

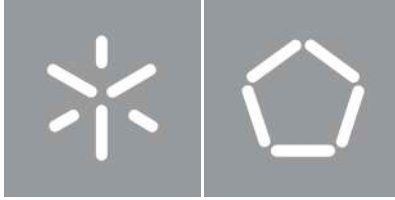


**University of Minho**  
School of Engineering

Gonalo Campos Martins

**Generative Design for Additive  
Manufacturing of  
Non-Conventional Moulding Tools**





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**Generative Design for Additive  
Manufacturing of  
Non-Conventional Moulding Tools**

Master's Dissertation in Polymer Engineering

Dissertation supervised by  
**Prof. Dr. Ant3nio Jos3 Vilela Pontes**  
**Dr. Ana Carina Ferreira Lopes**

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# Acknowledgements

This document marks the end of a chapter in my life, and since it is such an important milestone, I would like to express my gratitude to everyone who, in one way or another, helped make the completion of this stage possible.

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# **Statement of Integrity**

I hereby declare having conducted this academic work with integrity.

I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, Braga, october 2024

Gonçalo Campos Martins

# Abstract

This dissertation explores the application of generative design (GD) combined with additive manufacturing (AM) for the development of non-conventional mould tools used in injection moulding. Traditional mould-making methods face significant challenges in producing complex geometries and optimizing cooling systems, which are crucial for efficient and high-performance manufacturing. GD, an algorithmic approach that creates optimized structures based on predefined parameters, and AM, which enables the fabrication of intricate designs, provide innovative solutions to these challenges.

The research focuses on designing a mould tool that incorporates conformal cooling channels to enhance cooling efficiency and reduce cycle times. Through an iterative GD process, the mould tool was optimized for material usage, structural integrity, and production performance. AM was used to fabricate the designed mould, demonstrating its ability to produce complex geometries that traditional techniques cannot achieve.

The results showed significant improvements in mould performance, particularly in cooling efficiency and material optimization, confirming the potential of GD and AM for industrial mould-making applications. However, challenges remain regarding the scalability and cost-effectiveness of these methods for large-scale production. This work contributes to the growing body of knowledge on advanced mould-making technologies, providing a foundation for future research in sustainable and efficient manufacturing processes.

**Keywords** Generative design, additive manufacturing, injection moulding, mould tool fabrication, conformal cooling channels, sustainability.

# Resumo

Esta dissertação explora a aplicação do design generativo (DG) combinado com a fabricação aditiva (FA) para o desenvolvimento de ferramentas de moldes não convencionais utilizadas na moldação por injeção. Os métodos tradicionais de fabricação de moldes enfrentam desafios significativos na produção de geometrias complexas e na otimização dos sistemas de refrigeração, que são cruciais para uma fabricação eficiente e de alto desempenho. O DG, uma abordagem algorítmica que cria estruturas otimizadas com base em parâmetros predefinidos, e a FA, que possibilita a fabricação de designs intrincados, oferecem soluções inovadoras para esses desafios.

Esta dissertação foca no desenvolvimento de uma ferramenta de moldação que incorpora canais de refrigeração conformados para melhorar a eficiência do arrefecimento e reduzir os tempos de ciclo. Através de um processo iterativo de DG, a ferramenta de moldação foi otimizada para o uso de material, integridade estrutural e desempenho de produção. A FA foi utilizada para fabricar o molde projetado, demonstrando a sua capacidade de produzir geometrias complexas que não podem ser obtidas por meio de técnicas tradicionais.

Os resultados mostraram melhorias significativas no desempenho do molde, particularmente na eficiência de arrefecimento e otimização de material, confirmando o potencial do DG e da FA para aplicações industriais de fabricação de moldes. No entanto, desafios permanecem quanto à escalabilidade e custo-efetividade desses métodos para produção em larga escala. Este trabalho contribui para o crescente área de conhecimento sobre tecnologias avançadas de fabricação de moldes, proporcionando uma base para futuras pesquisas em processos de fabricação sustentável e eficiente.

**Palavras-chave** Design generativo, fabricação aditiva, moldação por injeção, fabricação de moldes, canais de refrigeração conformados, sustentabilidade.

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# Acronyms

**AM** Additive Manufacturing

**CAD** Computed Aided Design

**CCC** Conformal Cooling Channels

**CNC** Computer Numerical Control

**DED** Directed Energy Deposition

**DLP** Digital Light Processing

**DMLS** Direct Metal Laser Sintering

**EBM** Electron Beam Melting

**FDM** Fused Deposition Modeling

**FEA** Finite Element Analysis

**GD** Generative Design

**PBF** Powder Bed Fusion

**SLA** Stereolithography

**SLM** Selective Laser Melting

**SLS** Selective Laser Sintering

**TO** Topology Optimization

# Chapter 1

## Introduction

The Injection moulding (IM) industry is a cornerstone of modern manufacturing, playing a crucial role in producing a vast array of polymer products. As industries evolve, there is an increasing demand for more complex, lightweight, and high-performance parts. However, traditional mould design and manufacturing methods are facing limitations in meeting these demands. Complex geometries, intricate cooling channels, and the necessity for enhanced internal structures present significant challenges in the conventional design of moulding tools.

To address these challenges, GD, combined additive manufacturing (AM), offers an innovative solution. GD provides an algorithmic approach to create optimal mould geometries that are beyond the capabilities of traditional design methods. AM, on the other hand, allows the physical realization of these complex designs, offering flexibility and efficiency in mould tool fabrication. The integration of these technologies paves the way for non-conventional mould designs that can optimize performance, improve sustainability, and significantly reduce production time.

This thesis explores the application of GD for the development of non-conventional mould tools, focusing on the fabrication challenges and opportunities presented by AM. By leveraging GD, this work aims to produce moulds with optimized material usage, improved cooling systems through conformal cooling channels, and the ability to manufacture highly intricate structures that would otherwise be impossible using traditional methods.

The primary objective of this study is to design and fabricate a non-conventional mould using GD principles and AM techniques. This research also aims to expand the practical application of GD in mould making, contributing to the broader understanding of how these advanced technologies can be integrated into the IM industry. In doing so, this work seeks to improve the efficiency of mould production and align with modern goals for sustainability in manufacturing.

## **1.1 Motivation**

The motivation for this work stems from the ongoing need for innovation in mould design and manufacturing efficiency within the IM industry. As industries evolve and demand more complex, lightweight, and high-performance parts, traditional moulding tools and methods face limitations. AM, particularly when combined with GD, presents a unique opportunity to overcome these limitations, allowing for the creation of more intricate and optimized moulds.

The conventional methods of designing and producing moulds have been well-established for decades, but they often struggle with complex geometries, intricate cooling channels, and internal structures. By leveraging GD, there is an opportunity to revolutionize mould making, shifting from traditional design approaches to more advanced, optimized, and flexible solutions.

While AM has made significant strides in various sectors, its application in mould making remains under explored. AM allows for the production of highly complex structures, such as conformal cooling channels, which can dramatically improve the efficiency of the moulding process. Modern manufacturing industries face increasing pressure to adopt more sustainable and efficient production practices. Traditional mould making can be resource-intensive, often resulting in high material waste and longer production cycles. The ability to reduce material usage through GD, coupled with AM, can lead to more sustainable processes by minimizing waste and improving energy efficiency. This project is motivated by the desire to create eco-friendly solutions that align with modern sustainability goals.

The challenge of developing a non-conventional moulding tool is an exciting opportunity to deviate from established norms and bring fresh perspectives to the industry. Additionally, GD is a cutting-edge tool that has seen limited application in mould making. The motivation behind this work is to develop and expand the practical knowledge of using GD in industrial applications, particularly in moulding, where it can offer tremendous value by optimizing the placement of material and enhancing mould performance. This work will help bridge the gap between theoretical knowledge and practical application of GD in a field where its use is still nascent.

## **1.2 Objectives**

As it has been established previously, the main objective of this work is to design a non-conventional moulding tool, utilizing the GD tool. This main goal is divided into sub-objectives that should be achieved with development of the tool. Firstly the design must utilize the advantages of AM, where the goal is to

be able to fabricate the entire tool and its components in a single production. Also, as it should be a non-conventional mould, it must deviate from all the conventional concepts of a moulding tool. To achieve this goal, the crucial components of a mould must be defined, so that a concept can be developed around them. The final goal within the development of the moulding tool, is to fully exploit the GD tool. The goal is to obtain the model almost exclusively through GD, aiming to minimize post-generative operations.

Additionally, this work aims to broaden the understanding and expertise in IM principles. This involves a detailed exploration of mould design, cooling systems, and production efficiency in traditional moulds, which will be the basis for the innovative design approach proposed. Another important objective is to assess and integrate the benefits of AM into mould production. By leveraging AM, the intention is to overcome the limitations of traditional manufacturing techniques, such as obtaining complex geometries or internal structures like conformal cooling channels, which are difficult to achieve with conventional methods. This approach aims to improve mould performance and reduce cycle times.

By documenting and analyzing the GD process in the context of moulding tools, this work seeks to pave the way for future studies and applications in the field. The results will demonstrate the potential of GD to revolutionize mould manufacturing by reducing design times, improving design efficiency, and enabling more complex and optimized moulds.

Finally, the project aims to validate the practical feasibility of using GD in the creation of moulds through a case study. The success of the project will be measured not only by the innovative design of the mould but also by its practical manufacturability, performance in real-world scenarios, and its ability to meet or exceed the performance of conventional moulds.

## **Chapter 2**

### **State of the Art**

The work being developed is based on an innovative and ambitious procedure. For this reason, there are not many theoretical basis that can directly support the work. However, it is essential to establish strong theoretical foundations across the different fields of knowledge related to the main subject. Specifically, it is necessary to understand the IM industry, in order to identify the advantages and disadvantages arising from the use of a moulding tool like the one being developed. These points will be corroborated to a certain extent by the use of hybrid moulds, which combine conventional moulds with AM. Although there are not many case studies on the use of GD in this industry, it is essential to draw examples from its application in other fields. Additionally, in conducting this literature review, the goal is to establish several points of connection between the different topics addressed. To conduct this work deep knowledge in these different areas is needed.

#### **2.1 Injection Moulding**

IM is one of the most widely used polymer processing techniques globally, with a strong presence in the plastics industry, and is distinguished by the ability to produce highly detailed parts. The injection process involves several stages but can be summarized as a process where molten polymer flows into a mould cavity, solidifying and taking the shape imposed by the mould.

IM is approached as a cyclic process, with reducing its cycle time being one of the primary goals when optimizing the process. The injection cycle consists of three main phases: filling, packing, and cooling. The filling phase is characterized by the injection of molten polymer into the cooled mould cavity under high pressure exerted by the injection unit. During the packing phase, a high pressure is maintained to ensure that the polymer remains in the cavity, guaranteeing both full part filling and the prevention of warping. Finally, during cooling, the molten polymer solidifies, acquiring the shape of the mould (Fernandes et al., 2018).

The injection machine is divided into two distinct units: the injection unit and the mould unit. The injection unit is responsible for melting the polymer and creating both the injection pressure and packing pressure. Although both units of the machine are critical to the process, this work will focus strictly on the mould unit. This unit serves several functions, including securely supporting the mould, opening and closing the mould with a speed gradient to avoid damage, and applying sufficient clamping force to keep the molten polymer within the mould cavity by countering the injection pressure (Fu et al., 2020).

### 2.1.1 Injection mould

The mould is the primary tool in IM, and its development dictates how the injection process will unfold. Its function is both to shape the molten polymer and to solidify it. The concept of the mould is ancient and has been used for various purposes. When adapted to the polymer processing industry, it became dominant, being employed in different processing techniques. The injection mould is typically made of steel plates to ensure its durability. However, if mould durability is not a critical factor, alternative materials such as aluminum, less resistant metal alloys, or even certain polymers can be used. Commonly, the mould is divided into two parts: the fixed or injection side, and the moving or ejection side. The division between these two parts is referred to as the parting line, where the mould separates when it opens. Most of the parts produced through IM resemble the shape of a cup, in the sense that they have an interior and an exterior. Therefore, the concave part of the mould, corresponding to the exterior of the part, is called the cavity. Its counterpart is the convex area of the mould, known as the core. Typically, the cavity is found in the fixed part of the mould and the core in the moving part, but different moulds require different approaches, so mould development always varies from case to case (Rees, 2001). Figure 1 shows the typical components of a two-platen mould.

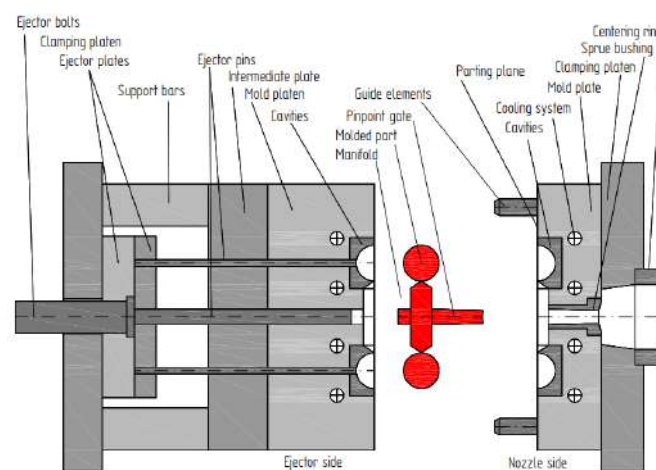


**Figure 1:** Principle of a two-platen mould (Pruner & Wolfgang, 2013)

Several variables must be considered when developing a moulding tool, such as the machine to be used, the geometry of the part, the number of cavities, etc. Developing a mould requires a deep understanding of the different mould variants and all the components that may be necessary to carry out a specific injection process. Rosato (2001, p. 236) identified six types of moulds: Two-plate mould, three-plate mould, hot runner mould, insulated hot runner mould, hot manifold mould, and stacked mould.

The two-plate mould is the basic type, where the runner system solidifies along with the part. This differs from the three-plate mould mainly in that the runner system is separated from the part, as they are on different mould plates, and the separation occurs when the mould opens. The hot runner mould is similar to the three-plate mould, with the distinction that in an isolated plate, there is a hot runner that keeps the polymer in a molten state. This plate is heated and insulated from the other plates, which are cooled to solidify the polymer. The use of this type of mould prevents the runner from solidifying at the end of the cycle, offering several advantages, such as reduced material waste, lower injection pressure, and, consequently, reduced clamping force. Insulated hot runner moulds and hot manifold moulds are variants of the hot runner mould. In the first case, the insulation between the plates allows the material to remain molten by retaining its own heat, while in the second, the runner is heated, not the plate. Finally, the stacked mould is essentially multiple two-plate moulds stacked on top of each other. Its main advantage is that it multiplies output without requiring additional clamping force.

The type of mould used will influence the components included, but there are other components that are common to all mould types and are essential for their operation. In 2003, Cunha et al. established the functional systems of the mould as the moulding zones, centering, feeding, venting, temperature control and extraction. This means that by guaranteeing these systems the moulding tool will be functional. This is a very important guiding line for the work, as the moulding tool to be developed must take away from conventional moulds only the crucial components to make it viable.

### **2.1.2 IM parameters**

When operating an IM machine, several parameters need to be adjusted according to the specific case at hand. This adjustment is influenced by the geometry being injected, the number of cavities in the mould, and the material to be injected. The main parameters that affect the IM process are injection speed and melt temperature. However, other parameters, with less impact on the process, include clamping force, cushion (or dosage), cycle time, mould stroke, and screw rotation during plasticization (Guerrica-Echevarría et al., 2001; Osswald & Menges, 2012). The determination of these parameters must be done with the utmost precision.

Process optimization is an extremely important phase. The goal of this optimization is to ensure the shortest possible cycle time, with the least material and energy consumption, without compromising the quality of the final part. Therefore, the respective parameters should be pushed to their limits. Computational simulation plays a crucial role in this process. Through specific software, all necessary information can be obtained to carry out the IM process with confidence in the determined parameters.

The use of incorrect parameters can lead to severe defects in the final part. Polymers are materials with very specific rheological properties that vary for each material. This makes the IM process highly sensitive, as it involves high material viscosities, pressures, and temperatures. The most common defects in IM are short shots, weld lines, warpage, flow marks, flashing, burn marks, and silver streaks (Mourya et al., 2023).

Some of these defects can be completely eliminated by adjusting the parameters to more appropriate values. However, certain defects may be linked to the geometry of the part itself, making them difficult or even impossible to avoid. For example, weld lines result from the separation of the material flow once it enters the cavity. This separation is often inherent to the geometry being injected, and there may be no way to eliminate it entirely. Table 1 represents the various mentioned defects, along with the parameter adjustments that can be made to eliminate or reduce them.

**Table 1:** Relevant Moulding Defects and Their Causing Parameters

| Moulding Defects | Causing Parameters          |                   |                  |              |              |                    |                 |
|------------------|-----------------------------|-------------------|------------------|--------------|--------------|--------------------|-----------------|
|                  | Melt (Material) Temperature | Mould Temperature | Holding Pressure | Cooling Time | Holding Time | Injection Pressure | Injection Speed |
| Short-shot       | Increase                    |                   | Increase         |              |              | Reduce             | Reduce          |
| Sink-marks       |                             |                   | Reduce           | Moderate     | Reduce       |                    |                 |
| Weld-lines       | Increase                    |                   |                  |              |              | Increase           | Increase        |
| Warpage          | Increase                    | Increase          |                  | Reduce       |              |                    |                 |
| Flow-marks       | Increase                    |                   |                  |              |              | Increase           | Increase        |
| Flashing         |                             | Increase          |                  | Reduce       |              | Increase           | Increase        |
| Burn-marks       | Reduce                      | Reduce            |                  | Increase     |              | Increase           |                 |
| Voids            |                             | Reduce            | Increase         | Reduce       | Increase     |                    |                 |
| Jetting          | Increase                    |                   |                  |              |              | Increase           | Increase        |
| Silver Streaks   | Increase                    | Increase          |                  |              |              |                    | Increase        |

### 2.1.3 IM future scope

Since its inception, IM has been dominant in the plastics processing sector. In 2006, Osswald and Hernández-Ortiz noted that it accounted for over one-third of polymer product production, and more than half of the polymer processing equipment in use was for IM. The main sectors utilizing this technology are automotive, electronics, medical, and packaging industries (Fernandes et al., 2018). Currently, there is limited data regarding the continued dominance of this technique over other processing methods. However, it is safe to assert that it remains the primary method for polymer processing. In 2023, Research estimated the IM market value at approximately USD 345.78 billion, with projections for growth to USD 423.75 billion

by 2030.

The primary objective in the IM industry is to maximize production, which means reducing cycle time. Most of the cycle time is spent cooling the polymer, which must cool sufficiently to solidify and be ejected. Therefore, significant advancements in this field revolve around reducing cooling time through more efficient cooling methods. One approach to achieving this is the use of conformal cooling channels (Farooque et al., 2021). Other innovations in the industry include integrating technologies to enhance the capabilities of injection moulds, such as AM for hybrid mould production or the use of sensors within moulds to collect real-time injection process data. The goal of these advancements is always to make the process faster, more efficient, and more autonomous.

## **2.2 Additive manufacturing**

AM is a processing technique in which a part is created by adding material layer by layer. Each layer represents a planar section of the part, designed using a Computer-aided design (CAD) program. This results in the final product being a representation of the desired part through the accumulation of these sections. The thinner the layers, the higher the fidelity of the part (Gibson et al., 2015). This standardized term was initially referred to as rapid prototyping. Rapid prototyping emerged in the 1980s, with the purpose of creating models and prototypes. It was particularly valuable due to its ability to reduce time and labor, while also enabling the production of geometries that would be very difficult to machine (Wong & Hernandez, 2012).

### **2.2.1 AM basic principles**

Conventional manufacturing processes, like Computer Numerical Control (CNC) machining, require a detailed evaluation of the desired geometry to determine the sequence of operations necessary to reproduce that geometry. In contrast, AM allows the production of parts with complex details using only basic information about dimensions and a general understanding of how the process works (Gibson et al., 2015). This process involves several stages, starting with the CAD design and ending with the final part. Zeltmann et al. (2016) identified three distinct phases of the AM process: design, manufacturing, and testing. Figure 2 illustrates these phases and how the progress advances toward the final product.

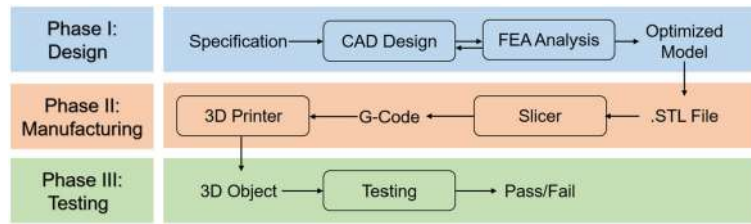


**Figure 2:** AM procedure (Zeltmann et al., 2016)

The main objective of the design phase is to develop an optimized model for AM. To achieve this, CAD programs are used to create the models, and Finite Element Analysis (FEA) is employed to optimize them. By analyzing simulation results, valuable insights about the design can be obtained, allowing modifications to bring it closer to the required specifications. Through an iterative process, an appropriate geometry for AM can be defined.

The output from the design phase is a file that is then input into a slicer program. The slicer refers to a software that allows the model to be divided into the individual layers that will be produced. The result of this process is a toolpath code, commonly referred to as G-code. This code contains the information the machine needs to carry out the desired production, specifically the movement of the print head along the x, y, and z axes. Depending on the specific AM technique being used, the G-code may contain additional information. Once the G-code is loaded into the printer, a 3D object can be produced.

The final phase is testing, where physical and mechanical tests are conducted on the manufactured part. The goal of these tests is both quality control and model validation. This phase is similar to the quality control measures carried out in other types of manufacturing. However, since AM imparts very specific properties to its products, these must be considered when conducting the tests.

## 2.2.2 AM techniques

Although there is a general process, the layer production occurs differently for each AM technique. These methods range from simple extrusion to the use of material jets. Table 2 lists the seven different categories typically considered for AM, along with a brief explanation of each category. This division presented in the table is based on the standard *ISO/ASTM 52900: Additive manufacturing – General principles – Terminology*, 2015.

**Table 2: AM Process Categories**

| Process Category                 | Brief Explanation                                                                                                                                                                                                                                                                              |
|----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Material Extrusion               | In this process, material is selectively dispensed through a nozzle or orifice. The material is usually deposited in layers to create the object. Commonly used materials include thermoplastics and pastes. Fused Deposition Modeling (FDM) is a popular example.                             |
| Vat Photopolymerization          | This process uses a vat of liquid photopolymer resin, which is selectively cured by light-activated polymerization. A light source, such as a laser or digital light projector, solidifies the material layer by layer. Stereolithography (SLA) is an example of this process.                 |
| Powder Bed Fusion (PBF)          | In PBF, a bed of powder material is selectively fused by an energy source such as a laser or electron beam. The process typically involves building the part layer by layer. Examples include Selective Laser Sintering (SLS) and Electron Beam Melting (EBM).                                 |
| Binder Jetting                   | This process involves selectively depositing a liquid binding agent onto a powder bed, bonding the powder particles together to form a solid part. After each layer, new powder is spread over the surface, and the process is repeated.                                                       |
| Material Jetting                 | In material jetting, droplets of build material are selectively deposited from one or more print heads onto the build platform. The material solidifies after deposition, often aided by UV light or other curing methods. This process can create highly detailed and multi-material objects. |
| Directed Energy Deposition (DED) | DED processes use focused thermal energy, such as a laser, electron beam, or plasma arc, to melt and fuse material as it is deposited. The material, usually in the form of powder or wire, is fed through a nozzle and applied layer by layer to build or repair parts.                       |
| Sheet Lamination                 | This category involves bonding sheets of material to create an object. The sheets can be metal, paper, or polymer, and are bonded using adhesives, heat, or ultrasonic welding. Layers are typically cut to shape before or after bonding.                                                     |
| Photopolymerization              | This is a broad category that includes any process where liquid photopolymers are selectively hardened by light, such as SLA, digital light processing (DLP), and others. This process is particularly suitable for creating highly detailed parts with smooth finishes.                       |

For this work, the focus resides in the PBF technologies. Some of the techniques included in this category are SLS, Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM). These techniques use lasers as their heat source, and therefore, their processes are quite similar, differing only in finer details. SLS can be considered the foundation for these three techniques, from which the others are derived. The SLS process involves depositing a thin layer of heated polymer powder onto a platform. A CO<sub>2</sub> laser selectively sinters the powder, solidifying each layer of the part. After each layer, the platform moves downward, and a new layer of powder is deposited. The process repeats until the part is complete. Unsintered powder remains in place, eliminating the need for supports.

The main difference between the processes is that DMLS and SLM are used for producing metal products. However, other distinctions between these techniques give them different applications. In the DMLS process, the powder is not melted but heated until the particles fuse at a molecular level. In contrast, in SLM, the laser completely melts the metallic powder, forming a homogeneous part with a single melting point, a feature not typically found in metal alloys. The key difference between DMLS and SLM is that DMLS produces parts from metal alloys, while SLM uses single-element metals.

Unlike SLS, DMLS and SLM processes require structural supports to limit distortion. Although the surrounding powder provides physical support, parts produced by DMLS/SLM are susceptible to warping due to residual stresses generated by the high processing temperatures. To reduce these stresses, the

parts are usually heat-treated after printing while still attached to the build plate (Redwood et al., 2017). Being that the objective of this work is the manufacturing of a moulding tool, the relevant techniques are those capable of working with metal.

The precision of these techniques depends on the laser spot size, powder particle size, and layer height. Machines that perform these operations require meticulous calibration to ensure the success of the technique. Although these processes offer high dimensional accuracy, post-processing is recommended for certain applications. This ensures critical dimensions, particularly important in the production of moulds or mould inserts, where high dimensional precision is essential for tool functionality.

### **2.2.3 AM developments**

The manufacturing process underwent a significant revolution with the introduction of AM. This technology represents an alternative to traditional manufacturing methods, being the only one capable of achieving a high level of complexity in the fabricated geometry. By increasing the level of complexity, AM also provides a high degree of freedom in the design phase. This has led to the introduction of new and distinct parts in the market, which can offer both aesthetic and functional advantages. However, the benefits of this technology extend further. Its nature allows for the reduction of material waste resulting from the manufacturing process, representing a significant environmental advantage, as certain conventional manufacturing methods generate substantial waste. This makes AM a more sustainable and efficient process (Bikas et al., 2015).

Despite these advantages, AM still involves high costs and has limitations inherent to each specific technique. However, these disadvantages tend to diminish over time as knowledge about these techniques increases.

AM is a technology in continuous development, and the shift from rapid prototyping to full-scale production using AM has impacted various sectors, notably aerospace, automotive, and medical. Kanishka and Acherjee (2023) observed that although the technology first appeared in the 1980s, research in this field only began to increase significantly in the early 2010s. Since this increase in research activity, the number of scientific articles on the topic has risen dramatically, as illustrated in Figure 3. This graph was developed by the authors, comparing the number of publications over the years since the emergence of AM.

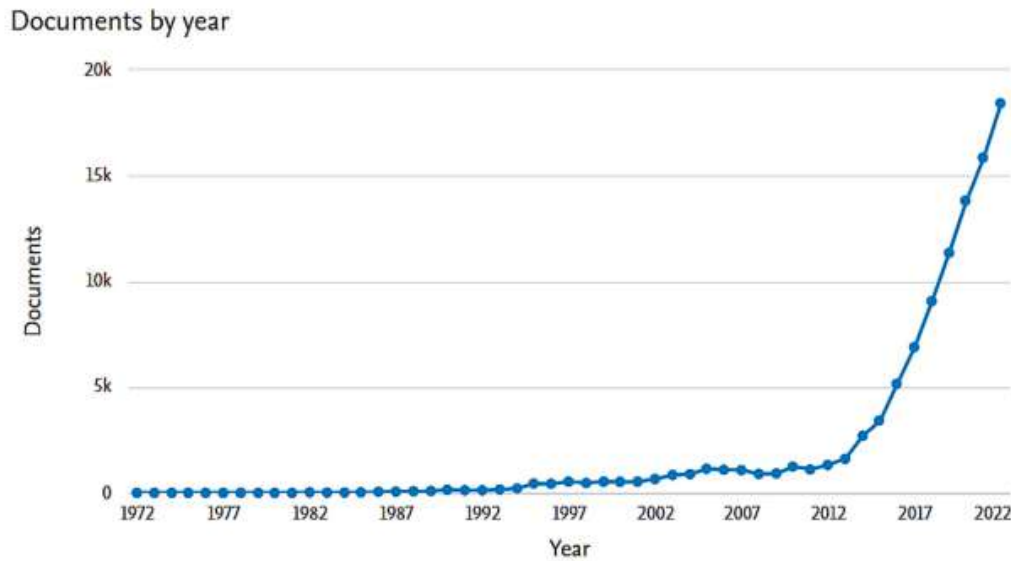


**Figure 3:** Papers on AM over the years (Kanishka and Acherjee, 2023)

This growth in research focused on AM has led to several technological advancements. The research has not only made the technology faster and more precise but has also resulted in the implementation of new methods. Pérez et al. (2020) identified the main current trends in AM as novel materials and multi-materials, 4D printing, micromanufacturing, control and monitoring, process optimization, novel technologies, post-processing, data acquisition, and sustainability. The authors noted that one of the current trends includes the development of hybrid machines that combine AM processes with conventional techniques, leveraging the advantages of both methods while minimizing their drawbacks.

Simultaneously, new materials are being researched and developed for various applications, particularly in bioprinting within the medical field, which drives the exploration of suitable biomaterials for implants. They also highlighted 4D printing as an emerging innovation, offering capabilities like self-assembly, self-repair, and multifunctionality, made possible by smart materials that allow printed parts to evolve over time in response to external stimuli. Although AM predominantly occurs on a macroscopic scale, several studies have already explored micro-AM.

In the IM industry, AM has already begun to emerge as an alternative to traditional manufacturing methods. Mould components fabricated through AM are becoming increasingly common. The use of these tools not only allows for mass customization but can also reduce production costs for more complex moulds (Lozano et al., 2022). These mould tools, produced through a combination of AM and traditional machining, are referred to as hybrid moulds.

## **2.3 Hybrid moulds**

As previously mentioned, the primary goal of research in IM is process optimization, which involves both cost reduction and cycle time improvement. One way to explore process optimization is through the use of different methods for mould design and fabrication. This has led to the concept of hybrid moulds, which are defined by the creation of mould inserts using different materials or manufacturing techniques (Martinho et al., 2005).

The use of these hybrid tools offers several advantages, particularly the ability to create different moulding cavities for the same mould structure. By leveraging the benefits of AM, we can create prototype moulds at a lower cost and with shorter production times compared to conventional moulds. However, these prototypes typically offer less durability and performance than conventional moulds, making hybrid moulds an ideal tool for low-volume production (Bagalkot et al., 2019).

When discussing metal-based inserts, it is not always the case that their production through AM is cheaper than conventional mould production. As previously noted, AM still involves high costs, especially when producing metallic parts. Nonetheless, the PBF technique has shown great potential by allowing the creation of complex geometries with fewer constraints and reduced lead times (Dehoff et al., 2013).

Thus, the use of hybrid moulds made with metallic materials directly competes with conventional inserts produced via machining. This requires the inserts to have high durability and dimensional precision. Asgari and Mohammadi (2018) observed that the technique for manufacturing these types of inserts is still under development and requires significant advancements to offer the necessary surface finish and dimensional accuracy. However, their study on the microstructures and tensile properties of parts produced via PBF concluded that the technique allows the production of parts with complex geometries, where the characteristic porosity of powder-based manufacturing can be overlooked. The analyzed parts exhibited a dense microstructure with excellent mechanical properties.

The relevance of these hybrid moulds to the work being developed lies in the fact that they represent the only known application of AM for producing parts of the mould. Since this project aims to fabricate the entire mould using AM, it is essential to understand the existing knowledge regarding hybrid moulds.

### **2.3.1 Conformal Cooling Channels**

AM offers several advantages when applied to IM. One notable benefit is its ability to generate more complex mould cavities with less processing. However, this concept can also be applied to other parts of the mould, particularly the cooling channels.

It has already been established that the moulding cycle's longest phase is cooling, and improved cooling leads to a shorter cycle time. Therefore, optimizing the cooling system is of great importance. By combining this need for improved cooling with the advantages provided by AM, the concept of conformal cooling channels (CCC) emerges. These are non-conventional channels, which represent a significant advantage of using hybrid moulds. With the freedom to create complex structures that follow the contour of the part, it becomes possible to maximize the performance of the cooling channels. This results not only in faster cooling but also in more uniform cooling across the produced part, reducing defects such as warping or sink marks (Gibson et al., 2015).

In 2015, Fado conducted a study to determine the effect of using CCC compared to conventional cooling channels. In this case study, they used a geometry (Figure 4) where it was not possible to optimally position conventional cooling channels, thus taking full advantage of the benefits offered by CCC.

The results of this test showed a significant difference between the two models. The cycle time was reduced by 54 s with the use of CCC. The model without CCC had a temperature of around 180°C at the 90 s mark, still too high for part ejection. Meanwhile, the model with CCC reached approximately 100°C at 36 seconds. This stark difference highlights the significant advantage of using such channels. However, it is worth noting that this difference will be more pronounced in models where conventional cooling struggles to perform optimally. For simpler geometries, conventional cooling methods often work reasonably well.

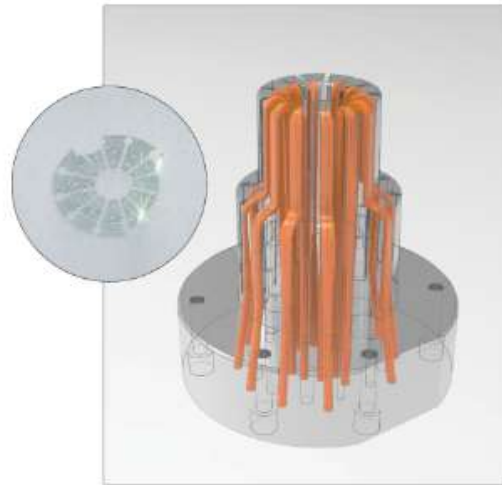
### CONVENTIONAL COOLING

Cycle time: 90 s  
Scrap rate: 9 %  
Steel: 1.2343  
Hardness: 52 HRC

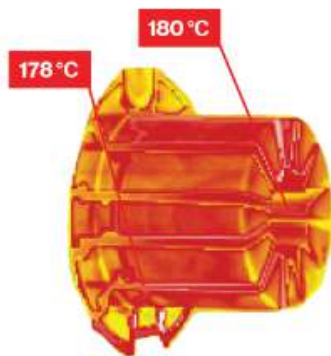


### CONFORMAL COOLING

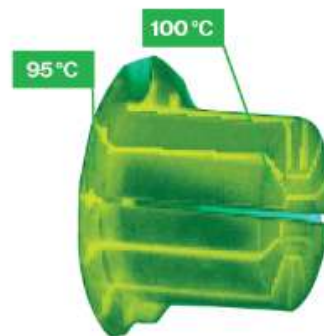
Cycle time: 36 s  
Scrap rate: 0,15 %  
Steel: 1.2709  
Hardness: 54 HRC



INSERT BUILT IN  
SELECTIVE LASER MELTING TECHNOLOGY



Insert temperature distribution after 90 sec.



Insert temperature distribution after 36 sec.

**Figure 4:** Results of CCC 's tests (Fado, 2015)

Mielonen (2016) tested different CCC systems and compared them to a conventional system. Their study revealed that the cooling results across the various conformal channel designs did not vary significantly, with cooling times ranging from 9.4 to 10 seconds among the six designs tested. Therefore, when selecting the most appropriate design, factors beyond cooling performance, such as ease of cleaning the channels and the mechanical integrity of the insert, must also be considered. However, the study demonstrated that the use of CCC resulted in a cycle time reduction of about 50% compared to a conventional cooling system.

## 2.4 Generative Design

With the exponential growth of AM, countless possibilities have emerged for designers to explore new forms and geometries. The lack of limitations offered by AM encourages creativity and enables the discovery of shapes that were previously considered impossible. A tool that has been used by designers for several years is parametric design, and it is one of the methods that benefits from the growth of AM. This tool works through parameters that define the shape being created. These parameters can vary significantly, but the most influential ones are the constraints imposed on the model. These constraints ultimately determine how the various components of the design relate to each other (Monedero, 2000).

Generative tools and artificial intelligence are increasingly present in society, enhancing work in various fields. One generative tool that has gained traction across different areas is GD. This is a form of parametric design that uses algorithms to create a 3D model based on user-provided inputs. Its purpose is to solve design challenges by presenting unconventional geometries through an iterative process that optimizes these forms. GD tools, therefore, encourage divergent thinking by generating different models for the same problem, which can then be refined to meet specific goals (Buonamici et al., 2021). In Figure 5 it's possible to see the result of a GD tool, where the obtained geometry exhibits an organic form.

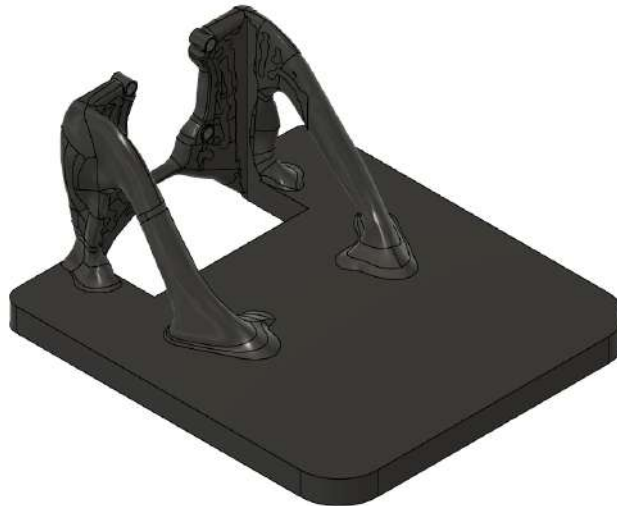


**Figure 5:** Example of GD result

### 2.4.1 GD process

The nature of GD induces a sequence of iterations to reach the desired final result. GD tools generate a wide range of solutions for a design problem. It is up to the user to evaluate each solution and decide which ones best align with the intended outcome. By readjusting the initial problem based on the obtained

results, the process moves forward. This iterative approach provides several advantages for design, such as the optimization of specific criteria and the generation of unimaginable geometries (Filippo et al., 2021).

Currently, the optimization process for a part typically begins with an initial design by the designer, based on their experience. From this CAD model, an optimization program simulates the mechanical stresses exerted on the body, with the applied forces designated by the user. By identifying areas with little or no stress, the program defines these regions as zones where material can be removed without compromising functionality. This process is known as Topology Optimization (TO), a tool already integrated into many CAD software packages and widely studied.

In contrast, GD proposes an optimization through addition, where material is only added in areas where it is needed, similar to processes observed in nature. In this approach, the user defines the volume and the loads applied to the part, and the algorithm presents multiple possible solutions to the problem. The user then iteratively evaluates and selects the best solutions until reaching the desired final result (Schrurs, 2021). Figure 6 illustrates a schematic of this process.

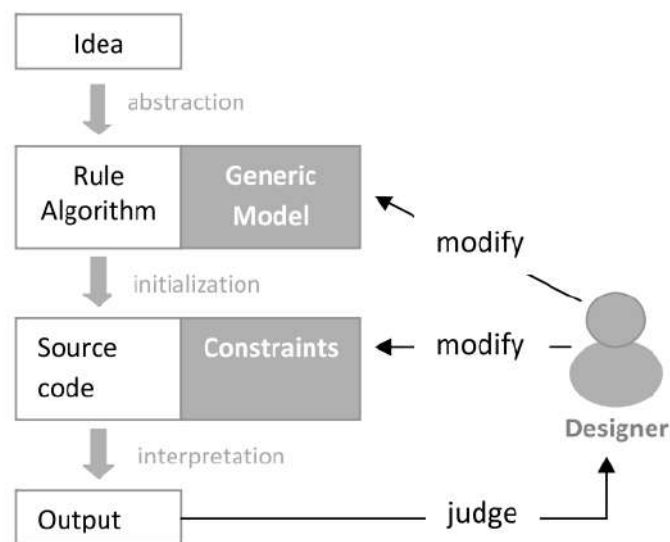


**Figure 6:** GD Process (Krish, 2011)

## 2.4.2 GD applications

GD is a growing technique that is receiving attention, particularly in fields where design plays a critical role, such as architecture. However, its adoption has encountered skepticism in some areas. In 2016, Agkathidis published a book detailing a study aimed at exploring how GD could be utilized by architecture students. For this study, he gathered 60 students for a 12-week project in which they used a GD tool to generate form ideas. These forms were then meant to be implemented in architectural constructions.

From the results, the author drew several conclusions. One common concern about GD is the per-

ceived loss of authenticity and creativity. However, despite the students following a similar process and using the same tool, the results varied significantly. Moreover, the study found that the GD process actually enhanced creativity, as students were able to move beyond conventional forms in architectural design. These were traits the author deemed crucial for learning, as generative tools allowed students to adapt to unconventional shapes, sparking new ideas for their own designs while leveraging the benefits of digital design tools.

However, the author identified the form-generation phase as the most challenging aspect of the process, as it was difficult for students to let go of conventional design methods. This is an important point for this work, as one of the primary goals is to apply generative tools to create a mould tool design. Therefore, it is critical to think beyond the traditional mould structure to fully utilize the potential of GD.

This study addresses a topic that remains relatively unexplored - applying a design tool in a specific engineering field, IM. These fields of knowledge do not naturally intersect. Nevertheless, combining them could offer substantial benefits for the final outcome. Looking at the broader application of GD in engineering highlights its potential advantages.

Barbieri and Muzzupappa (2022) conducted a study to identify both the potential and limitations of using tools like GD. To do this, they applied these tools to two components from a race car. The resulting models were then tested using FEA. The results showed not only a reduction in the mass of the parts but also improved mechanical properties. From their study, the authors concluded that GD is highly useful both in the conceptual phase and the modeling phase. This is because GD not only provides multiple solutions for a single problem but also allows for easy refinement of designs through CAD tools.

Although GD is a promising tool, literature addressing its use in IM is scarce. However, there are two notable case studies where this tool was applied to optimize CCC. These include the works conducted by Wilson et al. (2024) and by Panasonic Life Solutions Company (2020). In both cases, a cooling system with conformal channels was designed using the capabilities of GD. Panasonic's Life Solutions Company reported a 20% reduction in cycle time compared to conventional methods. In Wilson et al.'s case, a more significant cooling time reduction was recorded—70% compared to conventional methods and 50% compared to other conformal channels.

In Figure 7, the channels designed by the authors are presented, showcasing the effective use of GD for mould cooling optimization.

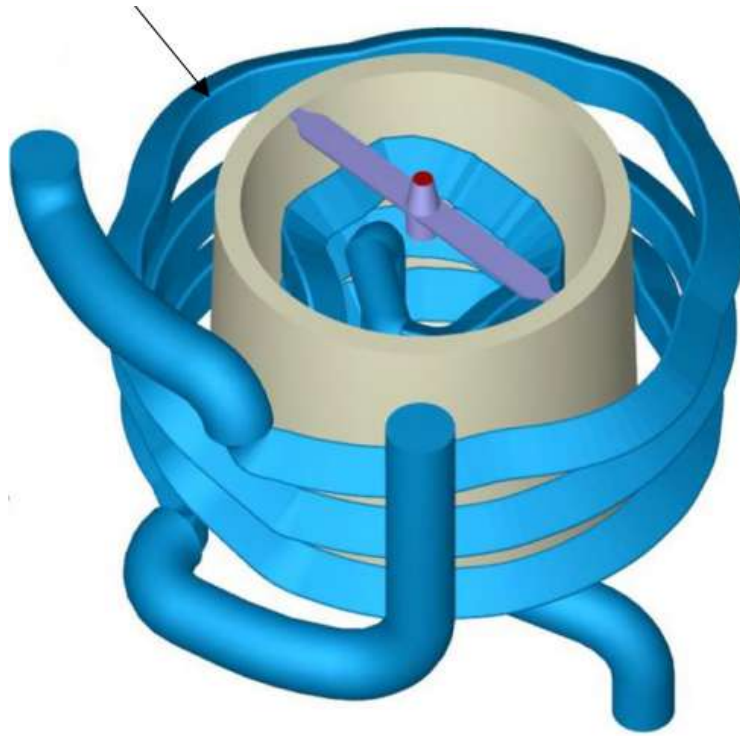


**Figure 7:** CCC obtained through GD (Wilson et al., 2024)

These results highlight the significance of generative tools in producing objects and shapes beyond human conception. Additionally, they underscore the importance of conducting research into these applications to gradually establish generative tools, such as GD, as commonplace in design and engineering. Agkathidis (2016) emphasized the importance of integrating digital tools, particularly GD, into education. By ensuring that students acquire knowledge in relevant fields and even mastery over these tools, they are prepared to adapt to the evolving landscape of their disciplines. GD offers revolutionary advantages, and its exponential growth is inevitable, making it crucial for future professionals to embrace and utilize these technologies.

## Chapter 3

### Methodology

The aim of this work is to develop a non-conventional mould by leveraging the advantages of AM to produce a lighter mould with fewer components. To achieve this, a methodology was developed utilizing both numerical and experimental approaches (Figure 8). In the initial phase, a part will be selected, followed by the development of various concepts for the CCC. These conformal channels will be numerically validated in adequate CAE software (Moldex3D) and then used as input for GD (Fusion 360). The GD phase represents the main stage of development, where a final geometry is obtained through an iterative process. Finally, this optimized shape will be numerically tested in proper CAE software (Ansys) and then prototyped through the PBF technology.

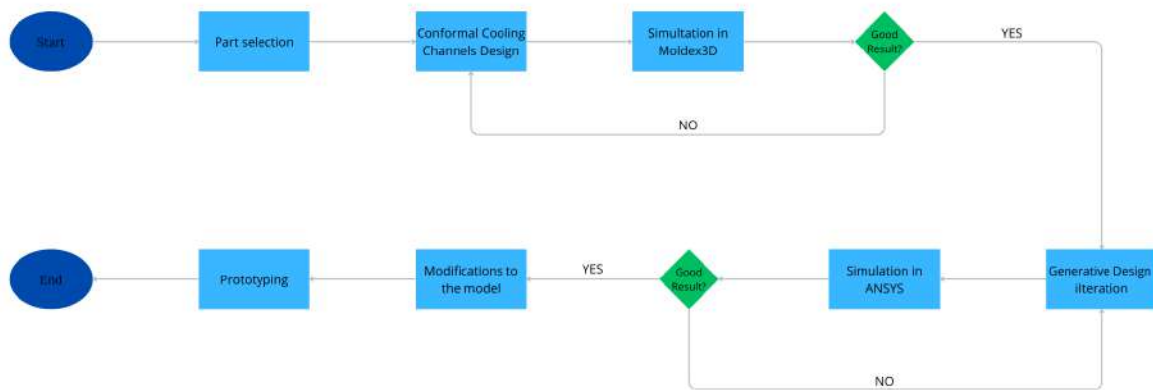


**Figure 8:** Flowchart of the methodology developed for this work

To develop this tool, a part is selected that will serve as the basis for the entire study. This work will be developed in collaboration with a company, so most of the parameters related to the part were defined

prior to the project start.

The material selected for the moulding tool is Uddeholm Corrax steel, and the material for injection is Polyamide 12, Grilamid TR 55 natural. The positioning of the parts was also specified by the company to ensure a spacing of 130 mm between the injection points. Injection will be carried out through direct hot nozzles to the part, and to carry out the needed simulations it is taken into account the company's nozzles. It is important to highlight the interconnected nature of these projects. The progression of the main project with the company, led to changes that were applied to this project as well. These changes culminated in the list presented. This information served as the starting point for initiating this work.

In the process of creating a moulding tool, various procedures will be conducted in alignment with each other. The iterative nature of the project necessitates the integration of different aspects in a cyclic way. The majority of the work will be developed in Fusion 360, specifically utilizing its GD tool. To understand how to conduct the process, first it's necessary to comprehend how this generative tool works. In Figure 9 its shown how a GD setup in Fusion 360 looks. GD in Fusion 360 requires various parameters controlled by the user. These inputs can vary significantly, but the most crucial for the process are:

- Preserve Geometry (Green figures)
- Obstacle Geometry (Red Figures)
- Load cases (Blue arrows)
- Structural constraints (Green geometries with a lock)
- Materials
- Manufacturing

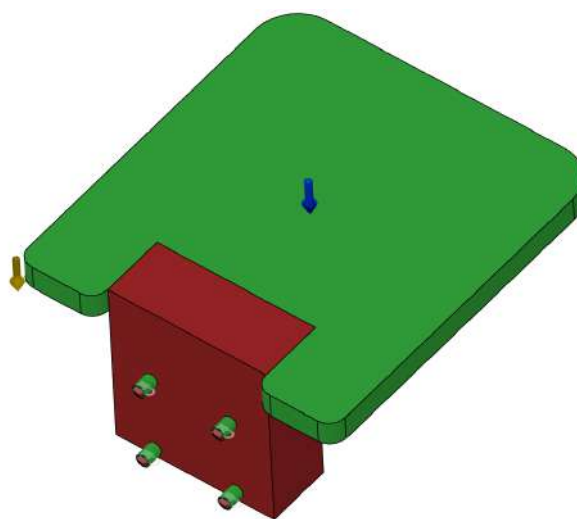


**Figure 9:** Example of a GD initial setup in Fusion 360

Upon analyzing these parameters, it was concluded that it is necessary to design some geometries

using CAD software and also define the boundary conditions. The designated tool for defining these conditions is Moldex3D, a software that allows to simulate the IM process. This simulation software works with parameters such as the geometry of the part, cooling channels, feed channel, as well as the materials to be injected and the mould itself. The simulation obtained from this program provides results from various aspects; however, for this study, the focus was on the results of the filling, packing, cooling, and warpage. The most important values for the procedure that can be extracted from these results are the clamping force and the injection pressure.

To conduct these simulations, the CAD design of the CCC is required. Initially, it is essential to conduct a study on the potential configurations of the CCC. Various designs shall be considered, and through numerical analysis, the most promising ones shall be identified. The selected design can further be used in the IM simulations. This approach allows to extract the previously mentioned parameters and the different performances of these CCC.

Based on the performance of the different CCC designs, the most efficient design will be selected. Utilizing the model of this design the generative process can be conducted. At this stage of the project, the objective will be to obtain an optimized final geometry through several iterations. Each GD iteration that represents an improvement over previous ones shall be verified through structural simulations.

The structural simulations will be conducted using Ansys software, where the most relevant results for this work are deformation and stress. Based on these results, cyclical adjustments are made to the GD process until the desired parameters are achieved.

Once a highly refined geometry is achieved, it will be prototyped through AM technologies to allow for more detailed analysis, in order to maximize its refinement. The prototype offers a better perspective on the dimensions of the mould and allows for the verification of component functionality. Additionally, the prototypes allow the mould assembly to be tested. If potential improvements are detected during this analysis, they shall be implemented in the final version to be produced during a final stage.

## Chapter 4

### Results

In this chapter the results obtained throughout the different phases of the work are presented. The selected part has a shape resembling a disk with several protrusions on both faces (Figure 10). This part is produced using bi-injection transfer moulding, with the same material but different colors in each injection. This part was chosen as the case study for the work, where the objective will be to develop a non-conventional moulding tool around this parts, while taking into account the already in use conventional mould.

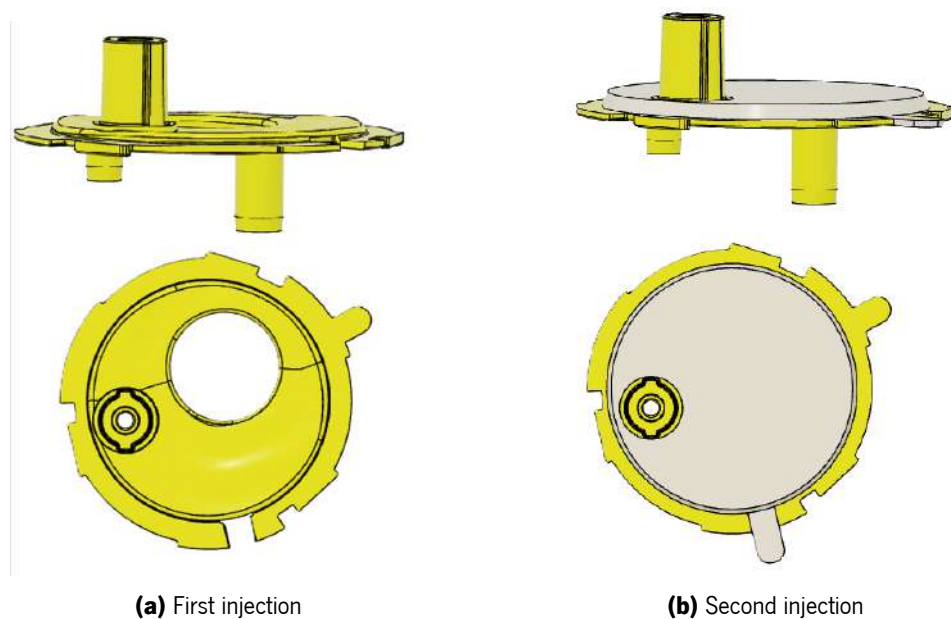


**Figure 10:** The part

This process started with only a model of the parts provided by the company (Figure 11), and the objective was to develop the moulding tool, passing through all the phases previously mentioned. The model was a representation of the injection and extraction system in a conventional mould.

In total, the company's model had five extractors and there were also some inserts responsible for moulding and cooling the protrusions of the part. These were needed because the mould was fabricated

through conventional methods (CNC) as using an insert is simpler process than machining certain geometries. As the moulding tool being developed will leverage the advantages of AM, the need for this inserts is eliminated.

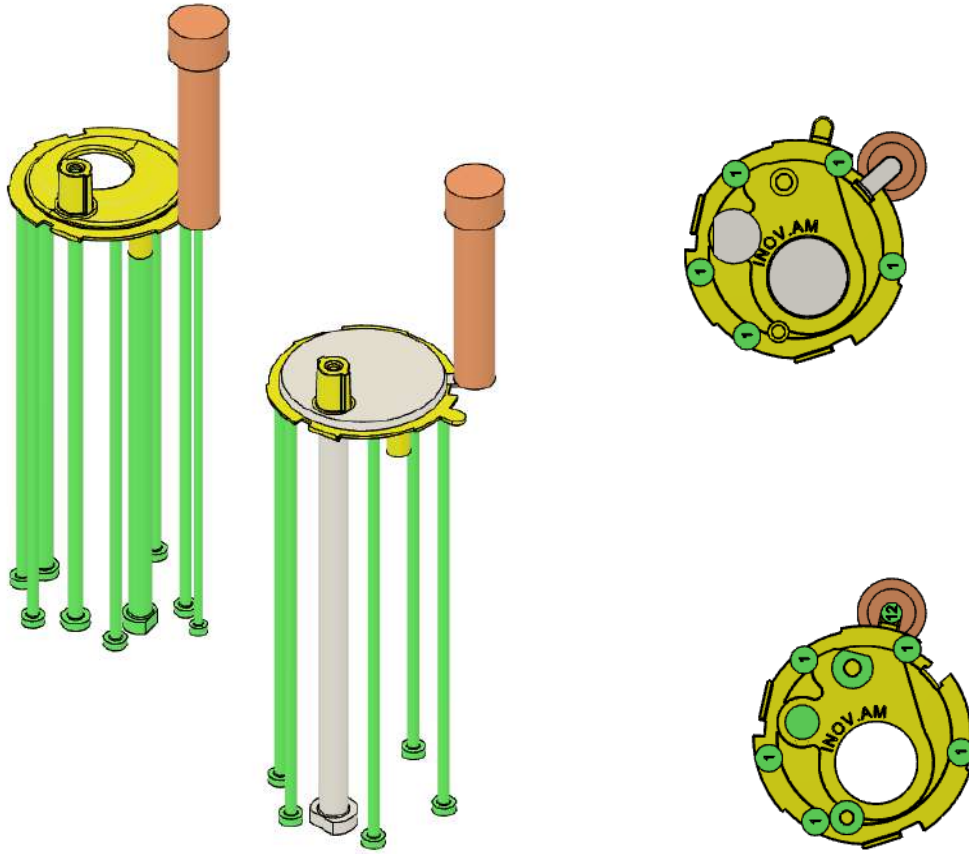


**Figure 11:** Initial parts model

Therefore, in the early stages of this work this model was simplified to enhance usability and reduce complexity, as it was determined that inclusion of some elements was unnecessary. The modifications involved removing the moulding inserts and some of the extractors. The model was left with only three extractors. The remaining extractors were repositioned, placing one closer to the injection point.. The simplified model is presented in Figure 12.

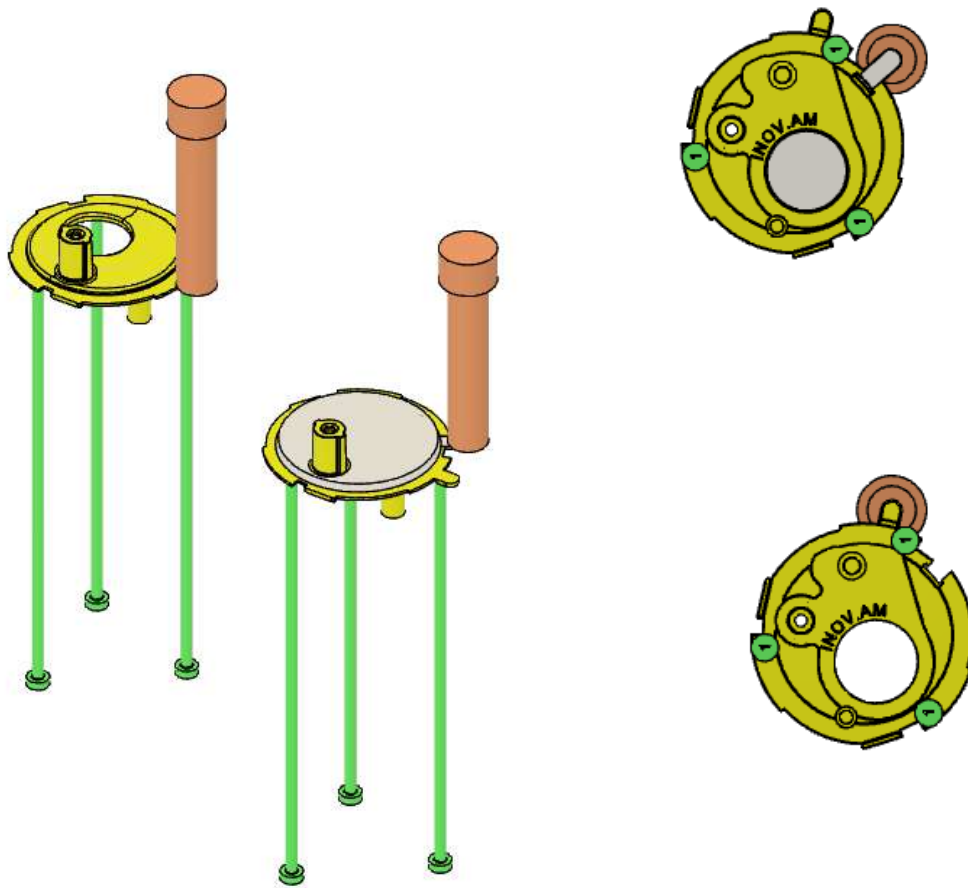


**Figure 12:** Simplified initial parts model

Making this modifications was the starting point of the work, as all of it was done based on this model. Consequently, this was a very important step, as if new changes had to be done, it would take the whole progress of the work back to beginning. These modifications needed to be precise as they should remain unaltered throughout the whole process. With this detail being settled the process of developing the moulding tool was started.

## 4.1 CCC Design

Designing the CCC was the first phase of the process, and as explained before, it is a iterative process between the designing and the simulations of the channels. As the selected part has a nearly flat geometry, the CCC lose some of what makes them so advantageous. However, since the mould must be produced using AM, there is no reason not to opt for CCC. Fusion 360 was the tool used to develop the CAD model of the CCC. To analyse and develop the designed CCC it was decided to use the Moldex3D software.

As previously mentioned, the part consists of a disc with conical protrusions on both faces. These

protrusions can pose a cooling challenge, which initially led to the consideration of channels that would have a level change, as illustrated in Figure 13. However, after analyzing the results, it was realized that this alternative could complicate the removal of metallic powders after the production of the moulding tool.

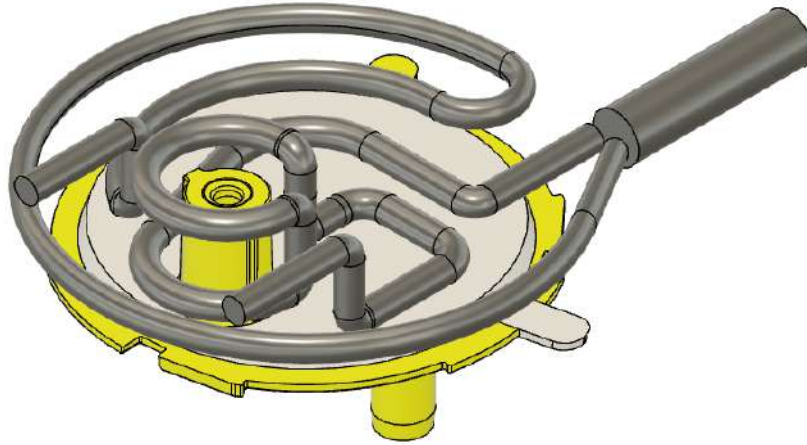


**Figure 13:** Initial design of CCC with a level change

Therefore, the CCC have been simplified by considering a single plane. Several solutions were then designed with the aim of understanding through simulations which channels would provide the best cooling. The general approach in these cases was to follow the circular shape of the part, always trying for a spiral-like format.

Initially, a diameter of 4 mm was considered for the CCC due to the small dimensions of the part, and the first GD outcomes featured channels of this size. As the generative process progressed, the layout of the CCC underwent modifications. Later, it was also realized that a 4 mm diameter could pose problems for the post-production cleaning process, leading to a decision to design the channels with a 6 mm diameter instead.

The various iterations of the CCC were validated through simulation using the Moldex3D software. The final design of the CCC (Figure 14) was chosen by analyzing both the results of the simulations and the geometry that was most fitting for the part. As the generative process evolved, more elements were introduced, which led to a lack of options for the layout of the CCC.

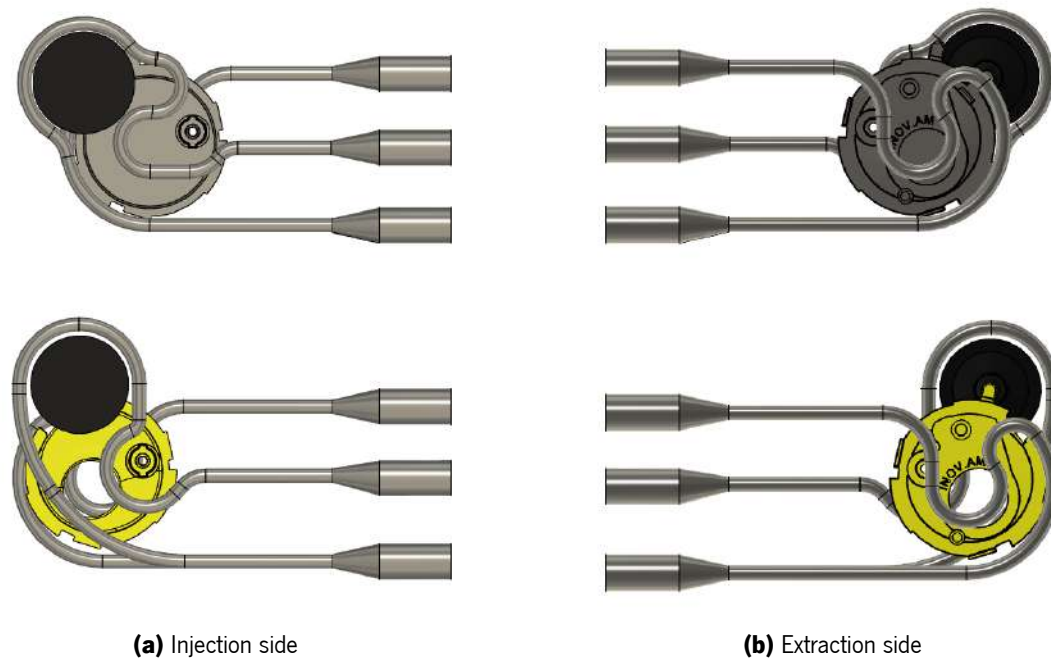


**Figure 14:** Final CCC design

The final model for the CCC was the result of a large number of iterations and adaptations to the generative process. As it can be observed, the geometry of the part and components such as the extractor pins and the hot runners restrained the design of the CCC. This limited the arrangement of this channels and ultimately led to the design shown.

#### 4.1.1 Numerical validation

During the design phase, various concepts were developed, and the most promising ones were tested with the Moldex3D software. This software allows to simulate the IM process, and through that it was possible to get a preview of the performance of each design tested. The purpose behind this testing was not only to validate the designs developed but also to obtain crucial parameters for the GD phase. These parameters were mainly the injection pressure and the clamping force, as these will be used as an input for the generative tool.

The Moldex3D software operates with inputs such as the part geometry, mould, cooling channels, material, feeding channels and some process parameters such as melt and mould temperature. To test the channels, the inputs given to the software were the CAD files of the part and corresponding CCC. The remaining inputs were defined in the software, mainly the mould base and the feeding channel. In this particular case, as it was a bi-injection mould, two runs were needed. However the geometry from the first injection was used as a part insert in the second injection run. With this link between runs, the data from

the first one was used in the second in order to achieve better results.

As mentioned previously, several concepts of the CCC were tested during this phase. However, the results presented in Figure 15 to Figure 20 are only referring to the tests done in the final design. These show the results from the filling pressure, packing pressure and packing clamping force for both runs. In Table 3 is shown the cooling efficiency for each of the runs.

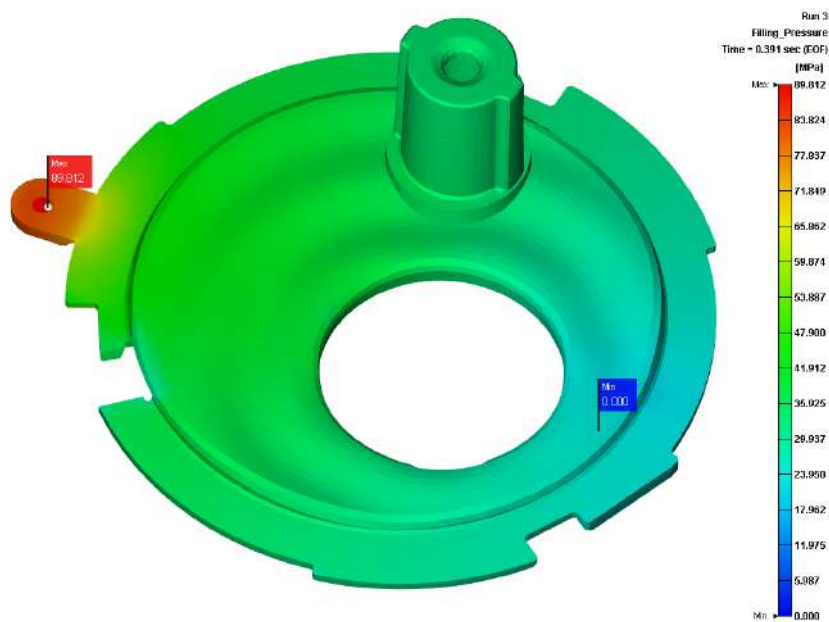


**Figure 15:** Filling pressure - First injection

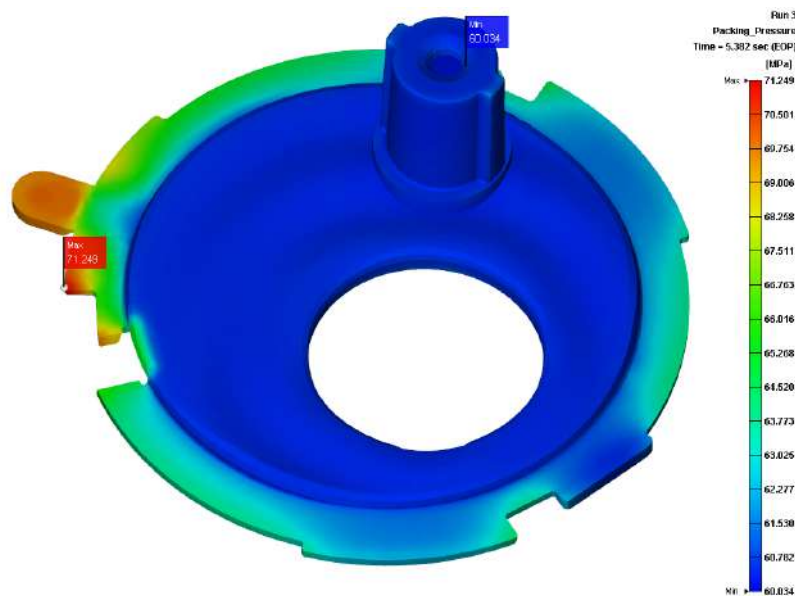


**Figure 16:** Packing pressure - First injection

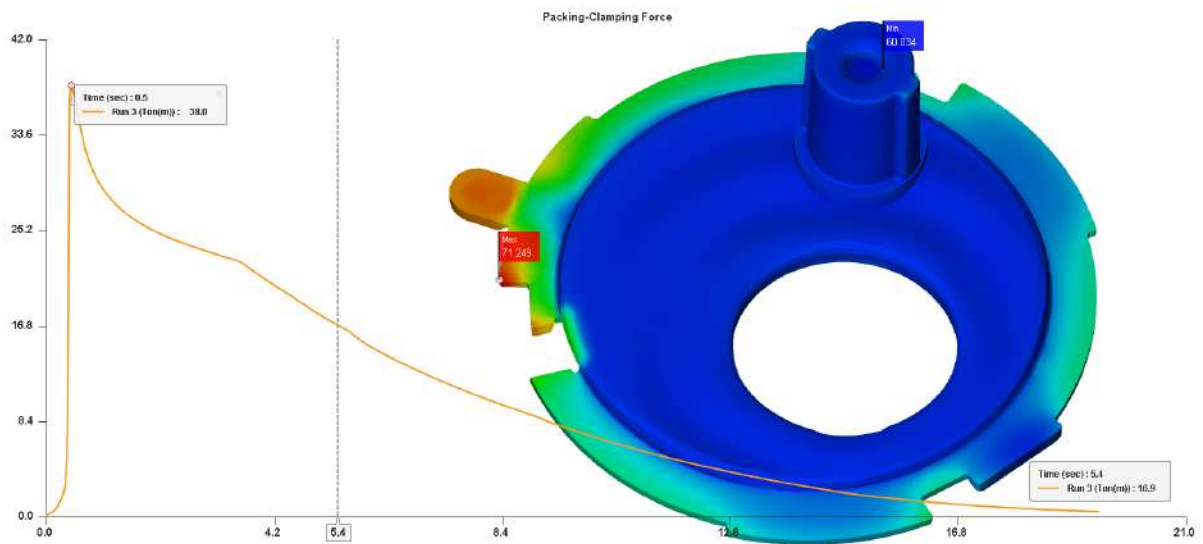


**Figure 17:** Clamping Force - First injection

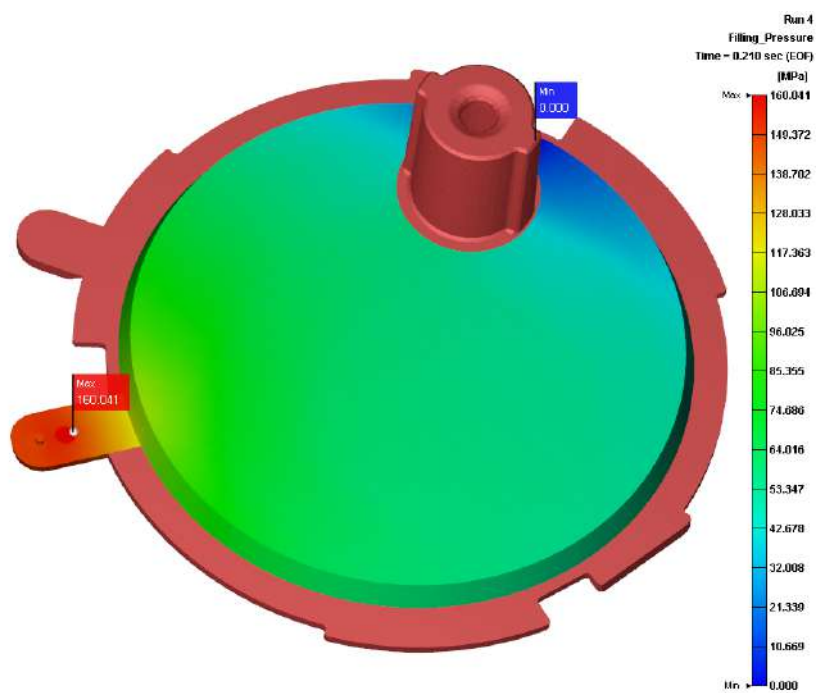


**Figure 18:** Filling pressure - Second injection

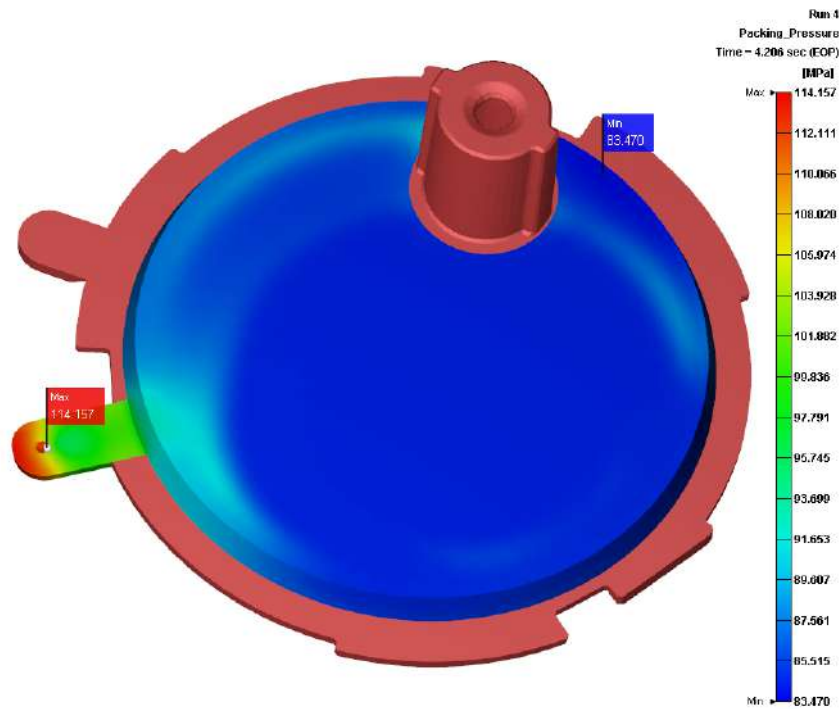


**Figure 19:** Packing pressure - Second injection

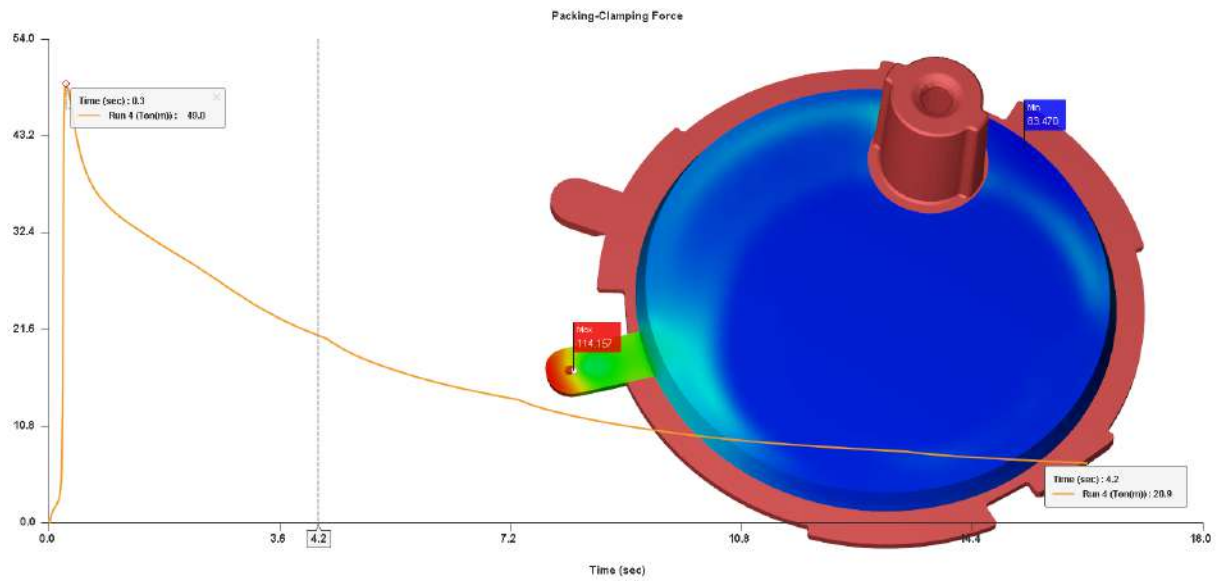


**Figure 20:** Clamping Force - Second injection

**Table 3:** Cooling Efficiency of the final CCC model

| Injection | Channel 1 Cooling Efficiency (%) | Channel 2 Cooling Efficiency (%) | Background (%) |
|-----------|----------------------------------|----------------------------------|----------------|
| First     | 10.15                            | 9.47                             | 80.38          |
| Second    | 3.29                             | 7.90                             | 88.81          |

As expected, the efficiency of the channels is very low. This was verified through all the simulations

in the various designs. The part's geometry presents a challenge for cooling, and consequently, for its optimization. Even so, the main objective of these simulations was to extract the IM parameters that would be used in the GD process. From analyzing Figure 15 and Figure 18 it was concluded that the injection pressure felt in the part has a maximum value of approximately 160 MPa during the second injection. This pressure is higher in the second injection due to the molten polymer having tighter pathways, and thus needing more pressure to fill the cavity. This translates in a higher clamping force for the second injection as well, as this force is a response to the high pressures generated in IM. The value of this clamping force can be observed in Figure 20, with a maximum value of 49 ton. Previous simulations presented results with similar values to this final simulations. This shows how the cooling channels design has a negligible effect, as different designs show very similar results. However, by consistently obtaining similar results in clamping force and injection pressure, these values can be used in the GD process with a certain assurance.

## **4.2 Generative process**

The use of the GD tool was the main focus of the entire project, as the primary objective was to obtain a moulding tool through this method. This phase was the most time-consuming part of the project. The iterative nature, coupled with the tool's resolution time and the complexity imposed by the geometries used, led to a prolonged study of the base shape used for the mould. Additionally, there was a steep learning curve regarding the use of this tool, due not only to the lack of experience with the tool but also the absence of prior research to establish the theoretical basis for this investigation.

To implement GD, it was first necessary to establish all the geometries that are crucial to the process. The approach involved providing inputs that minimally restricted the software to maximize its level of freedom. Initially, it was considered only the supports to secure the moulding tool to the injection machine plates, and some type of surface along the parting line to ensure that the material is allocated between these two areas. The additional inputs would be geometries to avoid, where the program should not allocate mass. These include the CCC, the part itself, and the ejectors or the hot runners and locating rings, depending on which half of the mould that is being considered.

To define the preserve geometries, the plates of the IM machine allocated for this project were taken into consideration. The mounting mechanism of this machine is through clamping claws, which have certain positions where they can be positioned. This information was used to select the dimensions of the base that best suited the parts, ensuring compatibility and functional integration with the machine's specific setup. Among the various possible dimensions, one particularly stood out. Since the goal was to

minimize mass and maintain a certain symmetry between the parts, while keeping them on the centre of the base, the smallest viable dimension (i.e., 320 x 200 mm) was selected. With these boundaries defined, both the shape and dimensions of the supports for the clamping claws were selected, as these are crucial preserve geometries. Initially, four bases of 50x50x20 mm with rounded edges were considered. All these dimensions are illustrated in the Figure 21, as well as the four platforms that will serve as the interface for locking the moulding tool in place.

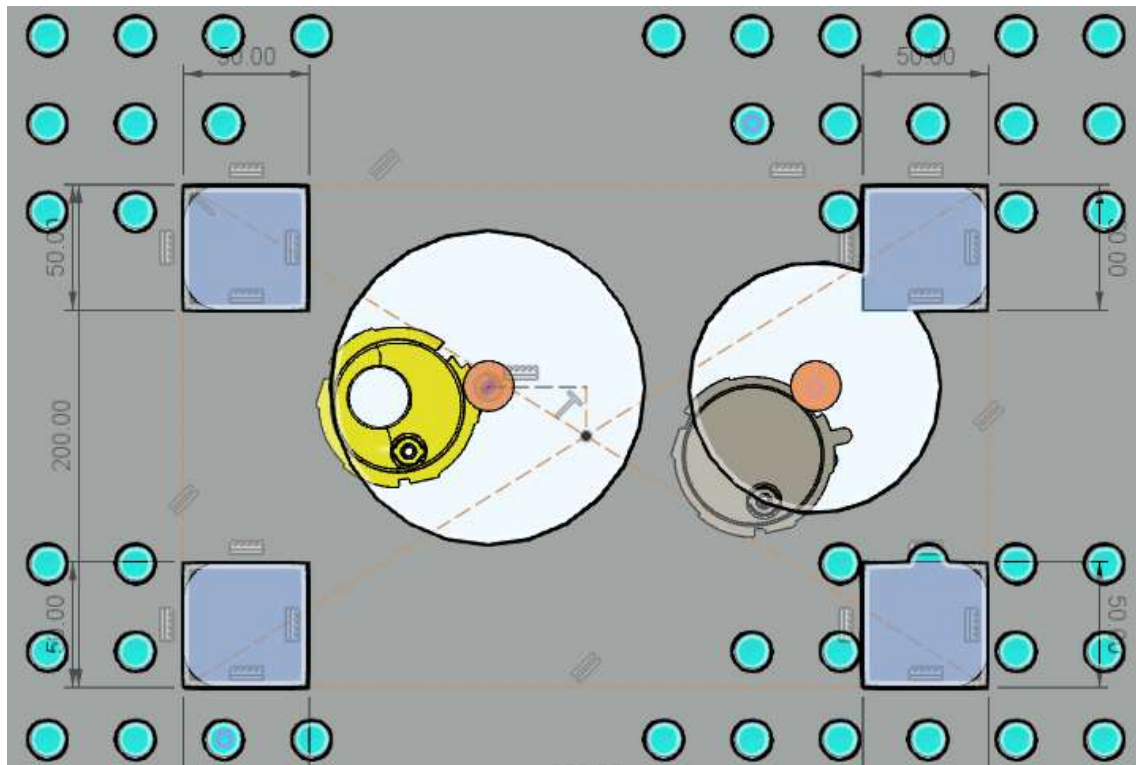


**Figure 21:** Initial design for the bases in relation to the base plate of the injection machine and the part (dimensions in mm)

Additionally, the results obtained through numerical simulations were adapted in order to be used as an input for the GD tool. The value of clamping force was rounded to 50 tons for a simplification of the process. The injection pressure was however further adjusted, as the maximum pressure is felt only in the melt entry. The value of 160 MPa lowered to 100 MPa, as this pressure will be represented through all the moulding surface. This value not only is close to the average value of filling pressure, but also to the average packing pressure, which ranges from 114 to 83 MPa.

In the initial approach along the parting line, the strategy was to use "inserts" that follow the geometry of the part and contain its negative, along with the runners, and, if applicable, the ejectors or hot runner. By instructing the program to maintain this specific geometry, it is ensured that the space between these structures is not filled, reinforcing this by designating them as geometries to avoid.

This initial approach was also the first interaction with Fusion 360's GD, aiming to understand the type of results that could be expected from the tool. With these initial results, a general understanding of best practices was established to facilitate this iterative GD process, which would be refined with each new design generated. However, the initial outcomes immediately highlighted a issue that persisted throughout the project: the program's tendency to allocate mass in areas designated as obstacle geometries. In many instances, this led to the negatives of parts, ejectors, CCC, and the hot runner being inadvertently filled, as demonstrated in Figure 22.



**Figure 22:** First result of the GD process

This situation led to the exploration of new approaches to ensure that these critical geometries remain unaltered. An attempt was made to create a type of "shell" that would follow only the shape of the part and be as thin as possible. Initially, the idea was to create just a surface, corresponding to the parting surface. However, the GD tool does not accept surfaces as inputs to generate results. A solid with minimal thickness was then created, where the offset from the part was about 2 mm. This method showed some potential, as it allowed significant freedom for the program to generate the most favorable result. However, this approach consistently returned unfinished outcomes. The program was unable to generate results, always stopping at the fifth iteration, whereas previous iterations typically reached around 30.

The complexity of the commands imposed on the program increased with its usage and experience. However, it was not expected that this would have implications on its process. After several iterations, it became clear that using complex geometries increased the probability of generative process failure. The results obtained were not meeting the defined objectives, and by this point was expected a demonstrative result of the geometry. Therefore, it became imperative to understand the practices we should follow to achieve good results. A study was conducted where several attempts were made to obtain various results and determine which returned suitable geometries. The conclusions drawn from this study led back to the use of an "insert". However, it was noted that if this insert was too thin, the generative process did not

conclude correctly. Since the program does not indicate the cause of the error, it was assumed to be due to the clamping force and injection pressure specified to be applied to this geometry. Thus, this structure must have considerable mass for the program to consider it possible to conduct the generative process. It was also concluded that using a block as an obstacle in the parting line to prevent mass from developing into the area where the other half of the mould would be also yielded good results. It also ensures a flat area at the interface between the two mould halves. The way these parameters were introduced in the solutions is demonstrated in Figure 23a, along with the resulting output, which was the first instance where the program preserved the moulding surface (Figure 23b).

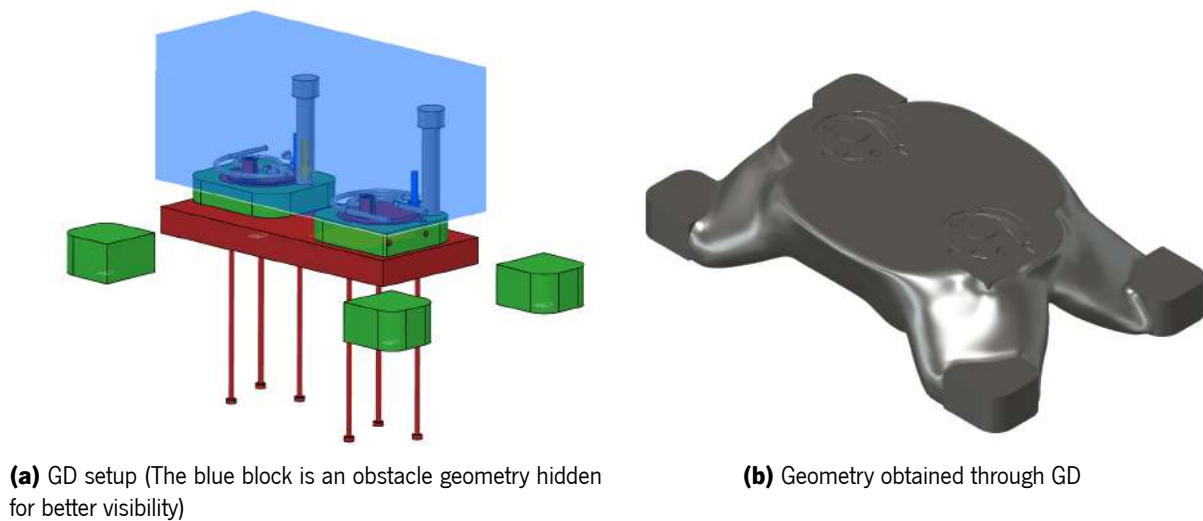


**Figure 23:** The first good GD result

With the conditions for obtaining good results established, the work continued with the validation of various hypotheses. The first hypothesis tested addressed a concern regarding how the program interprets the forces specified. These loads should be applied to one of the geometries to be preserved, and the parting surface is divided between the two inserts. To accurately represent the clamping force, it should be applied at the interface between the two mould halves. This means that the forces must be split so that the resultant force matches the clamping force, ensuring a correct representation of the load. Until this point in the process, a single force had always been used, indicating that it was applied to both bodies.

The results obtained from this test led to the conclusion that the program was not correctly interpreting the commands. The resulting geometries had a very reduced mass, which would not withstand the high applied forces. It is crucial to ensure that the force is accurately represented, and to definitively resolve this issue, it was established the use of a single body encompassing both injections. This allowed for the application of a force equivalent to the clamping force, thus ensuring a correct representation.

This implementation limits the program by imposing a large area where mass must be maintained.

However, it also has advantages, such as accurately representing the force and defining a stable parting plane where both mould halves come into contact. The setup used to test this new method is illustrated in Figure 24a. Given the large area involved, further attempts were made focused on reducing the thickness of this component without compromising its results. This tests settled in a minimum thickness of 20 mm. The results obtained (Figure 24b) did not present any errors and showed mass allocated in a seemingly correct and reasonable amount compared to previous results. This was the first promising outcome, opening the possibility to increase the complexity of future iterations to achieve a final result.

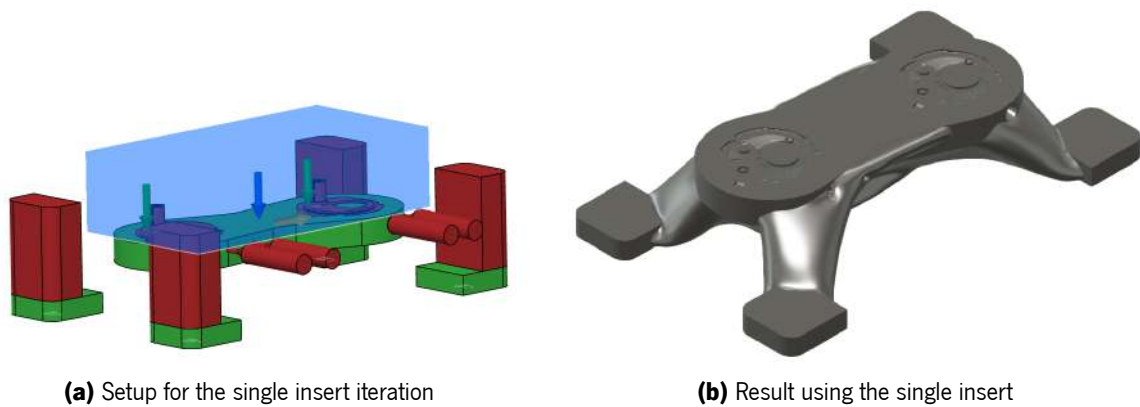


**Figure 24:** Solution with the single insert

One of the first conclusions drawn from the analysis of these results was that the size of the bases was over-dimensioned. This became clear from the proportion of mass in relation to the base itself. It was decided to reduce their dimensions to 35x35x15 mm.

At this stage of the process, it was determined that using a single body along the parting line would be the method adopted moving forward. In addition to providing the previously mentioned advantages, the results demonstrated a significantly appealing aesthetic level. Consequently, the work progressed towards a more complex GD setup. Additional functional components of the mould were integrated, such as centering rings, the hot nozzles, and a non-conventional extraction system. The operation of this extraction system will be detailed later.

The increase in complexity added several difficulties to the already identified problems. The initial analysis of the results indicated the need to manipulate the mass allocated in certain areas. All additional components require material around them to ensure a stable and fixed position. However, the results did not show sufficient mass in these areas. This addition of more components made the generative process more demanding, clearly increasing the frequency of errors in the process. Several adjustments were made to the setup to address these issues. However these adjustments happened over time. There were a lot of iterations between this single insert solution and a final model that reached the desirable objectives.

Every iteration returned some type of result, that pushed the work forward.

Given that the high complexity of the model became a restraint, the initial approach was to lower the level of complexity. Firstly, the geometry of the insert went through some modifications. The edges were rounded, as it was concluded that a fillet in the interface between generated surfaces and preserve geometries gave a better aesthetic result. Furthermore, the representation of the part was simplified to a circle. The part would be added to the model after achieving the final result. This not only simplified the inputs for the GD process, but also eliminated the error that could happen where the cavity of the part would get eliminated by the GD tool. Figure 25 shows how these modifications were implemented in the model.

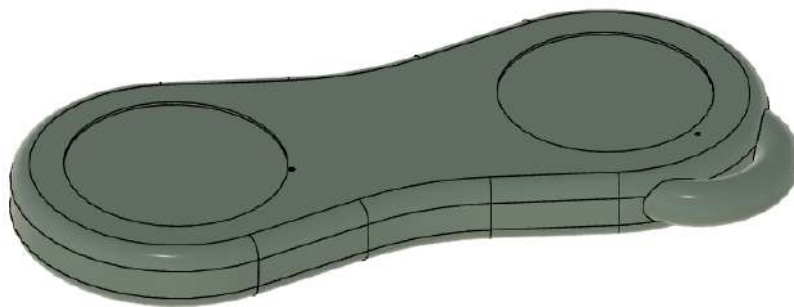


**Figure 25:** Modifications to the single insert model

This specific geometry is from the injection side, where an extension of the main body can be observed. This was the solution defined to cover the CCC that was salient from the insert model. This solution proved to be very helpful in maintaining the insert as small as possible while making sure the mass is allocated around the CCC. These modifications, however, were ineffective, as the generative process still failed to conclude. After several tests attempting to circumvent this issue, it was concluded that the model should be further simplified. This involved removing certain components from the setup, thereby excluding them from the GD process. These components would be added later, and the result from the GD would serve as a base geometry. This geometry would need further modifications by adding the missing components and making small adjustments to meet the defined objectives. The components that were discarded were the ones present in the extraction system. This structure is very intricate, which posed a challenge to the GD process. With the removal of this system, the setup for the extraction half (Figure 26), became very simple. It used only the insert, the CCC, the bases and some obstacle blocks.

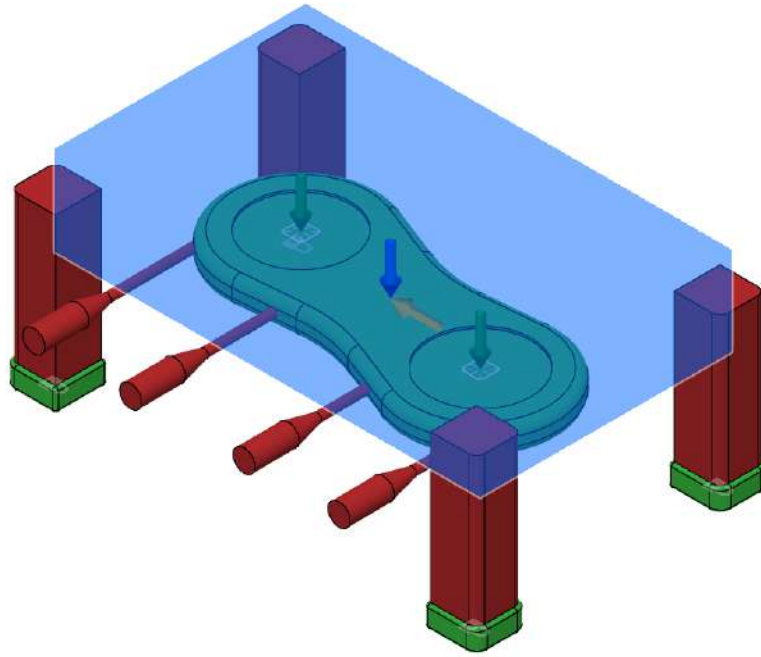


**Figure 26:** Extraction side setup for the final result

Additionally, it can be observed that the edges on the bases were also rounded. This was changed for the same reason as in the insert, as this translated in a smoother transition between generated and preserved geometries. These changes prevent achieving the initial goal of obtaining a final result that considers all mould components and is suitable for manufacturing. However, the project's trajectory indicated that this scenario might not be achievable.

To address the issue of mass allocation in crucial areas, a simpler solution was implemented. By adding preserve geometries in these specific zones, the GD ensured that the generated mass encompassed the necessary components. This was the case for the hot runners and the centering ring. The results obtained initially did not account for these structures. This resulted in geometries that did not cover the area where these structures would be. This would not be possible to work with, so the solution implemented was to have preserve geometries in those areas (Figure 27). Again, this takes away some of the level of freedom given to program. However, it was necessary in order to have a result that achieved the desired objectives.



**Figure 27:** Preserve geometries added for the implementation of the hot runners and centering rings

The setup for injection side was much more intricate than the extraction side. However this did not pose a problem for the GD tool as it returned good results. The setup considered for the development of solutions is shown in Figure 28. Another difference between the two setups is their height. In the extraction side it was used the minimal height that returned good results, i.e., 80 mm. However, the hot runners had around 90 mm. The height of the injection side would be determined by the height of the runners and the smaller ring on the centering ring. Therefore, the height of the injection side was set as approximately 99.5 mm, almost 20 mm more than the extraction side.

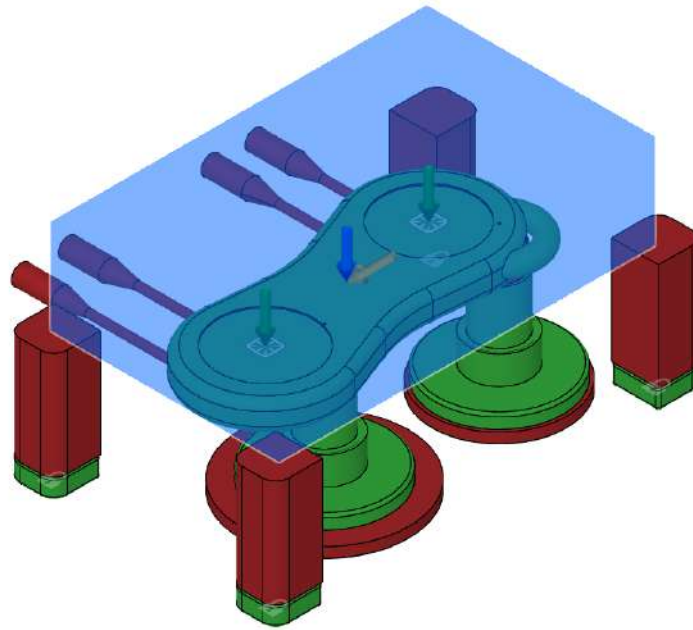


**Figure 28:** Injection side setup for the final result

With these difficulties overcome, and after several iterations, a geometry that exhibited the defined characteristics for the moulding tool was achieved. However, it was still necessary to refine the geometry by adding essential components to ensure the tool's functionality. The components already present in this base geometry were only the hot runners toward the piece and the cooling channels.

The results for both sides are shown in Figure 29.



**Figure 29:** Final results from the GD process

## 4.3 Extraction system

As previously mentioned, a non-conventional ejection system was chosen for the developed moulding tool. This system operates through compressed air, advancing or retracting the ejector pins. To ensure the

system's correct operation, it is essential to maintain an adequate seal, as any air leakage could compromise the efficiency and precision of the ejection process. This sealing is crucial because it maintains the necessary pressure to move the ejector pins reliably and consistently. Thus, it ensures that the moulded parts are ejected smoothly and without damage. This type of ejection system is particularly useful for the mould since the non-conventional structure does not have the necessary volume for a conventional ejection plate. This system aligns with the objective of minimizing the mass of the moulding tool. As this is a non-standardized system, a prototype should be made in order to test its functionality. This is mainly due to the use of a single air inlet for three distinct ejector pins, resulting in three different air paths. This could lead to a delay in the activation of the ejectors.

The system is composed by different components. The main components are the ejector pins, as the system revolves around advancing and retracting them. This motion is due to the actuation of compressed air. The air is fed to cavity where the pins are through two different channels. The system includes an o-ring placed on the ejector pin to separate the two entrances. Thus, once the top entrance actuates, the pins retract, and when the the bottom entrance actuates, the pins advance. This is why the sealing of these environments is so important, because any leak would cause a failure in the system. This layout for each pin is illustrated in Figure 30.

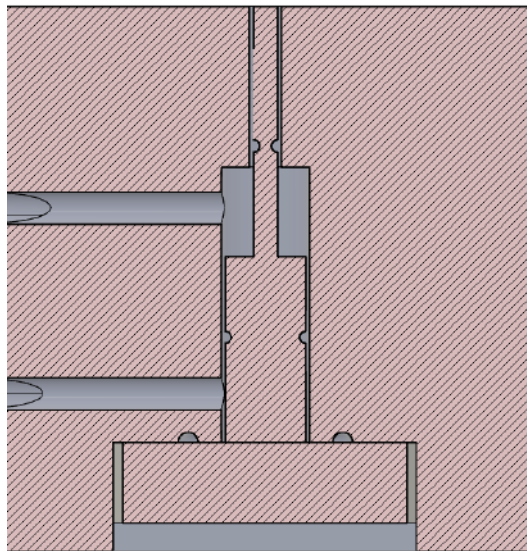


**Figure 30:** Ejector pin and its air channels

This non-conventional extraction system is represented with specific clearance in relation to the cavity where it is placed. However it must have very tight tolerances, specially in the top part of the pin, as it will be in direct contact with the moulding cavity. Additionally, the system has some more components to make it functional, such as the previously mentioned o-rings, or the cover for each of the systems. The

cavity in the mould tool itself is also a very important. A representation of this system is shown in Figure 31. This model can be used later to produce a prototype and test the extraction force that the system will produce.

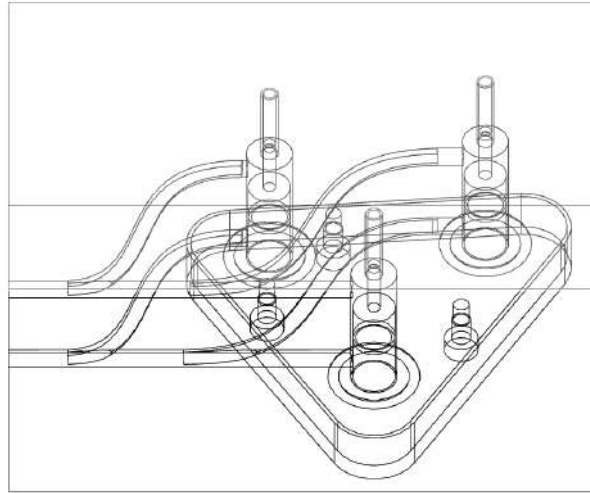


**Figure 31:** Extraction system

## 4.4 Moulding tool adjustments

To adapt the obtained model into a functional moulding tool, certain modifications were still required. Firstly the part's cavity needed to be added to both moulding halves. The geometry seems to be simple, however there are some details that need to be noted when splitting the mould halves. Simply splitting the cavity through the parting line did not return the correct geometry to add to the current model. This happened because the geometry has some protrusions that go above the parting line. These geometries must be represented in the right half of the mould in order to guarantee a correct moulding cavity. The mentioned protrusions are shown in Figure 32.

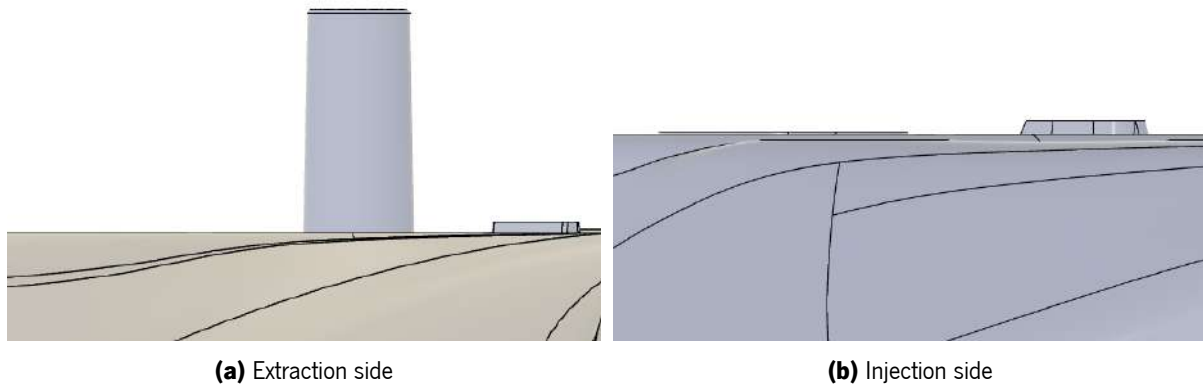


**Figure 32:** Protrusions that go above the parting line

Afterwards, the extraction system also needed to be included in the extraction side of the moulding tool. For the implementation of this system, the moulding tool needed some cavities for its components. Each injection will have associated three extractor pins, and each of these pins will have two air channels associated to them. Additionally, a structure was needed that serves as a cover for each of the systems. As it works with compressed air, there must be a tight seal around the systems. This also means that while implementing this to the model, it must account for the use of O-rings that guarantee this seal. The result of implementing these changes in the model is illustrated in Figure 33.

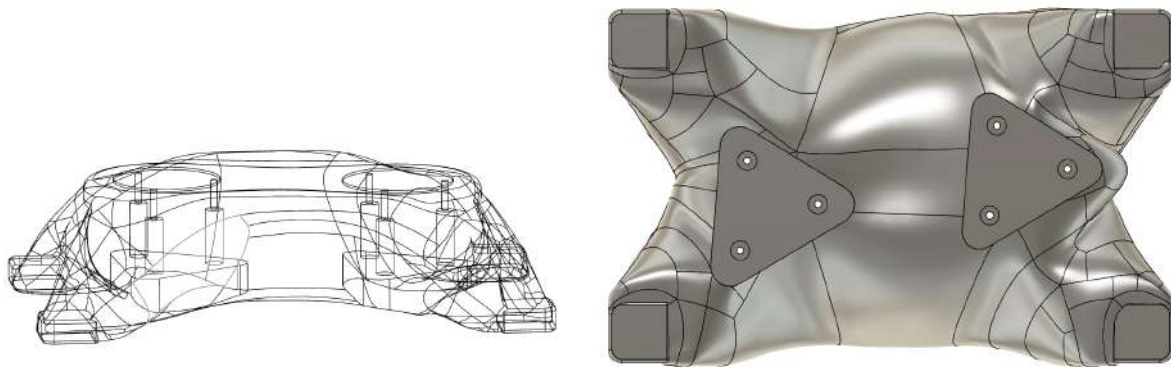


**Figure 33:** Model modifications in order to implement the Extraction system

An adjustment that also needed to be made was to make sure the GD did not allocate mass over the parting line and under the line where the bases meet the machine plate. This was actually the case, where it can be noted that Fusion 360's GD will sometimes overrule the parameters given to it and allocate mass where it should not. This was already observed in some results, where it had the part geometry as an obstacle geometry, but even then, there would be mass in that area. That being the case, those surpassing

areas should be trimmed. However, there were some zones that needed to be adjusted and not trimmed. This can be done by adjusting the T-spline, that is the structure that Fusion 360 used to represent the GD resulting geometry. This zones in particular were near the bases, where it would overlap the base line in every result obtained. An example of these modifications is shown in Figure 34.



**(a)** Before adjustments



**(b)** After adjustments

**Figure 34:** Trimming and adjusting done to the surpassing areas

The final adjustments performed in the model were the implementation of the interface between inlets and outlets, of either water (Cooling system) or air (Extraction system). Initially this was planned to be a machined area to obtain the planar area where the raccords would be placed. However, after some thought, a more interesting solution was chosen. This solution not only took advantage of using AM, but also reduced the need of using CNC machining. This solution was to make a cylindrical protrusion for each inlet or outlet (Figure 35). In this way, the only areas requiring CNC adjustments would be the threads for the raccords. The solution was considered not only an improvement fabrication wise, but also produced a more pleasant aesthetic.

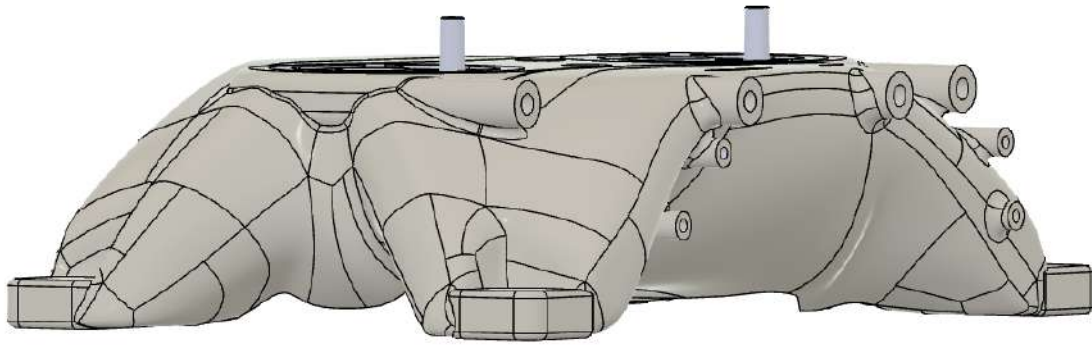


**Figure 35:** Addition of the interfaces between moulding tool and inlets/outlets

Another implementation to the model was the interlocks. The purpose of these structures is to guarantee the correct alignment of the moulding halves. Each half of the mould has an interlock, with the corresponding negative on the other half. The interlocks can have different geometries, but the main objective that all share is to come in contact with the other interlock before any of the moulding cavity structures. This way not only the alignment of the mould is guaranteed but also prevents any damage to the moulding cavity.

For this mould, the geometry chosen was a conical protrusion, taking advantage of the fabrication through AM to make a simple structure that fulfills its objective. Figure 36 shows these structures and their interface.

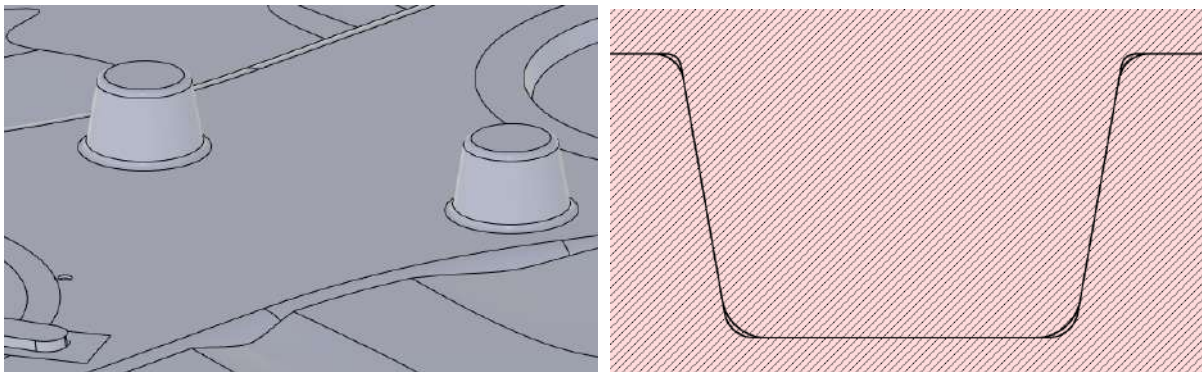


**Figure 36:** Interlocks display and interface

## 4.5 Structural Simulations

As the model obtained from the GD was modified, it was important to validate them through structural simulations. Fusion 360's GD tool details some performance values utilizing the loads that are used in the

input. These values can be used as a baseline, to compare them with the values obtained through these final simulations. During the GD process, some of the results were also tested with structural simulations. The aim of the tests was to actually validate the values that the GD tool would output. Through them it was validated that the values from Fusion 360 can be trusted and are very close to the values obtained in the simulations.

The tool used to run these simulations was Ansys software. The inputs given to the software were very similar to the GD inputs. The bases were constrained, and the injection pressure and clamping force were represented in the moulding cavity and parting surface, respectively. This software can obtain different results, but the ones that were considered crucial for this study were the total deformation, equivalent stress and equivalent elastic strain. The results obtained are demonstrated in Figure 37.

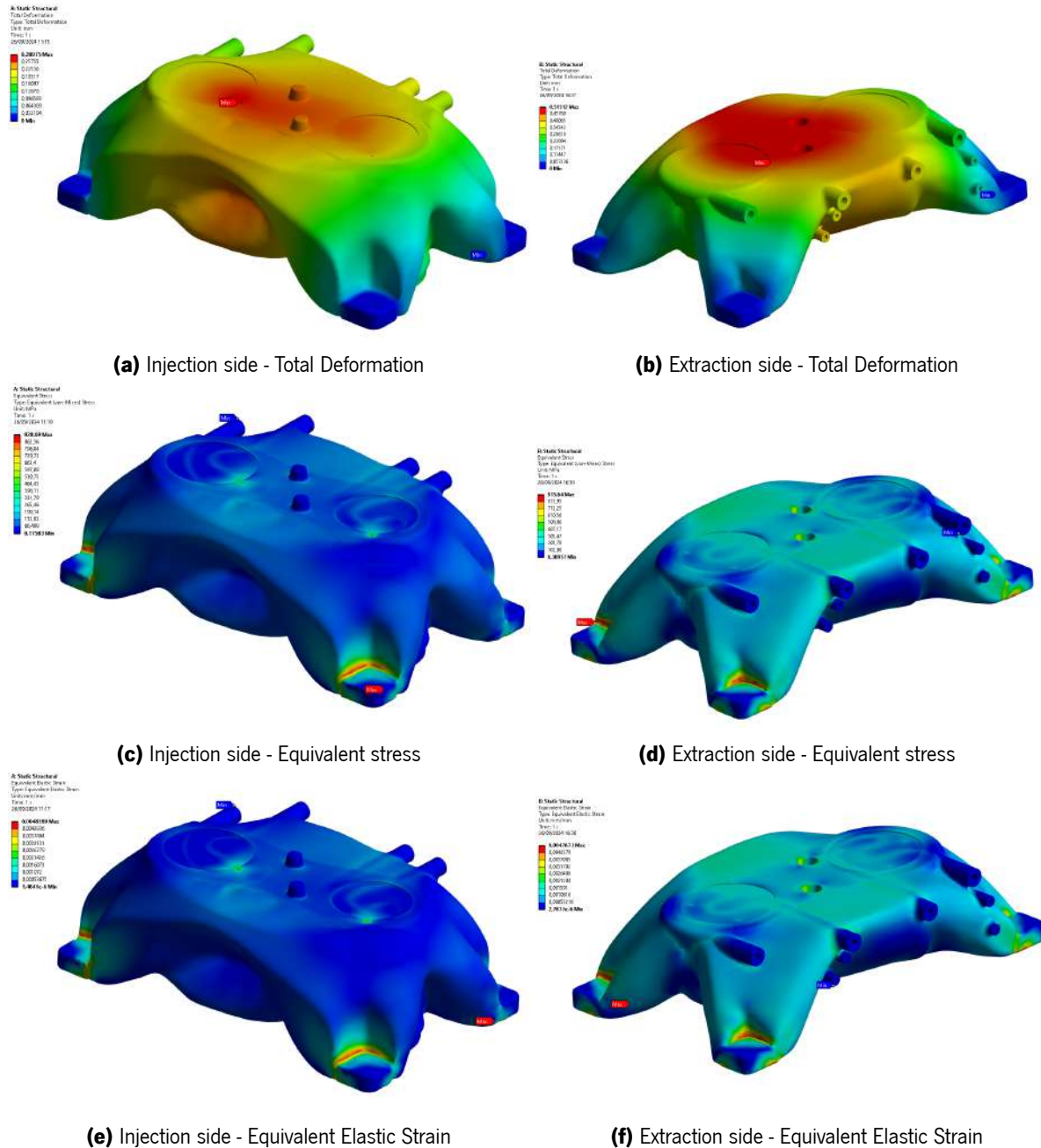


**Figure 37:** Results of the structural simulations (Ansys)

It is worth noting that the geometry of the part is not added to this model as it makes the model more complex. The part having an intricate geometry posed a problem for the meshing. Additionally, there was a problem that could not be solved and was an obstacle for the results wanted. The interface between generated geometries and preserve geometries was not smooth enough and the software could not solve the mesh properly in that zone. This resulted in higher values of stress in this area which adds a big spike in the total scale of the result.

However, there were some conclusions to be drawn from the analysis of the results. Firstly, the values for the maximum stress through the whole body do not surpass the limit of the material (1500 MPa).

However, the values are very distant from this limit, which shows that the GD output was overdimensioned and the mass could still be optimized. However, as the GD was overloaded with inputs, its level of freedom was limited.

Comparing these values with the ones obtained through the GD results, becomes clear that the modifications done to the model did not affect much the mechanical properties. For the injection side, Fusion 360 calculated a maximum stress of 506.67 MPa and a maximum displacement of 0.23 mm and for the extraction side a maximum stress of 506.67 MPa and a maximum displacement of 0.27 mm. The results obtained in the structural simulations are very close to these values. In the maximum stress values, it must be taken into account that the maximum value is so high due to the interface of the bases with the generated geometries. If those values are not taken into consideration its notable that the maximum stress is very similar to the one Fusion 360 established. However the value of the maximum displacement in the extraction side almost doubled the Fusion 360's value. This was due to the addition of the extraction system, which takes up a large volume.

The values of deformation on both sides are very high, being that this value should have a maximum value between 0.1 and 0.2 mm for most polymers (Neto, 2001). The values obtained surpass this limit by a considerable amount, which is an alarming result. As the tool developed is not a conventional moulding tool it was expected that these values would be higher. This result established the need for some reiterations of the design, trying to bring the values of a deformation closer to 0.1 mm.

## **4.6 Prototyping**

As the model developed achieved all the objectives that were set, the next stage of the work was to test this design. For this, a prototype could be fabricated, with the objective of validating the geometry. As it was a prototype, it was chosen to build it with materials and methods that had a lower cost. The method used to prototype this model was SLS, and the equipment was the EOS P 396. This machine has a build plate of 340x340 mm, and can print up to a height of 600 mm. This allowed for the fabrication of both mould halves simultaneously. The material used to build the prototype was PA2200, which is a material with a large use in AM, particularly in SLS. It is known for its low price and good mechanical properties. The result of this fabrication is shown in Figure 38. All of the components of the tool were also produced along with the moulding halves, such as the extractor pins, the cover for the extraction system and the centering rings, as well as an representation of the parts.



**Figure 38:** Prototype of the moulding tool

The prototyping of the moulding tool allowed for a much better visual analysis of the developed model. With a tangible object the dimensions and geometries become clearer. By inspecting this prototype some conclusions were drawn. The first one was a detail that was overlooked, which was the height of the interlocks. This had to be higher than the height of the protrusions in the moulding cavity. However it was concluded by analyzing the prototype that this was not the case, and so it had to be modified. Additionally, it was also concluded that the distance between the two interlocks could be widened to optimize their function. From this analysis it was also concluded that the moulding tool had higher dimensions than expected. This added to some of the values obtained in the mechanical simulations led to the possibility of the mould being overdimensioned and that was still some mass that could be optimized.

This possibility established the need to conduct future studies to understand if the mass of the moulding tool could be optimized. This study can explore some mass optimization techniques like TO and lattice structures to further enhance the design of the moulding tool. However, GD must not be overturned by the use of this techniques as it is the main technique for the design of this moulding tool.

## Chapter 5

### The moulding tool

After almost 180 iterations using the GD tool, a final model was developed. This final model (Figure 39) is not only the result of all these iterations but also the modifications applied to it. After the mechanical simulations and the prototyping of the model some conclusions were drawn. Firstly the mould appeared to have too much mass allocated that did not feel needed. This was corroborated by the simulations from which it could be stated that the stress it would sustain would be far from critical values. However the values of deformation did diverge from this, as it had values higher than the maximum value of deformation for injection moulds. To solve this issue, some other iterations of the GD process were applied, where the input of the clamping force was raised, from 50 to 70 tons. Simulations were done to this new model, but with the normal 50 tons clamping force. However the values of deformation did not change. This should not be the case, as the new model had more mass and should withstand the same force with less total deformation.

After this unexpected result, the decision was to maintain the model as it was. This is only a first model for a concept with no previous examples or bases. To draw conclusions on its functionality, it will be necessary to fabricate it through AM with metal material and try to inject the parts.

The only modification done to the model after the prototyping and simulations phase, was to change the interlocks. They were very near to each other, which is not optimal for their functionality. Additionally, their height was not higher than the protrusions of the moulding cavity. This meant that when the mould was closing there could be deformations in the moulding cavity. To eliminate this issues the position and dimensions of the interlocks were modified.



**Figure 39:** Final model of the moulding tool

The final model presented is the result of months of work, several iterations and going back and forth in the phases of the project. Various times, during the GD process, small mistakes that went unnoticed, were then found, which sent the work back a few steps. This was part of the process, and inevitably it helped to reach the desired objective of designing a mould through GD. The model developed shows great potential, and even though it is far from being perfect and from being a competitor with conventional moulds, it surely proves that it is possible to design one at that level.

This work not only demonstrated that using GD to develop a moulding tool is feasible, but also established several essential practices for its development. Firstly it became clear early in the work that utilizing a simple approach would be the best option. The amount of inputs that would be introduced in the software could easily reach really high numbers. Even though a complex group of inputs can generate

very interesting results, most of the times it will translate in the software not being able to compute the solution. This was a relative simple case study, where there were not many components that needed to be included. However, a mould can have a very high complexity, and to implement it on the GD tool can be very difficult. If the complexity of the work gets too demanding, it is better to use the GD as a base form generator, and then applying the modifications needed. This however, will not be taken into account by the software, which can be answered by validating through simulations after the modifications or by raising the security factor in the software.

In the early stages of the work, the belief was that the software should have the most amount of freedom possible. After reaching this final model, it is secure to conclude that it will not be the output in most cases. In order to get the desired outcomes, it is necessary to implement a lot of inputs, which inevitably will decrease the amount of freedom to generate geometries. However this is the nature of the parametric design, which as said previously, works with the constraints applied that will control how the different components will interact.

Even after all the work and iterations done, the understanding over the matter is far from reaching its peak. It is very important to continue the research in order to establish the best outcomes that can be extracted from the GD tool. This work sets the base line for a type of moulding tools that can revolutionize the moulding industry.

## **Chapter 6**

# **Conclusions and future work**

### **6.1 Conclusions**

This dissertation set out to explore the application of GD in the fabrication of non-conventional mould tools through AM. The IM industry faces increasing demands for complex geometries, optimized cooling systems, and higher production efficiency, which traditional methods often struggle to meet. Through the development and testing of a mould tool created via GD, this work has demonstrated the significant potential of combining this innovative approach with AM techniques.

The GD process enabled the creation of highly optimized mould geometries, particularly the integration of CCC, which can enhance the cooling efficiency. The ability to incorporate complex, organic shapes that are impossible to achieve through conventional design methods proved to be a major advantage of this approach. AM further supported this by enabling the fabrication of these intricate structures, showing that it can be a viable alternative to traditional mould-making techniques, especially for producing lightweight and performance-optimized mould tools.

Several key findings emerged from this study. First, GD provides a powerful tool for optimizing material usage and enhancing mould performance. The ability to iteratively refine the mould geometry based on simulation and structural testing resulted in a final design that not only reduced material waste but also improved the overall durability and functionality of the mould. Second, the integration of CCC using AM technology allowed for more effective heat dissipation, leading to faster cooling times and fewer defects in the moulded parts. This highlights the potential for significant improvements in production efficiency and quality control in the IM industry.

Despite these successes, challenges remain in fully realizing the potential of GD and AM in industrial mould making. The iterative nature of the GD process requires careful management to balance the complexity of designs with practical manufacturing constraints. Additionally, the cost and scalability of AM for large-scale mould production continue to be factors that must be addressed in future research.

In conclusion, this work has successfully demonstrated the feasibility and benefits of using GD and AM to develop non-conventional mould tools. The results show a clear path forward for improving the efficiency, sustainability, and performance of IM processes.

## **6.2 Prospect for future work**

This work represents the first steps towards a very promising outcome, although further efforts are needed to fully realise it. As this type of moulding tool was developed from the ground up, it will need a lot of testing and iterations. One of the most crucial tests planned is to prototype the extraction system. By having a tangible model of the system developed, experiments can be done with different weights and delimit the force generated by the system. This is a simple system, however the tolerances are very important to make it work properly. To guarantee the proper dimensions, the final production that will be produced through AM will need to be overdimensioned, so that afterwards it can be machined through CNC. Also, the planing and dimensioning done around the o-rings play a critical role in making the system work properly. By guaranteeing this details, the system will work as intended and the experiments can be conducted.

The aim of the work that is planned is to obtain a solution that works viably. A lot of iterations will be done until reaching such a solution. Initially the model that was obtained will be produced in steel so that it can be used and tested. The aim of these tests is not only to verify the part quality but also to monitor the moulding tool performance. The monitor will be via extensometers to obtain the values of local deformation, and a sensor that measures pressure and temperature in the cavity of the first injection. These values in addition to the part quality will set the level of performance delivered by the moulding tool. If this level is too low, adjustments will need to be done.

One of the first approaches that can be applied to the model is by utilizing TO and structural lattices combined. This approach appeared during a test where TO was applied to the solution obtained through GD. Although the TO removed a substantial amount of mass, most of it occurred in critical areas where mass could not be removed for the moulding tool to work. The solution found to work around this issue was to apply lattice structures where the TO removed mass in non critical areas. This would not only remove weight but could also help improving the moulding tool's mechanical properties.

The project will only be concluded once a solution is developed, tested and validated. To produce a final model, as well as any model that might be tested, the same overdimensioning used to produce the extraction system prototype, will need to be applied. A moulding tool has a very intricate model, and a lot

of its dimensions are very strict and need tight tolerances. The combine use of AM and CNC will be very crucial during the whole project. The work is clearly promising and can lead to very good results.

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# Appendix A

## Material Datasheets

Uddeholm Corrax

### GENERAL

Compared with conventional corrosion resistant tool steel, Uddeholm Corrax has the following advantages:

- Flexible hardness, 34–50 HRC, achieved by an ageing treatment in the temperature range 425–600°C (790–1110°F)
- Extremely good dimensional stability during the ageing
- High uniformity of properties also for large dimensions
- Very good weldability, no preheating necessary
- No hard "white" layer after EDM
- Corrosion resistance superior to that of AISI 420 and W.-Nr. 1.2083

| Typical analysis % | C                           | Si  | Mn  | Cr   | Ni  | Mo  | Al  |
|--------------------|-----------------------------|-----|-----|------|-----|-----|-----|
|                    | 0.03                        | 0.3 | 0.3 | 12.0 | 9.2 | 1.4 | 1.6 |
| Delivery condition | Solution treated to ~34 HRC |     |     |      |     |     |     |
| Colour code        | Black/grey                  |     |     |      |     |     |     |

### APPLICATIONS

- Injection moulds for
  - corrosive plastics
  - rubber
  - medical and food industry
- Extrusion dies
- Plastic processing
  - screws
- Engineering parts



### PROPERTIES

#### PHYSICAL DATA

Aged to approx. 46 HRC.

| Temperature                                                              | 20°C<br>(68°F)                  | 200°C<br>(390°F)                                  | 400°C<br>(750°F)                                  |
|--------------------------------------------------------------------------|---------------------------------|---------------------------------------------------|---------------------------------------------------|
| Density<br>kg/m <sup>3</sup><br>lbs/in <sup>3</sup>                      | 7 700<br>0.28                   | –<br>–                                            | –<br>–                                            |
| Modulus of elasticity<br>N/mm <sup>2</sup><br>psi                        | 200 000<br>29 x 10 <sup>6</sup> | 190 000<br>28 x 10 <sup>6</sup>                   | 170 000<br>25 x 10 <sup>6</sup>                   |
| Coefficient of thermal expansion<br>per °C from 20°C<br>per °F from 68°F | –<br>–                          | 11.7 x 10 <sup>-6</sup><br>6.5 x 10 <sup>-6</sup> | 12.3 x 10 <sup>-6</sup><br>6.8 x 10 <sup>-6</sup> |
| Thermal conductivity<br>W/m °C<br>Btu in/ft <sup>2</sup> h °F            | –<br>–                          | 18<br>125                                         | 21<br>146                                         |

#### MECHANICAL DATA

Tensile strength at room temperature.

|                                                                | Solution treated<br>~34 HRC | Aged to<br>~40 HRC | Aged to<br>~46 HRC | Aged to<br>~50 HRC |
|----------------------------------------------------------------|-----------------------------|--------------------|--------------------|--------------------|
| Yield strength<br>R <sub>0.2</sub><br>N/mm <sup>2</sup><br>psi | 700<br>100 000              | 1 000<br>150 000   | 1 400<br>200 000   | 1 600<br>230 000   |
| Tensile strength<br>R <sub>m</sub><br>N/mm <sup>2</sup><br>psi | 1 100<br>160 000            | 1 200<br>170 000   | 1 500<br>220 000   | 1 700<br>250 000   |
| Elongation<br>A <sub>5</sub> %                                 | 15                          | 15                 | 11                 | 10                 |

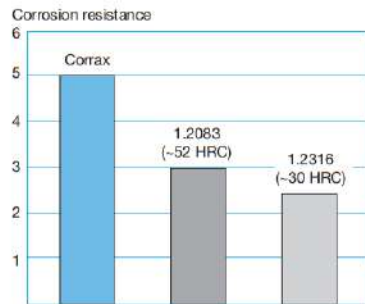
Compressive strength at room temperature.

|                                               | Solution treated<br>~34 HRC | Aged to<br>~40 HRC | Aged to<br>~46 HRC | Aged to<br>~50 HRC |
|-----------------------------------------------|-----------------------------|--------------------|--------------------|--------------------|
| R <sub>p0.2</sub><br>N/mm <sup>2</sup><br>psi | 900<br>130 000              | 1 300<br>190 000   | 1 600<br>230 000   | 1800<br>260 000    |

Production of PVC tubes or fittings places very high demands on the corrosion resistance of the mould. Uddeholm Corrax is a suitable mould steel for this application.

## CORROSION RESISTANCE

Uddeholm Corrax has a very good corrosion resistance, better than the corrosion resistant standard grades used for plastic moulding. The corrosion resistance is the same in all heat treated conditions (except after nitriding).



Uddeholm Corrax will withstand attacks from most corrosive plastics and diluted acids.

A mould made of Uddeholm Corrax will also have good resistance to humid working and storage conditions. Uddeholm Corrax also shows better resistance to stress corrosion cracking than standard hardenable corrosion resistant steel grades.

## HEAT TREATMENT

Uddeholm Corrax is delivered in solution treated condition and can be used in the as-delivered condition. When, however, the steel is to be heat treated to a higher hardness, the following instructions may be helpful.

### STRESS RELIEVING

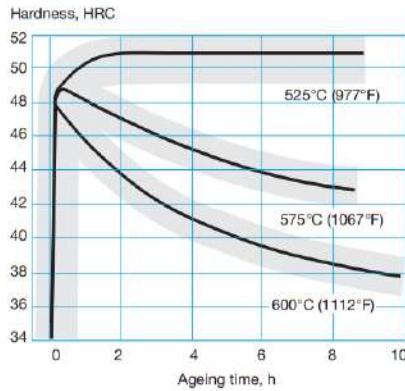
Stress relieving can not be performed as for other steel grades since an increase in temperature results in a higher hardness because of ageing effect.

### AGEING

Uddeholm Corrax can be used in as-delivered condition.

Higher hardness is obtained by ageing. Suitable ageing parameters can be obtained from the

figure below. Ageing time means the time at the ageing temperature after the tool is fully heated through.



When the ageing time is reached, cool the tool in air to room temperature. Ageing at high temperature gives a better toughness compared with ageing to the same hardness at a lower temperature.

### AGEING RECOMMENDATION

| Ageing temperature/time | Hardness  |
|-------------------------|-----------|
| 525°C/4 h (977°F/4 h)*  | 49–52 HRC |
| 575°C/4 h (1067°F/4 h)  | 44–47 HRC |
| 600°C/4 h (1112°F/4 h)  | 40–43 HRC |

\* Ageing 49–52 HRC is only recommended when toughness is not important

If Uddeholm Corrax is used at temperatures higher than 200°C (390°F) the solution treated condition (delivery condition) is not recommended because ageing can occur during use.

### SOLUTION TREATMENT

It is possible to solution treat Uddeholm Corrax, if aged, in order to get back to the delivery condition.

Solution treatment should be done at 850°C (1560°F), holding time 30 minutes. Cool in air.

## DIMENSIONAL CHANGE

Ageing results in a small and uniform decrease in volume. The following shrinkage can be expected during ageing.

| Ageing                            | Dimensional change %   |                       |                             |
|-----------------------------------|------------------------|-----------------------|-----------------------------|
|                                   | Longitudinal direction | Transversal direction | Short transversal direction |
| 525°C/4 h (977°F/4 h)<br>~50 HRC  | -0.07                  | -0.07                 | -0.07                       |
| 575°C/4 h (1067°F/4 h)<br>~46 HRC | -0.09                  | -0.09                 | -0.09                       |
| 600°C/4h (1112°F/4h)<br>~40 HRC   | -0.14                  | -0.14                 | -0.14                       |

## CUTTING DATA RECOMMENDATIONS

The cutting data below are to be considered as guiding values which must be adapted to existing local conditions. More information can be found in the Uddeholm publication "Cutting data recommendations".

*The recommendations, in the following tables, are valid for Uddeholm Corrax in solution treated condition approx. 34 HRC.*

## TURNING

| Cutting data parameters                    | Turning with carbide      |                                 | Turning with high speed steel |
|--------------------------------------------|---------------------------|---------------------------------|-------------------------------|
|                                            | Rough turning             | Fine turning                    | Fine turning                  |
| Cutting speed ( $v_c$ )<br>m/min<br>f.p.m. | 110-160<br>360-525        | 160-210<br>525-690              | 13-18<br>43-59                |
| Feed ( $f$ )<br>mm/rev<br>i.p.r.           | 0.2-0.4<br>0.008-0.016    | 0.05-0.2<br>0.002-0.008         | 0.05-0.2<br>0.002-0.008       |
| Depth of cut ( $a_p$ )<br>mm<br>inch       | 2-4<br>0.08-0.16          | 0.5-2<br>0.02-0.08              | 0.5-3<br>0.02-0.12            |
| Carbide designation ISO                    | P20-P40<br>Coated carbide | P10<br>Coated carbide or cermet | -                             |

## MILLING

### FACE- AND SQUARE SHOULDER MILLING

| Cutting data parameters                    | Milling with carbide      |                                     |
|--------------------------------------------|---------------------------|-------------------------------------|
|                                            | Rough milling             | Fine milling                        |
| Cutting speed ( $v_c$ )<br>m/min<br>f.p.m. | 70-90<br>230-295          | 90-110<br>295-360                   |
| Feed ( $f$ )<br>mm/tooth<br>inch/tooth     | 0.2-0.4<br>0.008-0.016    | 0.1-0.2<br>0.004-0.008              |
| Depth of cut ( $a_p$ )<br>mm<br>inch       | 2-5<br>0.08-0.20          | -2<br>-0.08                         |
| Carbide designation ISO                    | P20-P40<br>Coated carbide | P10-P20<br>Coated carbide or cermet |

### END MILLING

| Cutting data parameters                    | Type of milling                                        |                                                      |                                                       |
|--------------------------------------------|--------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------|
|                                            | Solid carbide                                          | Carbide indexable insert                             | High speed steel                                      |
| Cutting speed ( $v_c$ )<br>m/min<br>f.p.m. | 60-100<br>200-328                                      | 70-110<br>230-360                                    | 20-25 <sup>1)</sup><br>66-82 <sup>1)</sup>            |
| Feed ( $f$ )<br>mm/tooth<br>inch/tooth     | 0.006-0.20 <sup>2)</sup><br>0.0002-0.008 <sup>2)</sup> | 0.06-0.20 <sup>2)</sup><br>0.002-0.008 <sup>2)</sup> | 0.01-0.35 <sup>2)</sup><br>0.0004-0.014 <sup>2)</sup> |
| Carbide designation ISO                    | -                                                      | P20-P30                                              | -                                                     |

<sup>1)</sup> For coated HSS end mill  $v_c = 35-45$  m/min. (115-148 f.p.m.)

<sup>2)</sup> Depending on radial depth of cut and cutter diameter



*Uddeholm Corrax is used as a core material in the mould for production of this garden saw handle.*

## DRILLING

### HIGH SPEED STEEL TWIST DRILL

| Drill diameter |          | Cutting speed (v <sub>c</sub> ) |        | Feed (f)  |             |
|----------------|----------|---------------------------------|--------|-----------|-------------|
| mm             | inch     | m/min                           | f.p.m. | mm/rev    | i.p.r.      |
| – 5            | – 3/16   | 13–15*                          | 43–49* | 0.05–0.10 | 0.002–0.004 |
| 5–10           | 3/16–3/8 | 13–15*                          | 43–49* | 0.10–0.20 | 0.004–0.008 |
| 10–15          | 3/8–5/8  | 13–15*                          | 43–49* | 0.20–0.25 | 0.008–0.010 |
| 15–20          | 5/8–3/4  | 13–15*                          | 43–49* | 0.25–0.30 | 0.010–0.012 |

\* The same cutting speed when using coated HSS drill  
v<sub>c</sub> = 13–15 m/min. (43–49 f.p.m.)

### CARBIDE DRILL

| Cutting data parameters                            | Type of drill                                        |                                                     |                                                     |
|----------------------------------------------------|------------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
|                                                    | Indexable insert                                     | Solid carbide                                       | Carbide tip <sup>1)</sup>                           |
| Cutting speed (v <sub>c</sub> )<br>m/min<br>f.p.m. | 180–200<br>590–656                                   | 100–130<br>328–427                                  | 50–70<br>164–230                                    |
| Feed (f)<br>mm/rev<br>i.p.r.                       | 0.05–0.15 <sup>2)</sup><br>0.002–0.006 <sup>2)</sup> | 0.10–0.25 <sup>2)</sup><br>0.004–0.01 <sup>2)</sup> | 0.15–0.25 <sup>2)</sup><br>0.006–0.01 <sup>2)</sup> |

<sup>1)</sup> Drill with replaceable or brazed carbide tip

<sup>2)</sup> Depending on drill diameter

## GRINDING

A general grinding wheel recommendation is given below. More information can be found in the Uddeholm publication "Grinding of Tool Steel".

| Type of grinding             | Delivery condition and aged condition |
|------------------------------|---------------------------------------|
| Face grinding straight wheel | A 46 GV                               |
| Face grinding segments       | A 36 FV                               |
| Cylindrical grinding         | A 60 JV                               |
| Internal grinding            | A 60 IV                               |
| Profile grinding             | A 120 JV                              |

When good surface finish is required a SiC-wheel could be an alternative.

## PHOTO-ETCHING

Uddeholm Corrax has a very good corrosion resistance and a special process is thus required for chemical photo-etching. Fine patterns with shallow depths <0.04 mm (0.002") are readily achievable.

## EDM

Uddeholm Corrax can be EDM'd in the same way as ordinary tool steels. The "white layer" will, however, not be as hard and is therefore more easily removed.

## WELDING

Preheating is not necessary. When welding on Uddeholm Corrax in delivery condition, intermittent welding is recommended.

In order to obtain an even hardness, it is necessary to carry out a heat treatment after welding. The temperature and time are determined by the required hardness and the filler material. Corrax TIG-Weld is recommended to be used as filler material.

For further information, please contact your local Uddeholm office.

## PROPERTY COMPARISON CHART

| Uddeholm steel grade | Hardness HRC | Wear resistance | Corrosion resistance |
|----------------------|--------------|-----------------|----------------------|
| Corrax               | 34           |                 |                      |
| Corrax               | 50           |                 |                      |
| Mirrax ESR           | 50           |                 |                      |
| Stavax ESR           | 52           |                 |                      |
| Elmax                | 56           |                 |                      |
| Ramax HH             | 37           |                 |                      |
| Impax Supreme        | 32           |                 |                      |

## FURTHER INFORMATION

Please, contact your local Uddeholm office for further information on the selection, heat treatment, application and availability of Uddeholm tool steels.

# CAMPUS® Datasheet

Grilamid TR 55 natural - PA12/MACMI  
EMS-GRIVORY | a unit of EMS-CHEMIE AG



## Product Texts

Product-nomenclature: ISO 16396-PA12/MACMI,,GT,C11-020

Co Polyamide

Transparent Polyamide

## Product Attributes

Highly transparent

## Markets

**Automotive**  
Automotive electr. and electronics, lighting, Cooling and climate control, Fuel systems, Powertrain and Chassis, Interior  
**Electricals & Electronics**  
Electrical appliances, Electrical equipment, Cables & Tubes, Energy distribution, Mobile phones and other portable devices, Lighting  
**Industry & Consumer goods**  
Heating systems, Housewares, Hydraulics & Pneumatics, Mechanical Engineering, Medical devices, Power transmission, Sanitary, water and gas supply, Sports & Leisure, Tools & Accessories  
**Optics**  
Lenses, Optical components  
**Packaging**  
Non oriented film, Cosmetics / Personal care, Medical packaging

## Approvals

**Burning Behaviour**  
UL V2  
**Food Contact**  
EU Requirements, FDA  
**Medical**  
USP VI, ISO 10993  
**Potable Water Contact**  
NSF 61, KTW, WRAS, DVGW W270

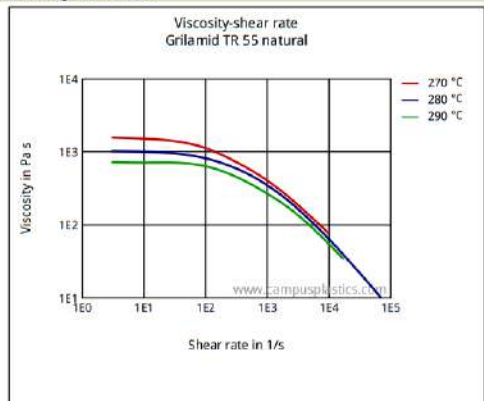
| Rheological properties                 | dry / cond  | Unit              | Test Standard   |
|----------------------------------------|-------------|-------------------|-----------------|
| Molding shrinkage, parallel            | 0.6 / *     | %                 | ISO 294-4, 2577 |
| Molding shrinkage, normal              | 0.7 / *     | %                 | ISO 294-4, 2577 |
| Mechanical properties                  | dry / cond  | Unit              | Test Standard   |
| Tensile modulus                        | 2300 / 2200 | MPa               | ISO 527-1/-2    |
| Yield stress                           | 80 / 75     | MPa               | ISO 527-1/-2    |
| Yield strain                           | 7 / 9       | %                 | ISO 527-1/-2    |
| Nominal strain at break                | >50 / >50   | %                 | ISO 527-1/-2    |
| Charpy impact strength, +23°C          | N / N       | kJ/m <sup>2</sup> | ISO 179/1eU     |
| Charpy impact strength, -30°C          | N / N       | kJ/m <sup>2</sup> | ISO 179/1eU     |
| Charpy notched impact strength, +23°C  | 8 / 8       | kJ/m <sup>2</sup> | ISO 179/1eA     |
| Charpy notched impact strength, -30°C  | 7 / 7       | kJ/m <sup>2</sup> | ISO 179/1eA     |
| Shore D hardness                       | - / 85      | -                 | ISO 48-4        |
| Thermal properties                     | dry / cond  | Unit              | Test Standard   |
| Glass transition temperature, 10°C/min | 160 / *     | °C                | ISO 11357-1/-2  |

**Grilamid TR 55 natural - PA12/MACMI**  
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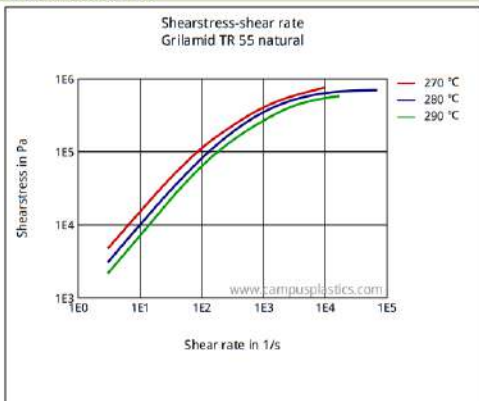
|                                             |             |       |                 |
|---------------------------------------------|-------------|-------|-----------------|
| Temp. of deflection under load, 1.80 MPa    | 130 / *     | °C    | ISO 75-1/-2     |
| Temp. of deflection under load, 0.45 MPa    | 145 / *     | °C    | ISO 75-1/-2     |
| Vicat softening temperature, 50°C/h 50N     | 135 / *     | °C    | ISO 306         |
| Coeff. of linear therm. expansion, parallel | 80 / *      | E-6/K | ISO 11359-1/-2  |
| Coeff. of linear therm. expansion, normal   | 80 / *      | E-6/K | ISO 11359-1/-2  |
| Burning behavior at thickness h             | HB / *      | class | IEC 60695-11-10 |
| Thickness tested (h)                        | 0.8 / *     | mm    | IEC 60695-11-10 |
| <b>Electrical properties</b>                |             |       |                 |
|                                             | dry / cond  | Unit  | Test Standard   |
| Volume resistivity                          | 1E11 / 1E11 | Ohm*m | IEC 62631-3-1   |
| Surface resistivity                         | * / 1E12    | Ohm   | IEC 62631-3-2   |
| Electric strength                           | 31 / 31     | kV/mm | IEC 60243-1     |
| Comparative tracking index                  | - / 600     | -     | IEC 60112       |
| <b>Other properties</b>                     |             |       |                 |
|                                             | dry / cond  | Unit  | Test Standard   |
| Water absorption                            | 3.5 / *     | %     | Sim. to ISO 62  |
| Humidity absorption                         | 1.5 / *     | %     | Sim. to ISO 62  |
| Density                                     | 1060 / -    | kg/m³ | ISO 1183        |

**Diagrams**

**Viscosity-shear rate**

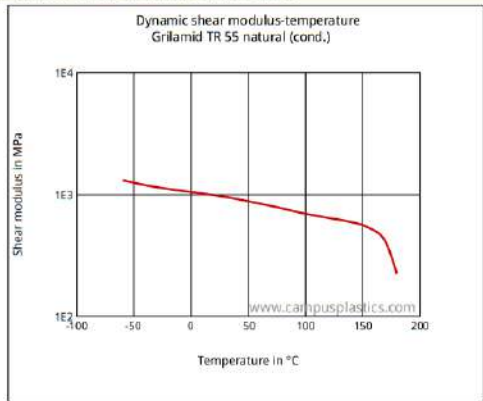


**Shearstress-shear rate**

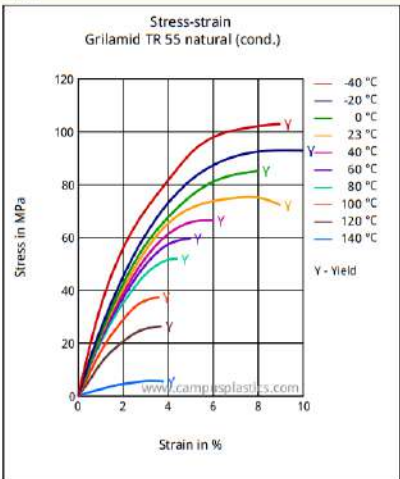


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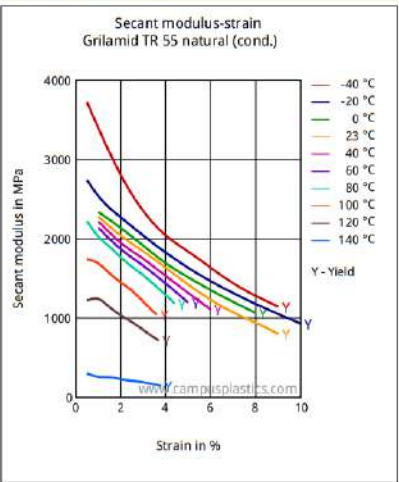
Dynamic shear modulus-temperature



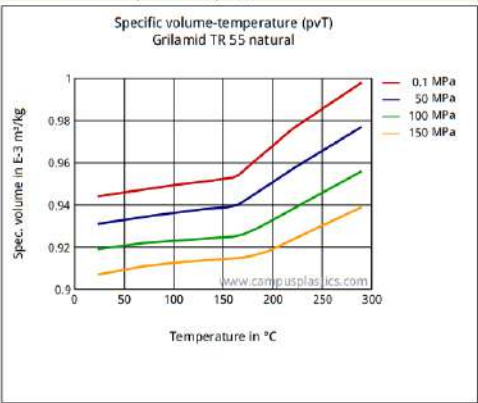
Stress-strain



Secant modulus-strain

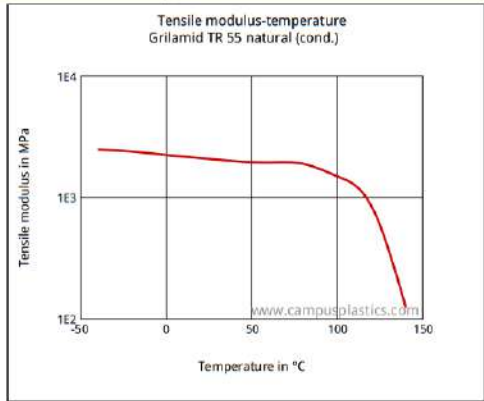


Specific volume-temperature (pvT)

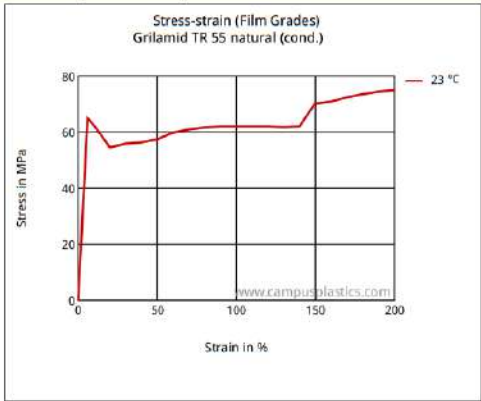


**Grilamid TR 55 natural - PA12/MACMI**  
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**Tensile modulus-temperature**



**Stress-strain (Film Grades)**



**Characteristics**

**Processing**

Injection Molding, Other Extrusion

**Delivery form**

Granules

**Special Characteristics**

Transparent

**Regional Availability**

North America, Europe, Asia Pacific, South and Central America, Near East/Africa

**Other text information**

**Film extrusion**

**PREPROCESSING**

Max. water content : <=0.08 %

**PROCESSING**

Melt temperature : 260-280 °C

Smooth or roughened feeding zone : 60-90 °C

Barrel temp. profile : 250-260 °C

Head temp. : 260-250 °C

Please consider the information about the application of the materials.

**Other extrusion**

-- PIPE EXTRUSION --

-- SHEETING --

**PROCESSING**

Melt temperature : 250-270 °C

Feeding bush : 60-90

Barrel temp. profile : 240-250 °C

Head temp. : 250-240 °C

Please consider the information about the application of the materials.

**Chemical Media Resistance**

**Acids**

😊 Acetic Acid (5% by mass) (23°C)

😊 Citric Acid solution (10% by mass) (23°C)

😊 Lactic Acid (10% by mass) (23°C)

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-  Hydrochloric Acid (36% by mass) (23°C)
-  Nitric Acid (40% by mass) (23°C)
-  Sulfuric Acid (38% by mass) (23°C)
-  Sulfuric Acid (5% by mass) (23°C)
-  Chromic Acid solution (40% by mass) (23°C)

**Bases**

-  Sodium Hydroxide solution (35% by mass) (23°C)
-  Sodium Hydroxide solution (1% by mass) (23°C)
-  Ammonium Hydroxide solution (10% by mass) (23°C)

**Alcohols**

-  Isopropyl alcohol (23°C)
-  Methanol (23°C)
-  Ethanol (23°C)

**Hydrocarbons**

-  n-Hexane (23°C)
-  Toluene (23°C)
-  iso-Octane (23°C)

**Ketones**

-  Acetone (23°C)

**Ethers**

-  Diethyl ether (23°C)

**Mineral oils**

-  SAE 10W40 multigrade motor oil (23°C)
-  SAE 10W40 multigrade motor oil (130°C)
-  SAE 80/90 hypoid-gear oil (130°C)
-  Insulating Oil (23°C)

**Standard Fuels**

-  ISO 1817 Liquid 1 (60°C)
-  ISO 1817 Liquid 2 (60°C)
-  ISO 1817 Liquid 3 (60°C)
-  ISO 1817 Liquid 4 (60°C)
-  Standard fuel without alcohol (pref. ISO 1817 Liquid C) (23°C)
-  Standard fuel with alcohol (pref. ISO 1817 Liquid 4) (23°C)
-  Diesel fuel (pref. ISO 1817 Liquid F) (23°C)
-  Diesel fuel (pref. ISO 1817 Liquid F) (90°C)
-  Diesel fuel (pref. ISO 1817 Liquid F) (>90°C)

**Salt solutions**

-  Sodium Chloride solution (10% by mass) (23°C)
-  Sodium Hypochlorite solution (10% by mass) (23°C)
-  Sodium Carbonate solution (20% by mass) (23°C)
-  Sodium Carbonate solution (2% by mass) (23°C)
-  Zinc Chloride solution (50% by mass) (23°C)

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**Other**

-  Ethyl Acetate (23°C)
-  Hydrogen peroxide (23°C)
-  DOT No. 4 Brake fluid (130°C)
-  Ethylene Glycol (50% by mass) in water (108°C)
-  1% nonylphenoxy-polyethyleneoxy ethanol in water (23°C)
-  50% Oleic acid + 50% Olive Oil (23°C)
-  Water (23°C)
-  Deionized water (90°C)
-  Phenol solution (5% by mass) (23°C)

EMS-CHEMIE AG Business Unit EMS-GRIVORY Homepage: [EMS-GRIVORY](https://www.ems-grivory.com)

eMail: [welcome@emsgrivory.com](mailto:welcome@emsgrivory.com) The values are intended to serve as an aid in preselecting materials and for an overview of the EMS-GRIVORY

product range. The information contained in this publication is based on our present knowledge and experience.

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