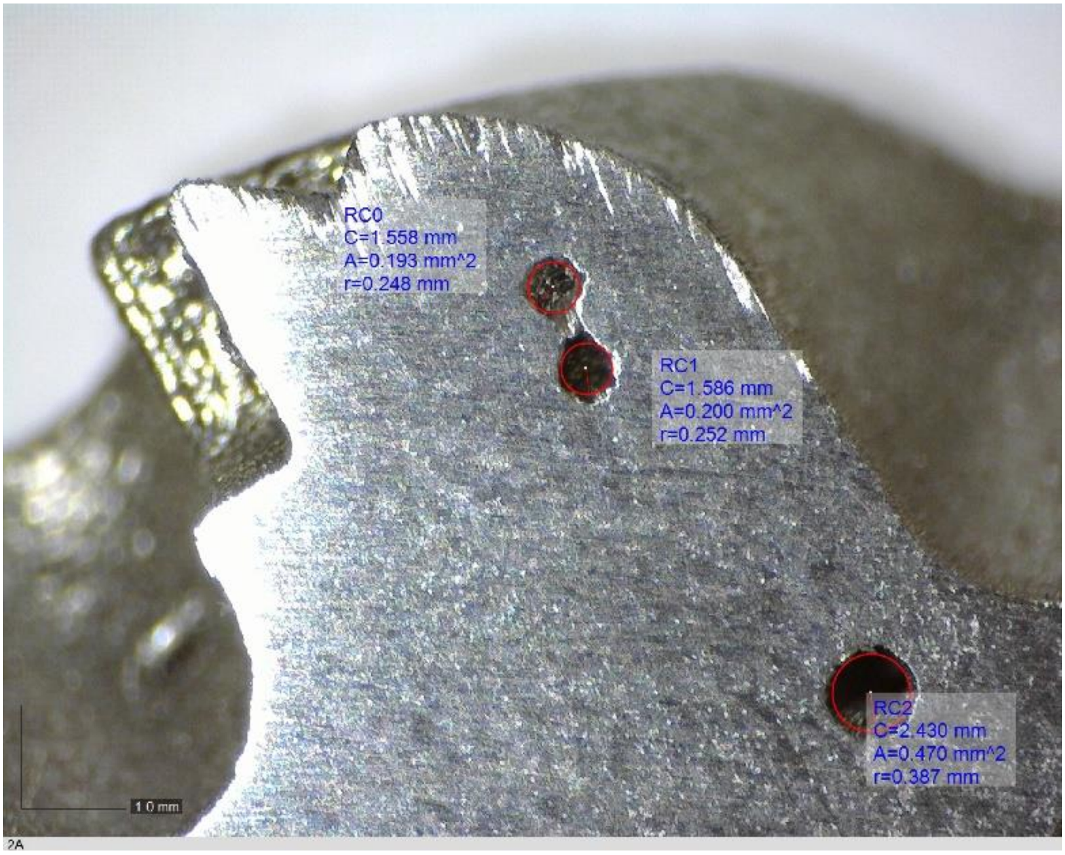


Figure 30 - Comparison between cut sections and the respective design

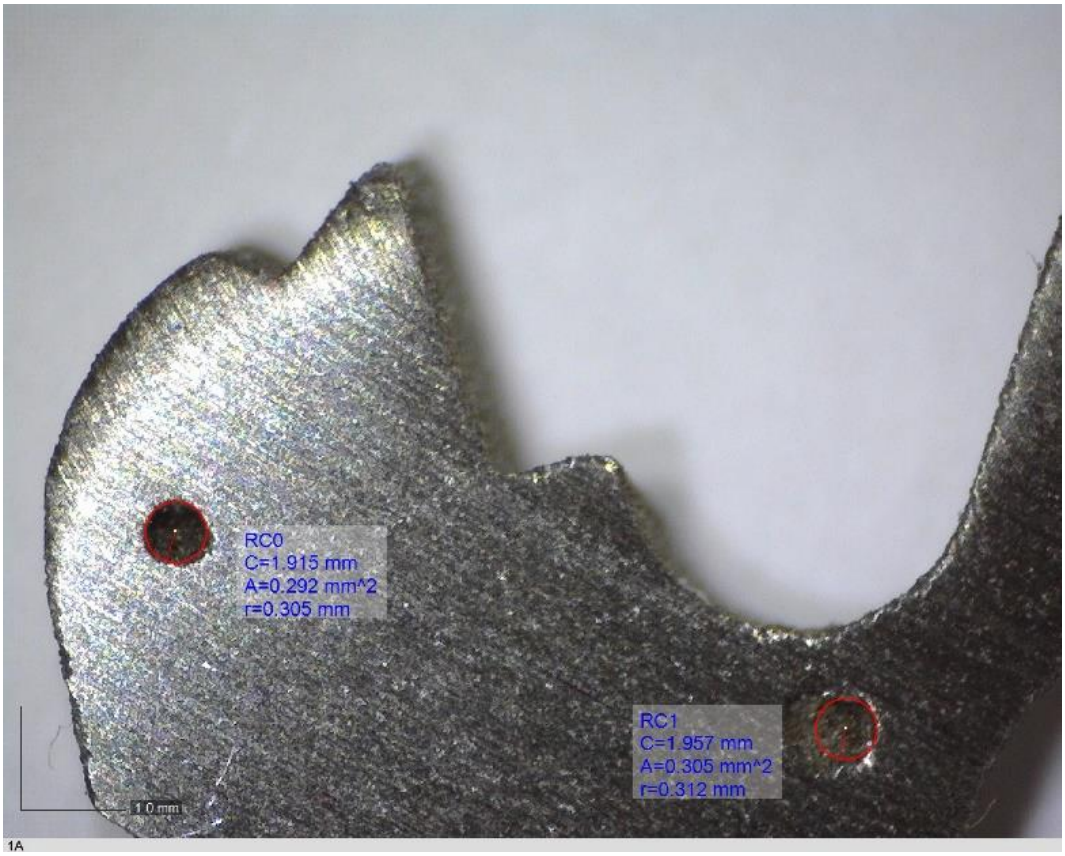
The dimensional measurements of the largest internal circumferences (or diameters) were then conducted with a digital microscope, and are displayed in Figure 31.


DL4
L=0.510 mm
DL0
L=0.587 mm
DL1
L=0.356 mm
DL2
L=0.501 mm
DL3
L=0.549 mm
DL5
L=0.716 mm
DL6
L=0.494 mm
DL7
L=0.698 mm
DL8
L=0.664 mm
1.0 mm

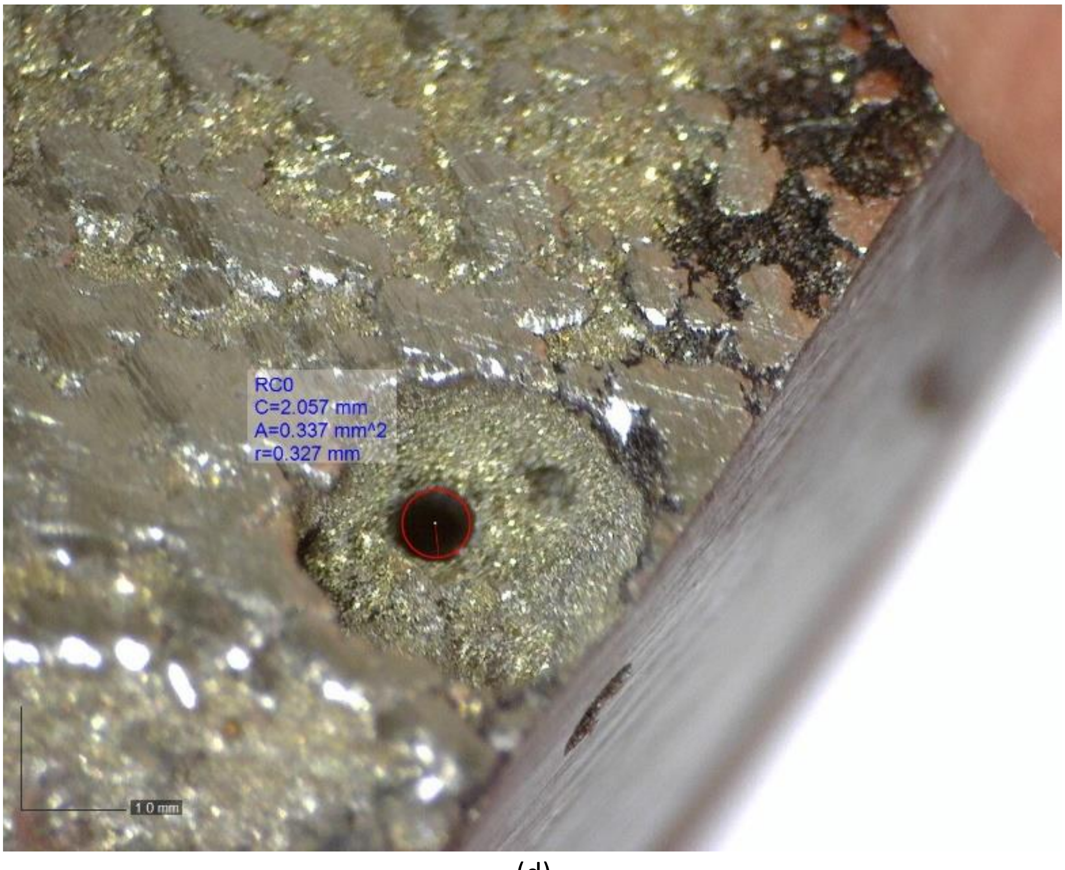
(a)


RC0
C=1.558 mm
A=0.193 mm^2
r=0.248 mm
RC1
C=1.586 mm
A=0.200 mm^2
r=0.252 mm
RC2
C=2.430 mm
A=0.470 mm^2
r=0.387 mm
1.0 mm
2A

(b)



(c)



(d)

Figure 31 – First iteration internal channel measurements

These images in Figure 31 reveal the imperfections of the channels' dimensions and high roughness of its insides. Through the conducted measurements, it is possible to compare the channels' dimensions (colour-coded with blueish grey for the (a) measurements, green for the (b) measurements, brown for the (c) measurements, and yellow for the (d) measurements) with their design counterparts (colour-coded with bright blue).

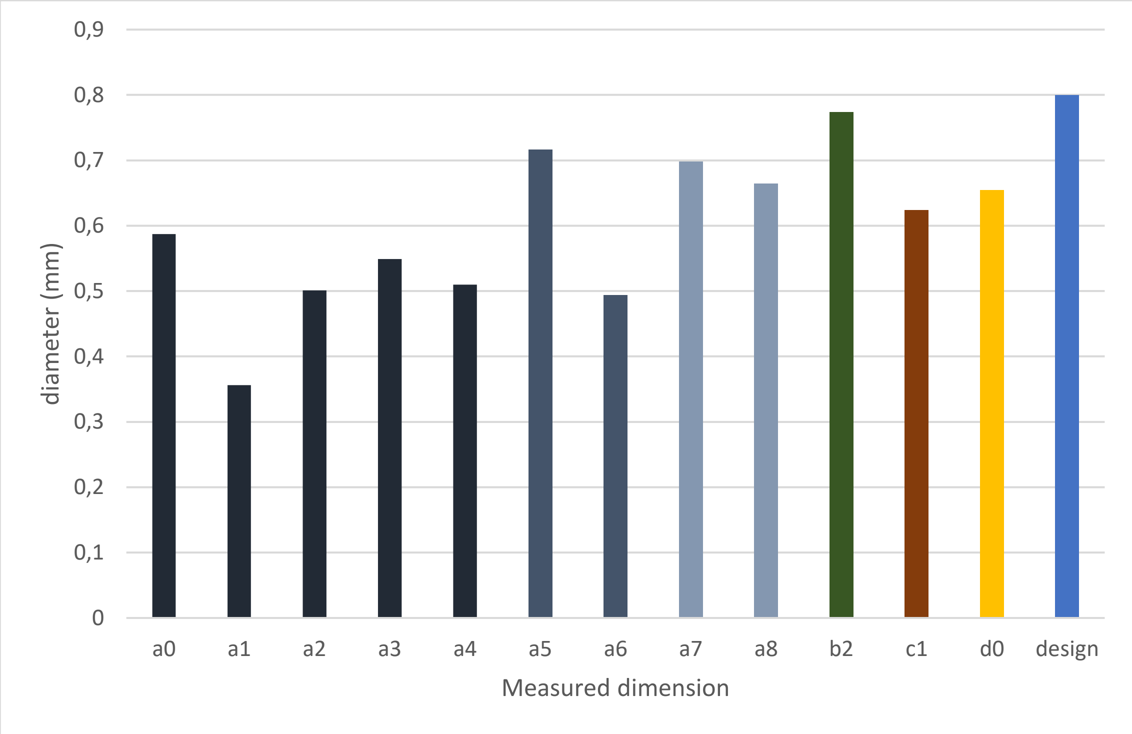


Figure 32 - Graph of the measurements of the 0,8mm channels

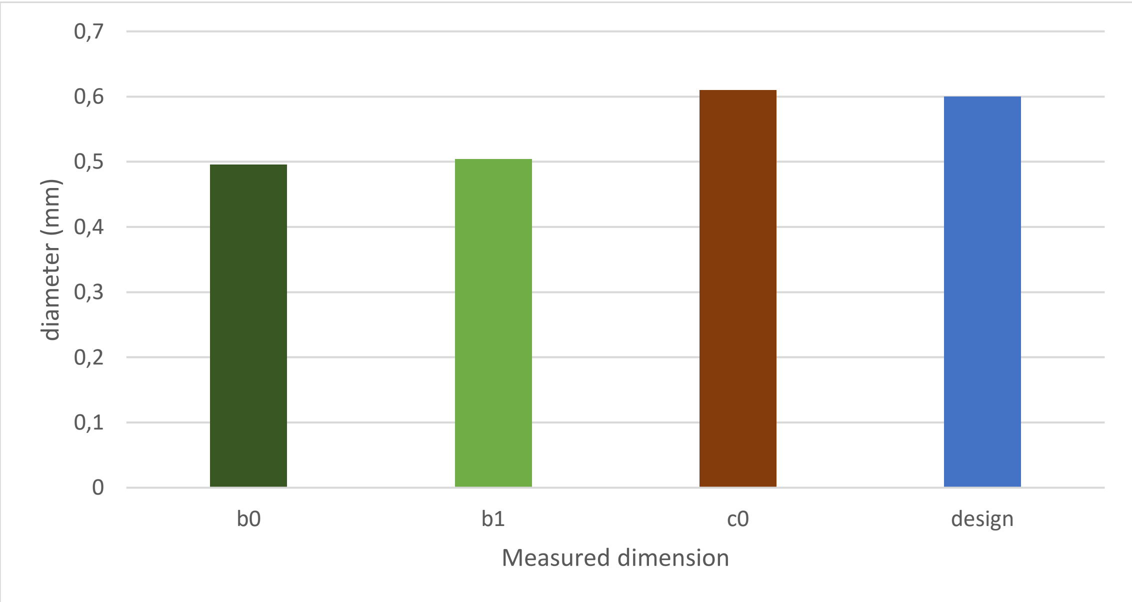
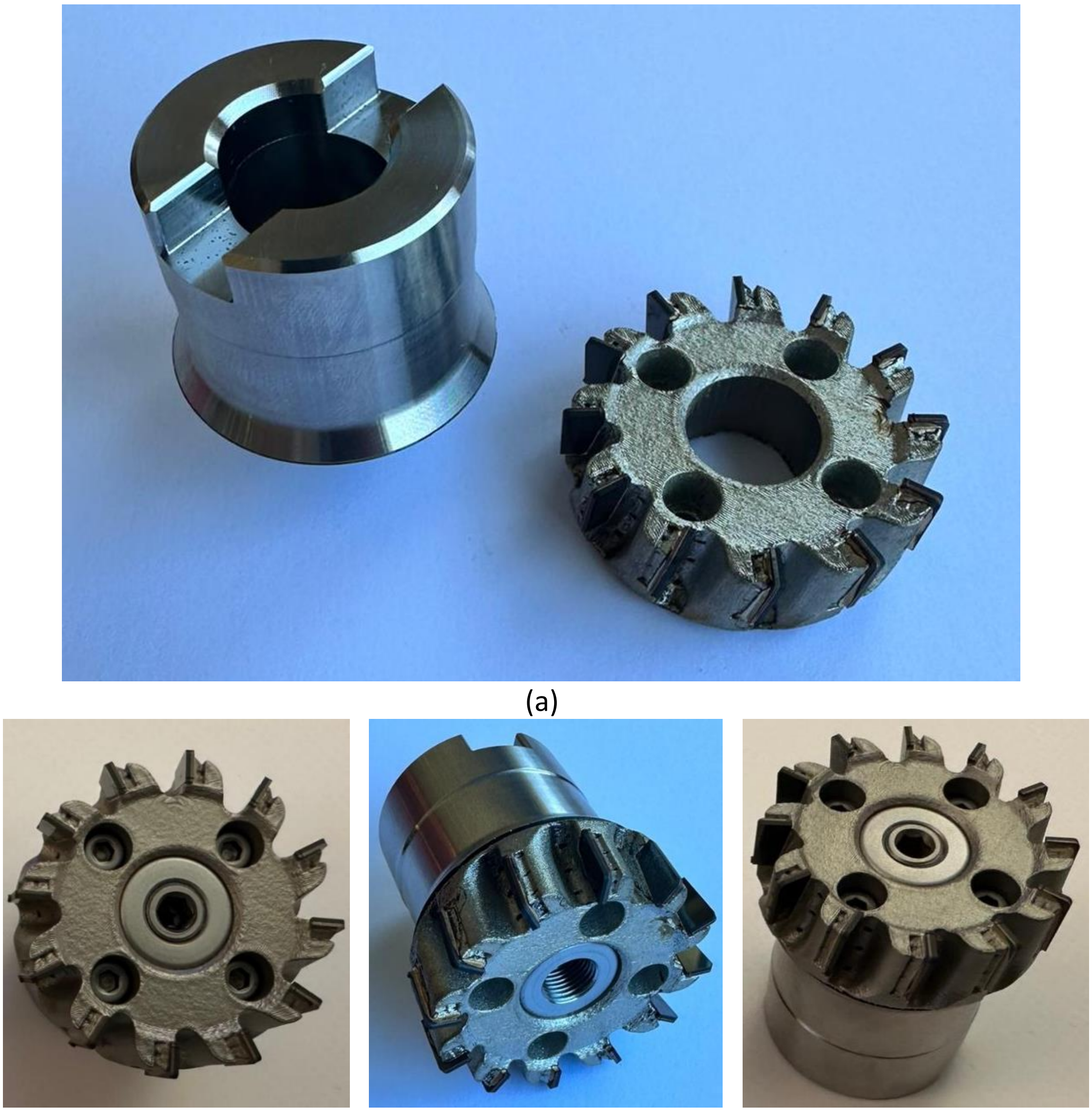


Figure 33 - Graph of the measurements of the 0,6mm channels

With this data it is possible to observe that the measurements are not consistent, especially the channels of cut (a), which is to be expected, as these might be subject to the highest amount of human error, and because the deviations are bigger for the more horizontally manufactured channel. For the dimensions of cuts (b), (c), and (d) there are deviations from the intended design dimensions, though these are smaller, which is again expected from these horizontally cut sections.

Finally, a collet was manufactured, via CNC machining, to meet the specifications set by the part design, and an assembly of the two was made possible, thus creating a milling cutter fit to be tested and subsequently used. In Figure 34, below, it is possible to observe the collet and the AM milling cutter, with the already soldered cutting inserts, separately in (a), and in various dispositions in (b), (c), and (d).



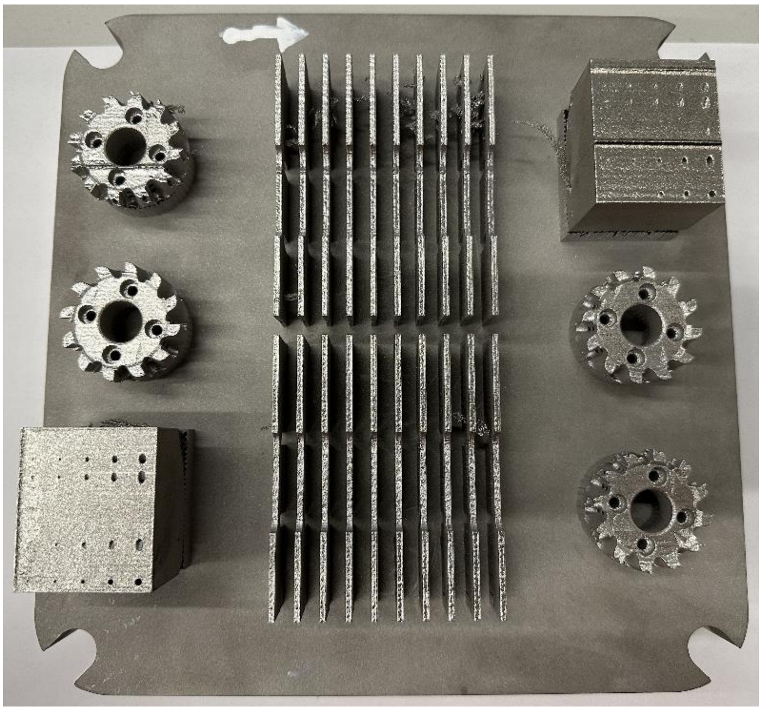
(a)

(b) (c) (d)

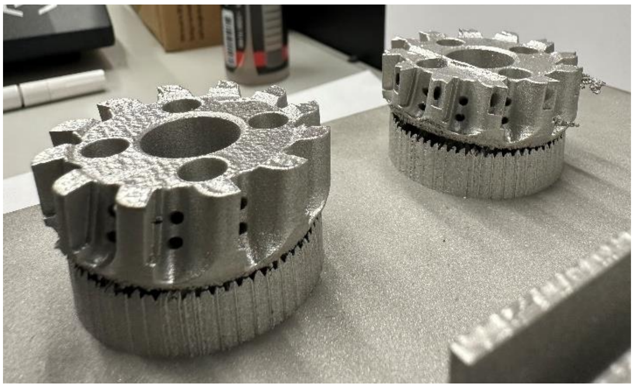
Figure 34 - Assembly of the specially manufactured collet and AM milling cutter

4.2. Second Iteration

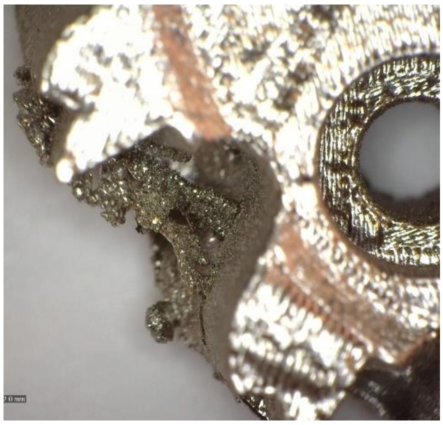
With the second iteration, the newly created parts were victims of errors, both from the machine, that suffered an accident that damaged the re-coater, and of poor planning, as, unlike with the first iteration, too many parts filled the building base, which caused thermal deformation as the laser took too long to pass through the same area again, leading to further doubt about the machine's well-function, and, with the supports being made too thin, this led to warping and defects in the parts.



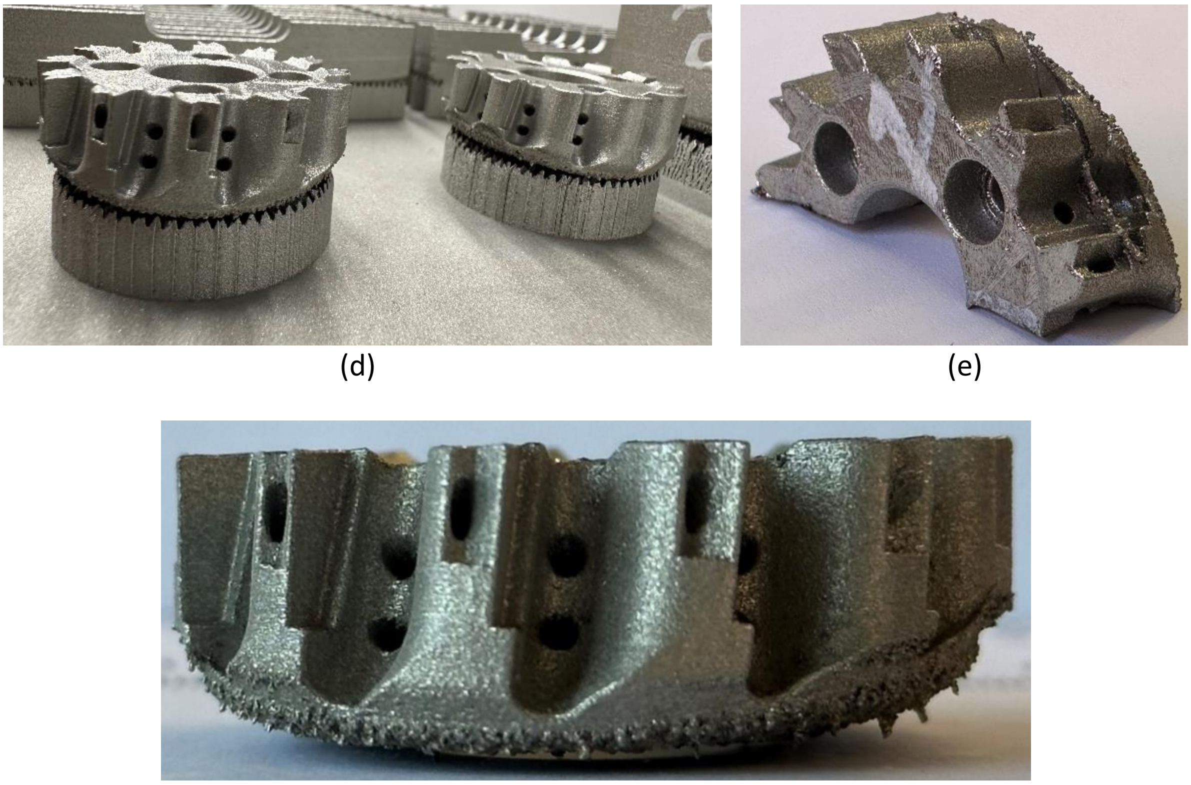
(a)



(b)



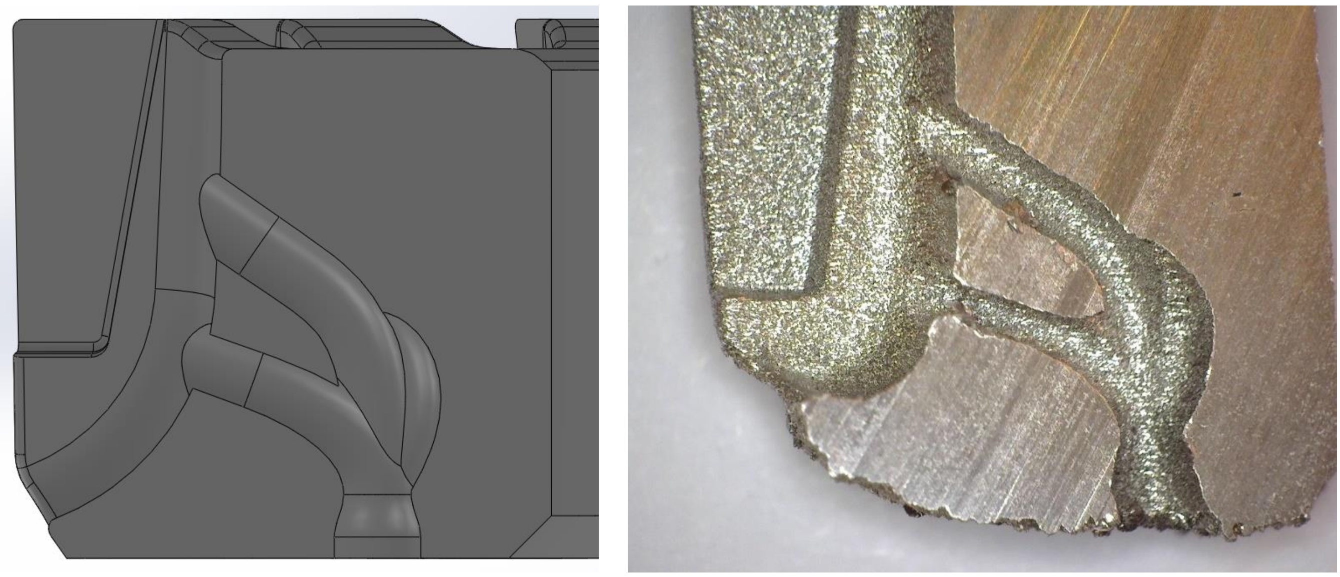
(c)



(d) (e) (f)

Figure 35 - Result of additively manufacturing the first design iteration (building base (a); details of defects (b), (c), (d), (e), and (f))

Nevertheless, the manufactured parts were salvageable enough to be cut and have its surfaces polished, and to be subsequently analysed and have its channels measured with the digital microscope. Again, it is possible to compare the cut made with the design section, in Figure 36. With this iteration, the same observations of human error in the cut apply, since, even with the channel dimensions being bigger, they remain smaller than the cutting wheel thickness.



(a_0) (a_1)

Figure 36 - Comparison between cut section and the respective design

With the cut conducted, the following measurements were then made:

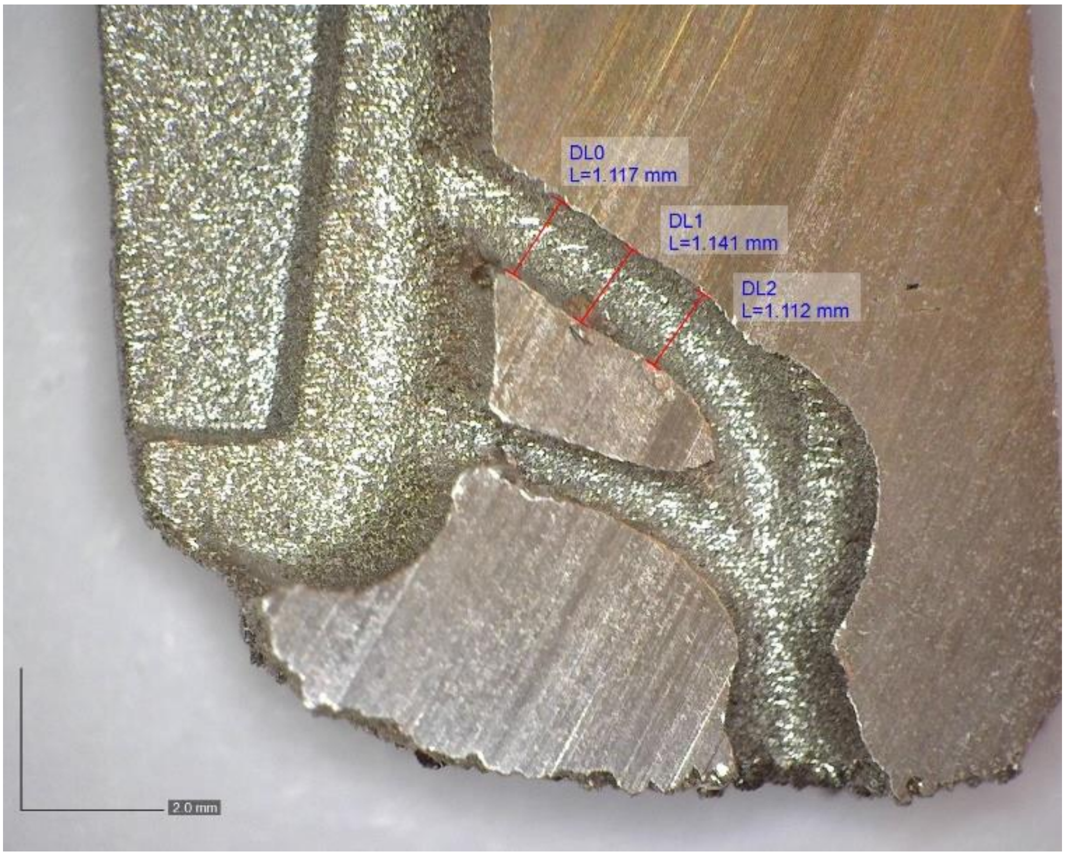


Figure 37 - Second iteration internal channel measurements

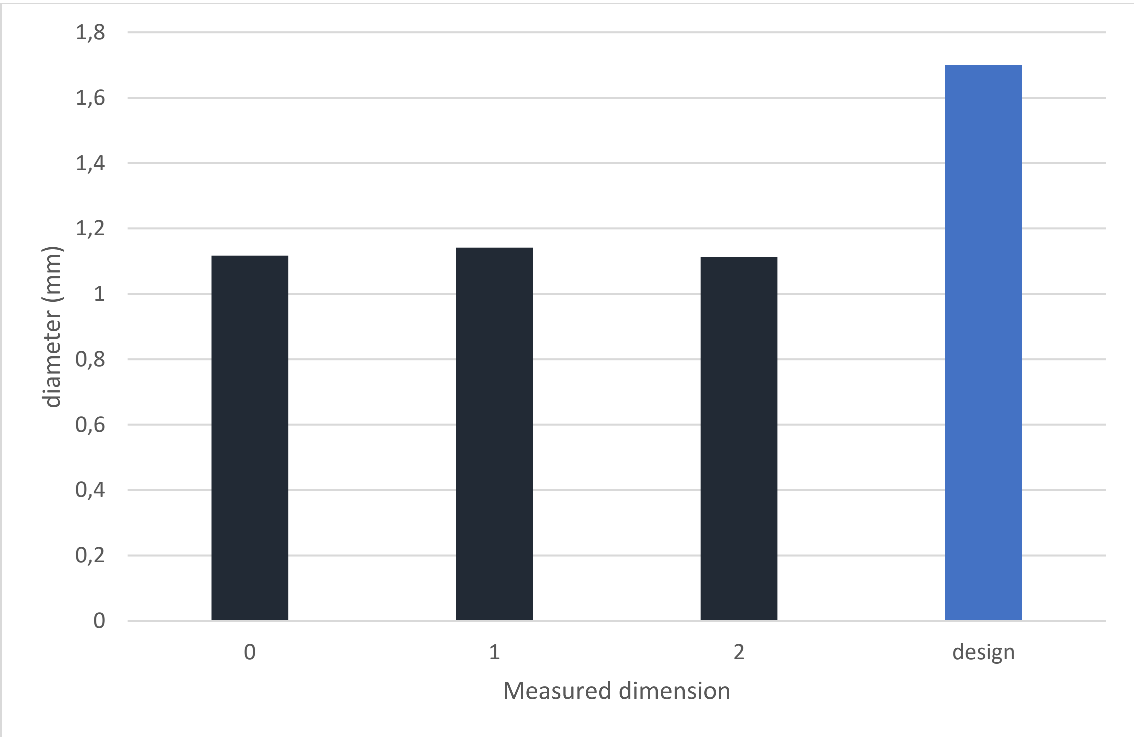


Figure 38 - Graph of the measurements of the 1,7mm channels

Comparing it with the design dimension, however, reveals the effect of the low accuracy of the cut, as the conducted measurements highly deviate from the design specification of 1,7, but they do show low variance between themselves, showing the accuracy of the manufacturing process.

Another aspect in which an improvement is shown in relation to the first iteration is regarding the roughness. The images alone already show that the internal roughness of the channels is comparable with the outside surface of the part, specifically with the cutting edge surface to which the insert will be soldered to, and is lower than in the first iteration. This means that measurements can be conducted on the side of the part and said to be comparable with the roughness of the channels. By conducting a roughness test on this surface, it is then possible to arrive at an average roughness (R_a) of 7,11 µm, and maximum vertical distance from the highest peak to the lowest valley (R_z) of 34,85 µm, which is compatible with roughnesses measured in other studies [58].

Figure 39 - Roughness measurement of the cutting edge

For this iteration it was not possible to produce the final assembly with the collet as with the first iteration, due to the aforementioned manufacturing defects.

5. Conclusions and Future Works

5.1. Conclusions

With this work it was set out to test and study the feasibility of additively manufacturing internal cooling channels for tools to be used in machining operations, and the objectives set for this dissertation can be said to have been met.

The production of a high-feed milling tool featuring internal refrigeration channels with small diameters, comprehended between 0,6 mm and 1,7 mm, revealed to be feasible through LPBF. It was also concluded that an increase in channel diameter led to better dimensional accuracy and constancy, and better internal surface quality, comparable with the outer surfaces of the part, thus resulting in more clearly defined channel boundaries and paths. Regarding the build direction, vertical channels are shown to have better surface quality, given that the staircase effect is avoided, or at the very least, reduced.

AM has allowed for the creation of an intricate and detailed part, featuring a significant number of small teeth, which would have been exceptionally challenging to produce using conventional manufacturing methods. By consolidating the production of the tool into a single step, AM minimizes the need for intricate machining, thereby optimizing both time and resource utilization.

5.2. Future Works

Even with this being the conclusion of this dissertation, the work can always be continued and expanded. Some examples of future works that can be carried out are:

- Further development of internal channels design for cutting tools;
- Using computer tomography to better study the dimensional accuracy of AM internal channels;
- Performing abrasive low machining finishing to improve channels' surface roughness;
- Performing topology optimization of the design;
- Testing the design with CFD numerical models;
- Testing the design in a real milling operation.

6. References

[1] I. Gibson, D. Rosen and B. Stucker, Additive Manufacturing Technologies - 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Springer, 2015.

[2] C. Turk, H. Zunko, C. Aumayr, H. Leitner and M. Kapp, “Advances in Maraging Steels for Additive Manufacturing,” *Berg Huettenmaenn Monatsh,* vol. 164, p. 112–116, 2019.

[3] L. Guoa, L. Zhang, J. Andersson and O. Ojo, “Additive manufacturing of 18% nickel maraging steels: Defect, structure and mechanical properties: A review,” *Journal of Materials Science & Technology,* no. 120, pp. 227-252, 2022.

[4] T. Wohlers, “Wohlers Report 2022,” Wohlers Associates, 2022.

[5] Formnext, *AM Field Guide Compact,* Frankfurt: Messe Frankfurt Group, 2022.

[6] B. Sartin, T. Pond, B. Griffith, W. Everhart, L. Elder, E. Wenski, C. Cook, D. Wieliczka, W. King, A. Rubenchik, S. Wu, B. Brown, C. Johnson and J. Crow, “Manufacturing, 316L Powder Reuse for Metal Additive,” in *Solid Freeform Fabrication 2017*, 2017.

[7] TWI Global, “What is Powder Bed Fusion? Process Definition and Advantages,” TWI Global, [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-powder-bed-fusion. [Accessed 2023].

[8] Loughborough University Additive Manufacturing Research Group, “About Additive Manufacturing,” Loughborough University, [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/. [Accessed 2023].

[9] TWI Global, “What is Direct Energy Deposition (DED)?,” TWI Global, [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/directed-energy-deposition. [Accessed 2023].

[10] K. Vartanian, L. Brewer, K. Manley and T.Cobbs, “Powder Bed Fusion vs. Directed Energy Deposition Benchmark Study: Mid-size Part with Simple Geometry,” Optomec Corporation, 2018.

[11] L. Jiao, Z. Y. Chua, S. K. Moon, J. Song, G. Bi and H. Y. Zheng, “Femtosecond Laser Produced Hydrophobic Hierarchical Structures on Additive Manufacturing Parts,” *Nanomaterials,* vol. 8, no. 601, 2018.

[12] N. T. Aboulkhair, N. M. Everitt, I. Ashcroft and C. Tuck, “Reducing porosity in AlSi10Mg parts processed by selective laser melting,” *Additive Manufacturing,* Vols. 1-4, pp. 77-86, 2014.

[13] C. Y. Yap, C. K. Chua, Z. L. Dong, Z. H. Liu, D. Q. Zhang and S. L. S. L. E. Loh, “Review of selective laser melting: Materials and applications,” *Applied Physics Reviews,* vol. 2, 2015.

[14] H. Jia, H. Sun, H. Wang, Y. Wu and H. Wang, "Scanning strategy in selective laser melting (SLM): a review," *The International Journal of Advanced Manufacturing Technology,* no. 113, p. 2413–2435, 2021.

[15] J. Coyne, J. E. Barnes, W. King, K. Slattery and C. Cummings, "I want to break free: The journey towards reducing or eliminating support structures," *Metal AM,* vol. 7, no. 3, pp. 155-163, 2021.

[16] Inside Metal Additive Manufacturing, "Considerations for supports design in metal SLM," 2015. [Online]. Available: https://www.insidemetaladditivemanufacturing.com/. [Accessed 2023].

[17] Inside Metal Additive Manufacturing, "The role of (super) powders in SLM," 2014. [Online]. Available: https://www.insidemetaladditivemanufacturing.com/. [Accessed 2023].

[18] J. Barnes, F. Francqui and R. Dehoff, "Understanding metal powder requirements for Additive Manufacturing: Views from the industry," *Metal AM,* vol. 5, no. 3, pp. 175-182, 2019.

[19] Woodhead Publishing Limited, "Steels for aircraft structures," *Introduction to Aerospace Materials,* pp. 232-250, 2012.

[20] W. Sha, Steels: From Materials Science to Structural Engineering, Springer, 2013.

[21] Renishaw, *Maraging steel M300 powder for additive manufacturing,* Renishaw, 2017.

[22] N. Takata, R. Nishida, A. Suzuki, M. Kobashi and M. Kato, "Crystallographic Features of Microstructure in Maraging Steel Fabricated by Selective Laser Melting," *Metals,* vol. 8, no. 440, 2018.

[23] D. Gatões, R. Alves, B. Alves and M. T. Vieira, "Selective Laser Melting and Mechanical Properties of Stainless Steels," *Materials (Basel),* 2022.

[24] AZO Materials, "Stainless Steel - Grade 316L - Properties, Fabrication and Applications (UNS S31603)," 2004. [Online]. Available: https://www.azom.com/. [Accessed 2023].

[25] T. Tingskog, "An introduction to metal powders for AM: Manufacturing processes and properties," *Metal AM,* vol. 4, no. 2, pp. 111-119, 2018.

[26] European Powder Metallurgy Association, "Introduction to Press and Sinter Technology: A guide for Designers and Engineers," 2018.

[27] Goodwin University, "What is Computer-Aided Design (CAD)?," 2022. [Online]. Available: https://www.goodwin.edu/. [Accessed 2023].

[28] C. BasuMallick, "What is CAD (Computer Aided Design)? Definition, Types, and Applications," 2022. [Online]. Available: https://www.spiceworks.com/. [Accessed 2023].

[29] Drexel University, “Advantages and Disadvantages of CAD,” 2021. [Online]. Available: https://drexel.edu/. [Accessed 2023].

[30] D. Marmik and S. Sunasara, “Advanced Manufacturing Technique: 3D Printing,” *International Journal of Advance Research in Engineering, Science & Technology,* vol. 2, no. 3, 2015.

[31] Dassault Systems, “Solidworks,” Dassault Systems, [Online]. Available: solidworks.com. [Accessed 2023].

[32] Materialise, “Materialise Magics,” Materialise, [Online]. Available: https://www.materialise.com/. [Accessed 2023].

[33] M. P. Groover, Fundamentals Of Modern Manufacturing: Materials, Processes And Systems, JOHN WILEY & SONS INC, 2021.

[34] J. R. Walker, Machining Fundamentals, The Goodheart-Willcox Company, 1973.

[35] Micro, Nano & Precision Manufacturing, [Online]. Available: http://www.minaprem.com/. [Accessed 2023].

[36] Ceratizit Group, “Additive manufacturing at CERATIZIT Team Cutting Tools,” [Online]. Available: https://cuttingtools.ceratizit.com/. [Accessed 2023].

[37] J. Duplák, M. Hatala, D. Dupláková and J. Steranka, “Evaluation of Time Efficiency of High Feed Milling,” *TEM Journal,* vol. 7, no. 1, pp. 13-18, 2018.

[38] T. Miller, “6 Ways to Optimize High-Feed Milling,” MoldMaking Technology, 2012. [Online]. Available: https://www.moldmakingtechnology.com/. [Accessed 2023].

[39] Canadian Metalworking, “High-feed Milling,” Canadian Metalworking, 2011. [Online]. Available: https://www.canadianmetalworking.com/. [Accessed 2023].

[40] M. Kuruc, M. Vozár, V. Šimna, T. Vopát, R. Hrušecký, J. Milde, I. Buranský, M. Necpal and J. Peterka, “Comparison Of High Feed Machining With Conventional Milling In Terms Of Dimension Accuracy And Productivity,” in *29th DAAAM International Symposium On Intelligent Manufacturing And Automation*, Vienna, Austria, 2018.

[41] M. Kuruc, M. Vozár, V. Šimna, T. Vopát, J. Moravčíková and J. Peterka, “Comparison Of High Feed Machining With Conventional Milling In Terms Of Surface Quality And Productivity,” in *29th DAAAM International Symposium On Intelligent Manufacturing And Automation*, Vienna, Austria, 2018.

[42] Wayken Rapid Manufacturing, “Face Milling: Definition, Process, Differences, And Practical Tips,” [Online]. Available: https://waykenrm.com/. [Accessed 2023].

[43] Manufacturing Guide, [Online]. Available: https://www.manufacturingguide.com/. [Accessed 2023].

[44] DZsalesllc, “End Milling vs. Face Milling: What’s the Difference?,” 12 May 2021. [Online]. Available: https://dzsalesllc.com/. [Accessed 2023].

[45] Palbit, “Palbit,” [Online]. Available: https://www.palbit.pt/. [Accessed 2023].

[46] Karnasch, “Internal Cooling,” [Online]. Available: https://karnasch.tools/. [Accessed 2023].

[47] R. Penga, H. Jiang, X. Tang, X. Huang, Y. Xu and Y. Hu, “Design and performance of an internal-cooling turning tool with microchannel structures,” *Journal of Manufacturing Processes,* vol. 45, pp. 690-701, 2019.

[48] Cutting Tool Engineering, “Cool the tool with efficient new cutting tool solutions,” 2021. [Online]. Available: https://www.ctemag.com/. [Accessed 2023].

[49] Palbit, “Improve your performance with high-feed milling,” [Online]. Available: https://www.palbit.pt/. [Accessed 2023].

[50] GE Additive, “Concept Laser M2 Series 5,” [Online]. Available: https://www.ge.com/additive. [Accessed 2023].

[51] GE Additive, “Concept Laser M2 Series 5: Enabling repeatability at scale,” [Online]. Available: https://www.ge.com/additive/sites/default/files/2021-02/DMLM_M2Series5_Bro_4_US_EN_v2_0.pdf. [Accessed 2023].

[52] GE Additive, “GE Additive 316L .material data,” [Online]. Available: ge.com/additive. [Accessed 2023].

[53] C. Zachert, H. Liu, T. Lakner, D. Schraknepper and T. Bergs, “CFD simulation to optimize the internal coolant channels of an additively manufactured milling tool,” in *18th CIRP Conference on Modeling of Machining Operations*, Ljubljana, Slovenia, 2021.

[54] Materflow, “Design Guidelines For Metal Printing,” [Online]. Available: https://www.materflow.com/. [Accessed 2023].

[55] A. J. Wildgoose, K. A. Thole, P. Sanders and L. Wang, “Impact of Additive Manufacturing on Internal Cooling Channels With Varying Diameters and Build Directions,” *Journal of Turbomachining,* vol. 143, no. 7, pp. 071003-11, 2021.

[56] Crucible, “Design guidelines for Direct Metal Laser Sintering (DMLS),” 2015.

[57] K. Kempen, F. Welkenhuyzen, J. Qian and J.-P. Kruth, “Dimensional accuracy of internal channels in SLM produced parts,” in *ASPE Spring Topical meeting*, San Francisco, USA, 2014.

[58] S. Han, F. Salvatore, J. Rech, J. Bajolet and J. Courbon, “Effect of abrasive flow machining (AFM) finish of selective laser melting (SLM) internal channels on fatigue performance,” *Journal of Manufacturing Processes ,* vol. 59, pp. 248-257, 2020.