FEDERAL UNIVERSITY OF SANTA CATARINA
TECHNOLOGICAL CENTER OF JOINVILLE
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EDUARDO DE BITTENCOURT RIBEIRO

FEASIBILITY RESEARCH OF ADDITIVELY MANUFACTURED MOLD INSERTS FOR REPLICATIVE OPTICS PRODUCTION VIA INJECTION MOLDING AND PRECISION GLASS MOLDING

Aachen
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Bachelor Thesis submitted as a requirement for obtaining the bachelor's degree in the Naval Engineering Course at the Technological Center of Joinville of the Federal University of Santa Catarina.

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This Thesis was judged appropriate for obtaining the title of Bachelor in Naval Engineering, at the Federal University of Santa Catarina, Technological Center of Joinville.

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ABSTRACT

Optical parts such as lenses are the basic element of any optical system used in electronic, medical, military, and metrology devices, for example. These parts can be produced by injection molding (IM) and precision glass molding (PGM) processes, using molds and inserts to achieve the final shape of the product. In general, molds are complex tooling that require multiple machining and finishing steps, which to ensure optical functionality must have high levels of surface quality. In this context, additive manufacturing (AM) represents a promising solution to manufacture these tooling in less time and with less costs in some stages of the production chain. Therefore, this work investigates the feasibility of applying molds and inserts manufactured by AM to produce optical parts in IM and PGM processes. Using the information obtained by scientific papers, industrial case studies and qualitative survey with experts, the technologies and materials related to additive manufacturing were evaluated by selection criteria, determining Powder Fusion as the most suitable solution so far, as well as ranking the others. Next, a physical prototype was implemented and manufactured for testing and comparison of experimental and theoretical data on surface quality. Thus, it was concluded in first instance that it is possible to use additive manufacturing to fabricate molds and inserts for optical parts production.

Keywords: Optics. Molds. Glass molding. Injection molding. Additive manufacturing.

RESUMO

Partes ópticas como lentes constituem o elemento básico de qualquer sistema óptico utilizado em dispositivos eletrônicos, médicos, militares e metrológicos, por exemplo. Essas partes podem ser produzidas por processos de moldagem por injeção (IM) e moldagem de precisão de vidro (PGM), usando moldes e insertos para adquirir a forma final do produto. Em geral, moldes são ferramentais complexos que necessitam de múltiplas etapas de usinagem e acabamento, as quais para garantir a funcionalidade óptica devem possuir níveis de qualidade superficial altas. Nesse âmbito, a manufatura aditiva (AM) representa uma solução promissora para a fabricação destes ferramentais em menor tempo e com menos custos em alguns estágios da cadeia de produção. Por isso, o presente trabalho investiga a viabilidade de aplicação de moldes e insertos fabricados por AM para a produção de partes ópticas nos processos de IM e PGM. Utilizando as informações obtidas por periódicos científicos, estudos de caso industriais e pesquisa qualitativa com especialistas, as tecnologias e materiais relacionados a manufatura aditiva foram avaliados por critérios de seleção, determinando a Fusão em Pó como a solução mais adequada até o momento, assim como a classificação das outras. Em seguida, foi realizada a implementação e fabricação de um protótipo físico para testes e comparação de dados experimentais e teóricos sobre qualidade superficial. Assim, concluiu-se em primeira etapa que é possível utilizar manufatura aditiva para produzir moldes e insertos para a produção de peças ópticas.

Palavras-chave: Óptica. Moldes. Moldagem de vidro. Moldagem por injeção. Manufatura aditiva.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABS	Acrylonitrile Butadiene Styrene
ACOP	Aachen Center for Optics Production
AM	Additive Manufacturing
BJT	Binder Jetting
CAD	Computer Aided Design
CDLP	Continuous Digital Light Processing
ChG	Chalcogenide Glass
CNC	Computer Numerical Control
COC	Cyclic Olefin Copolymer
DED	Directed Energy Deposition
DLP	Digital Light Processing
DOD	Drop-On-Demand
EBM	Electron Beam Melting
EBW	E-Beam Writing
ECM	Electrochemical Machining
EDM	Electric Discharge Machining
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
GHG	Greenhouse Gas
HIPS	High Impact Polystyrene
IBL	Ion Beam Lithography
IM	Injection Molding
LDW	Laser Direct Writing
LIGA	Electroplating and Replication
LM	Laser Machining
LOM	Laminated Object Manufacturing
MEX	Material Extrusion
MJT	Material Jetting
NIL	Nanoimprint Lithography
NPJ	Nanoparticle Jetting
PA	Polyamide

PBF	Powder Bed Fusion
PC	Polycarbonate
PCC	Polymer Cement Concrete
PEI	Polyethylenimine
PES	Polyethersulfone
PGM	Precision Glass Molding
PJ	PolyJet
PLA	Polylactic Acid
PLG	Polishing, Lapping and Grinding
PMMA	Polymethylmethacrylate
PMMI	Polymethacrylmethylimide
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
R&D	Research and Development
Ra	Arithmetic Average Roughness
RIS	Research Information Systems
SHL	Sheet Lamination
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SS	Stainless Steel
UAM	Ultrasonic Additive Manufacturing
UPM	Ultra-Precision Machining
USD	United States Dollar
VPP	Vat Photopolymerization

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1. INTRODUCTION

Currently, photonics and optics are associated with technological advances, from which industry and society benefit. While photonics refers to the science of generation, detection and manipulation of light, optics deals with the physics that studies the laws of light radiation and the phenomena of vision (SMITH; KING; WILKINS, 2007). Together, these areas develop optical parts that constitute the basic element of any optical system in everyday life (SHANK et al., 1998).

Perhaps, the most known utilization of optics is in telecommunications: cameras in products such as computers and mobile devices, and fiber optics in the cables that transmit information. However, optics is a versatile field and the products that require those parts are diverse: microscopes, telescopes, medical equipment, measuring tools, displays, lighting, laser systems, military systems, TVs, surveillance and so on (NELSON, 2020). Figure 1 depicts some mentioned applications of the optical parts.

Figure 1 - Optical components applications

Source: Adapted from Fraunhofer IPT (2022).

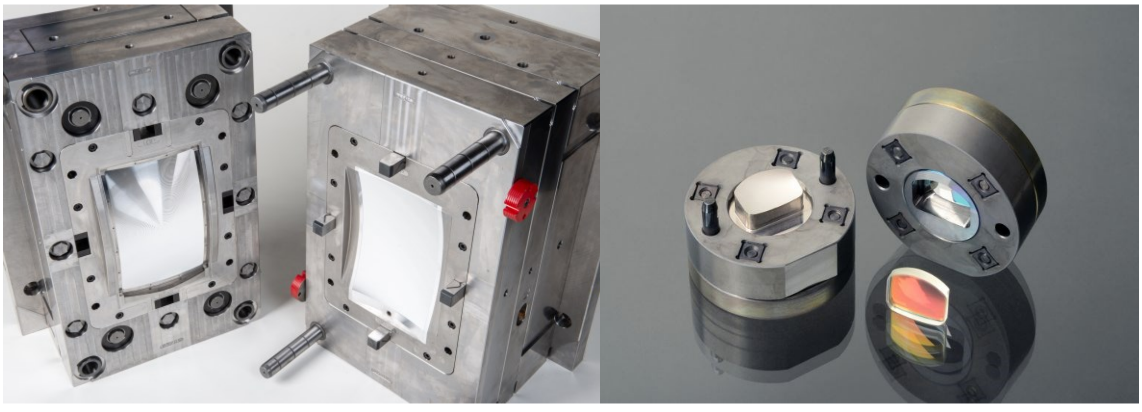
These parts are commonly made of transparent plastics and glass due to their optical properties, which vary depending on composition and type of material (MICHAELI; WALACH, 2012). Although most optical parts, especially glass, are produced by grinding and polishing (NELSON, 2020), there are two other processes of fabrication – which will be the focus of this research – injection molding (IM) and precision glass molding (PGM), that share a common characteristic: both require molds and inserts.

Injection molding is a replicative process that consists of heating polymers in granular form until plasticization occurs, then, the molten material is injected into the cavity of a mold, cools, solidifies and acquires the predetermined shape (GOODSHIP, 2004). On the other hand, precision glass molding is done by heating the mold and glass preforms to the glass transition temperature of the material, then, the softened material is pressed into the cavity of a mold, reshaping, and obtaining the desired form after cooling the assembly (NELSON, 2020).

The mold plays a crucial role in those processes, they need strength and hardness at elevated temperatures and pressures, resistance to oxidation, low thermal expansion, high thermal conductivity, and a lifetime of thousands of cycles (YIN et al., 2022). Also, the part quality is directly connected to the shape and surface quality of the mold insert, as well as the production time is related to the thermal conductivity of this tool (CATOEN; REES, 2021). Thus, it must be ensured during the design and conception of these molds that all the requirements are fulfilled (YIN et al., 2022).

In fact, since the mold must have configurations that allow optimal heat exchange with internal cooling channels, high surface quality and low levels of roughness, they are usually complex components produced by multi-stage machining, commonly using metal and composite materials. Due to this, the cost and time for the design and manufacturing of a mold is high (KAMPKER; AYVAZ; LUKAS, 2020), affecting the production chain. Figure 2 shows typical molds used in IM and PGM.

Figure 2 - Mold and optical part (left – IM, right - PGM)

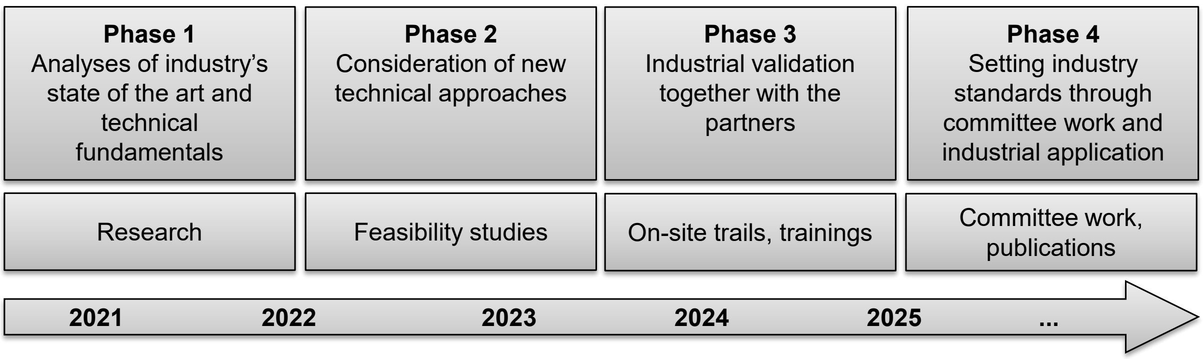


Source: Adapted from Fraunhofer IPT (2022).

The current additive manufacturing (AM) technologies, or 3D printing, as it is popularly known, have been growing in the last years and may represent a promising solution for such demands. Some advantages over conventional methods are rapid prototyping for small-scale production, design freedom, manufacture of complex structures and energy and material savings (GIBSON; ROSEN; STUCKER; KHORASANI, 2020). However, as additively manufactured molds are in their early stages of development, it is not an easy task to find a production system that assure all the mold requirements mentioned before.

To this end, as part of the technology roadmap (Figure 3) phase 1 and 2 of the ACOP (Aachen Center for Optics Production) from Fraunhofer IPT (Institute for Production Technology), this research conducts a feasibility study on the state-of-the-art processes, technologies and materials involved in the additive manufacturing of molds for optic parts production, collecting data from academic papers, literature, case studies, interviews, survey answers and prototype creation, to help determine the most feasible production chain so far to manufacture high-quality optics and optical systems.

Figure 3 - Technology roadmap



Source: Adapted from Fraunhofer IPT (2022).

1.1. OBJECTIVES

To contribute on additively manufactured mold inserts for optical parts production, the following objectives are proposed in this research:

1.1.1. General objective

The general objective of this research is to investigate the feasibility of using additively manufactured mold inserts in the injection molding and precision glass molding processes of optical parts production to determine the most suitable technologies and materials so far.

1.1.2. Specific objectives

Aiming the general objective, the following specific objectives are defined:

- Gather information about additively manufactured mold inserts through academic papers, industrial case studies and survey answers from experts, and organize the found data.
- Analyze the theoretical results from the additively manufactured mold inserts by applying a selection criteria to classify the technologies and materials from most to least suitable for optical production
- Develop and fabricate a physical prototype mold insert using the most suitable process determined from the selection criteria and evaluate its surface quality.

2. THEORETICAL BACKGROUND

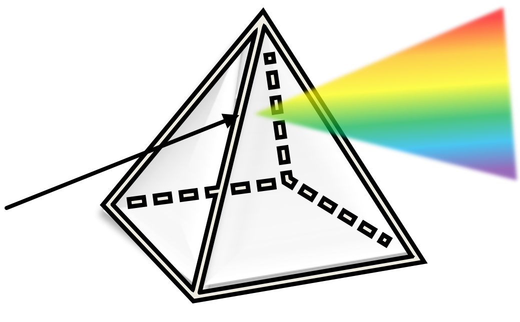
This chapter covers the fundamental concepts associated with the development of the research, which can be divided into three major areas: optics and photonics, part production methods, and mold-making methods. Starting with the characteristics and properties of optical parts, followed by their production methods (IM and PGM), ending with the state-of-the-art of conventional manufacturing and additive manufacturing of mold inserts.

2.1. OPTICS AND PHOTONICS

In his famous book *Opticks*, published in 1704, Isaac Newton described light as a flow of particles and explained the rectilinear propagation of light. This allowed him to develop theories of reflection, refraction and his studies also included the famous experimental demonstration of the dispersion of light into a spectrum of colors through a prism (Figure 4).

Over the centuries, the characteristics of light continued to be investigated, seeking to develop technologies to generate, control, and detect this phenomenon. The study of the fundamental properties of light and its use in practical applications are what define photonics and optics, terms that are commonly used together due to the dual nature of light: wave (electromagnetic spectrum) and particles (photons) (WILLNER et al., 2012).

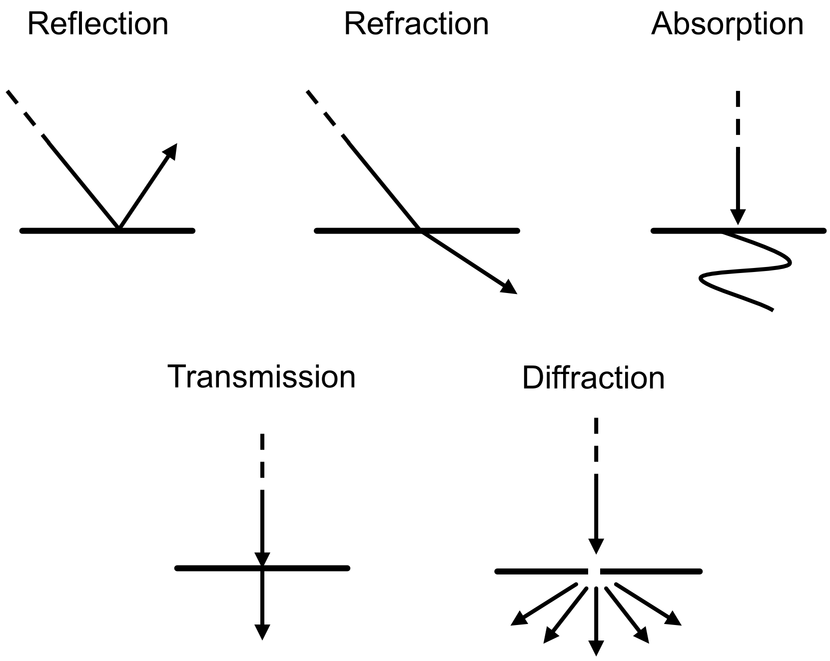
Figure 4 - Dispersion of light through a prism



Source: Author (2022).

Besides the dispersion, there are other ways in which light interacts with the environment producing optical phenomena and they are called light principles (Figure 5). Reflection occurs when light strikes a surface and returns or changes its direction; refraction, when light passes from one medium to another, changing its speed; absorption, when light is partially or completely absorbed; transmission, when light passes through a medium; and diffraction, when light passes through an obstacle or slit and acquires a circular characteristic (BUTCHER et al., 2016).

Figure 5 - Principles of light

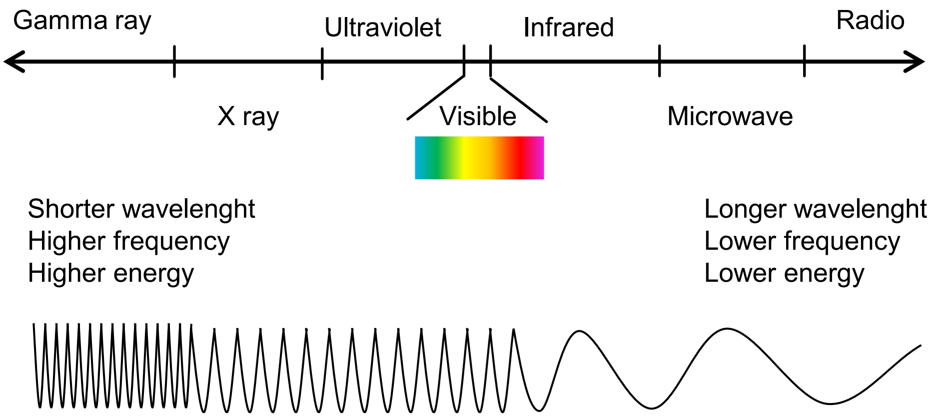


Source: Adapted from Physics Weekly (2022).

The mediums which light can interact are divided into three categories: transparent, translucent, and opaque. Transparent mediums are the ones in which light can be transmitted with little or no loss and it is possible to see clearly through it; the translucent ones allow the partial transmission of light, and it is not possible to see clearly through it; and opaque, interrupts the passage of light, either reflecting or absorbing it (BUTCHER et al., 2016).

Lastly, besides the visible light, photonics and optics also deals with the entire wave range of the electromagnetic spectrum (Figure 6). Gamma rays, x-rays, ultraviolet light, visible spectrum, infrared, microwaves, and long-wavelength radio waves are all forms of its manifestation (CULSHAW, 2020). Thus, the material used, the principles adopted, and which wavelength is chosen for the design of an optical device are directly related and interfere in its performance.

Figure 6 - Electromagnetic spectrum



Source: Adapted from NASA's Imagine the Universe (2013).

Based on that, in the project of an optical part, usually three important properties must be known: transmittance, absorbance and refractive index. Transmittance is the ratio of light that passes through a given material in relation to the light that is incident and is inversely proportional to the absorbance (BRYDSON, 1999).

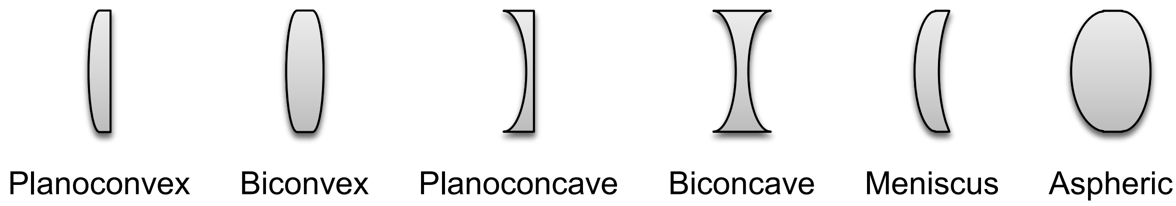
This property is particularly important for fiber optics and opto-electronics applications, which require high transmissibility for their operation. In comparison, optical filters that aims the attenuation of light, require more absorbability (MICHAELI; WALACH, 2012).

On other hand, refractive index is defined as the ratio of the speed of light in a vacuum to the speed of light in a denser medium (AGHAMOLLAEI et al., 2019), and in general, the higher the index, the slower the light propagates in the medium, which corresponds to a greater change in the direction of light within the material, meaning that the profile of the optical device can be smaller (MICHAELI; WALACH, 2012).

Thereby, optical components fall into two basic groups: transmissives and reflectives. Lenses, filters, windows, optical flats, prisms, polarizers, beam splitters, wave plates and fiber optics are all common applications of transmissive products, meanwhile, reflectives include mirrors and retroreflectors (CVI MELLES GRIOT, 2009).

Also, the profile of optical parts can vary between a lot of shapes (Figure 7) and sizes, they can be made of a single piece or multiple elements, and its crucial for its operation that it has the required surface quality and geometrical accuracy (MICHAELI; WALACH, 2012).

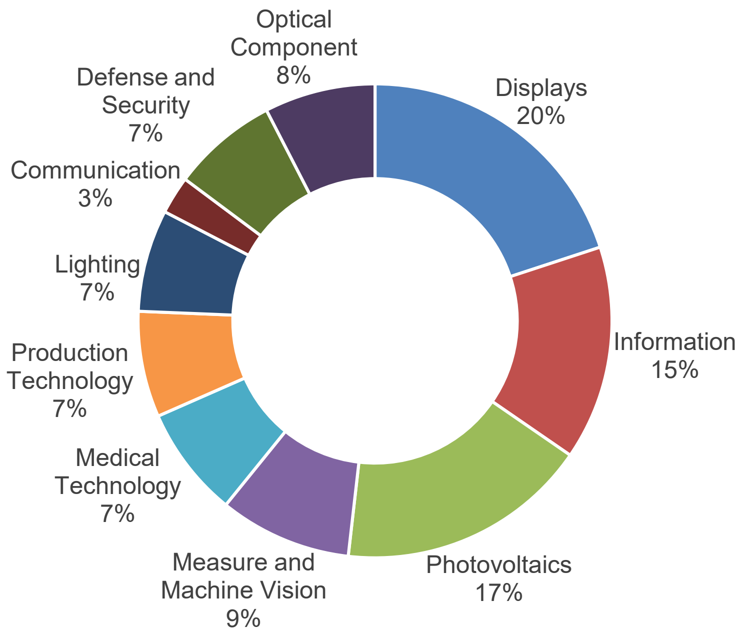
Figure 7 - Shapes of optical parts



Source: Author (2022).

As seen, optics and photonics are a complex area and is segmented in many sectors (Figure 8) within the industry. With a global market value estimated of USD 593,7 billion in 2020, this field tends to grow even more, thus, to produce such components, it is necessary to understand the requirements and how to fulfill them with the current available production methods, technologies, and materials, as well as improve the production chain of those products.

Figure 8 - Global photonics and optics market segmentation in 2020



Source: Adapted from Fortune Business Insights (2022).

2.2. PRODUCTION METHODS FOR OPTICAL PARTS

The term manufacturing refers to the processing of raw materials into finished goods using tools, human labor, machinery, and chemical treatments (KENTON, 2022). There are several ways of fabricating products in the industry and all of them can be organized into four categories: subtractive, additive, forming and molding. Each one has a key feature that differs from the others, which is exemplified in Table 1.

Table 1 - Manufacturing methods

Method	Key Feature	Examples
Subtractive	Gradual material removal.	Machining (Turning, Milling, Drilling, Boring, Reaming).
Additive	Addition of layered material.	Stereolithography (SLA), Selective Laser Sintering (SLS).
Forming	Reshaping of material to acquire a form.	Forging, Extrusion, Drawing, Stamping, Rolling, Precision Glass Molding
Molding	Insertion of raw material into a mold to obtain a form.	Casting, Vacuum Molding, Injection Molding.

Source: Author (2022).

In this section, the methods for optical parts fabrication will be presented: injection molding and precision glass molding. Furthermore, in Section 2.3, the mold-making will be discussed, covering the subtractive and additive methods.

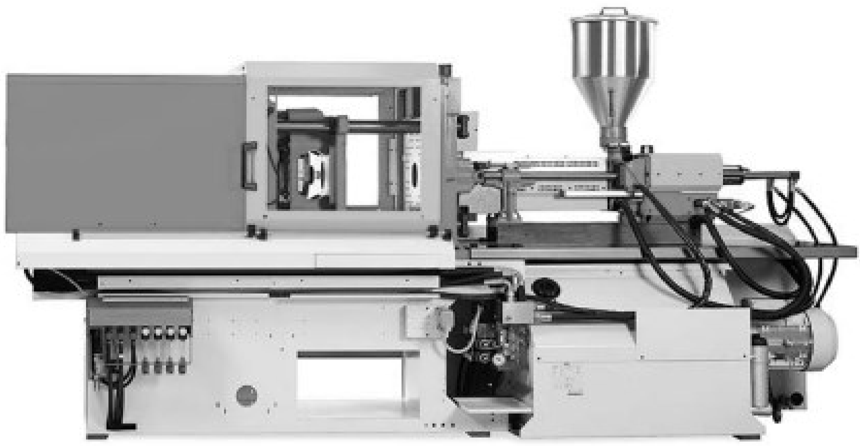
2.2.1. Injection molding: process and materials

Injection molding is the most used process to fabricate plastic parts. It is a cyclical process with high replicative and mass production capacity. As mentioned before, IM consists of heating polymeric granules until it plasticizes, the molten material is filled into the cavity of a mold insert, cools, solidifies and obtain the desired shape, at the end, the product is ejected from the machine, and the cycle repeats (GOODSHIP, 2004).

The products fabricated via injection molding are everywhere: electronics housings, medical equipment, toys, furniture, automobile structures and so on. In recent years, polymer optical parts have been gaining attention as the market for such products grows more and more, leading to the development of new materials and research in the area (BHAGYARAJ; OLUWAFEMI; KRUPA, 2020).

Injection molding uses robust machinery and tooling to conduct the stages of its production cycle. It has several components, systems, and variables within the process, playing major roles during the fabrication of the parts (GOODSHIP, 2004). To better understand the cycle, the machine (Figure 9) will be introduced.

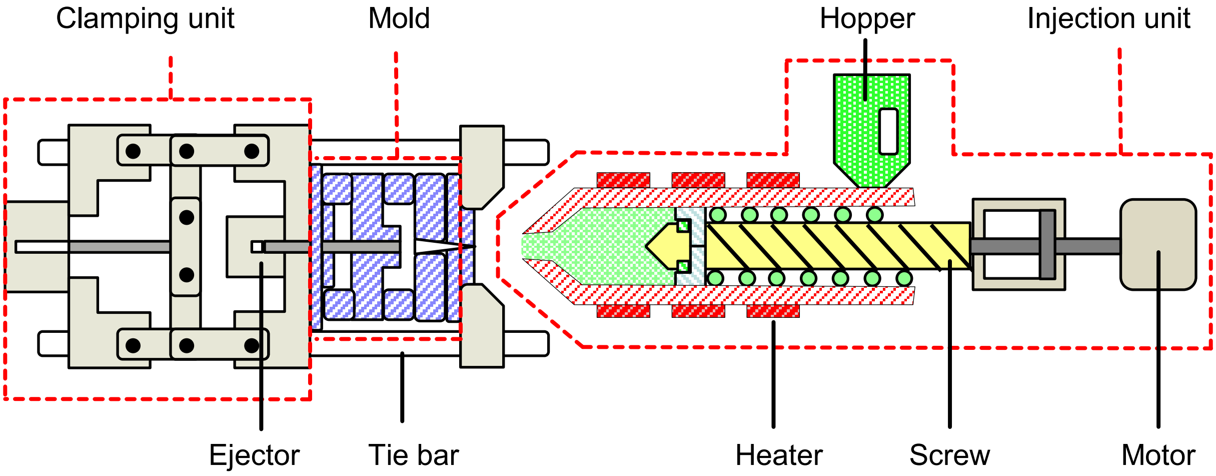
Figure 9 - Injection molding machine



Source: GOODSHIP (2004).

The injection molding machine can be divided into two main parts (Figure 10): the clamping unit and the injection unit (VALERO, 2020). The clamping unit has the function to close, hold and open the mold, as well as eject the parts, it is composed of a hydraulic arm or an electrical motor that provides force and movement to the process by two plates, where the two halves of the mold are mounted, being the left one movable and the right one fixed (GOODSHIP, 2004).

Figure 10 - Clamping unit and injection unit scheme



Source: Adapted from Polyplastics (2022).

On its turn, the injection unit has as main components the hopper, responsible for drying and feeding the material; the cylinder, where the heating of the material occurs; the screw, which transports, mixes, plasticizes and injects the material; and the nozzle, through which the melted material exits to enter the mold (GOODSHIP, 2004).

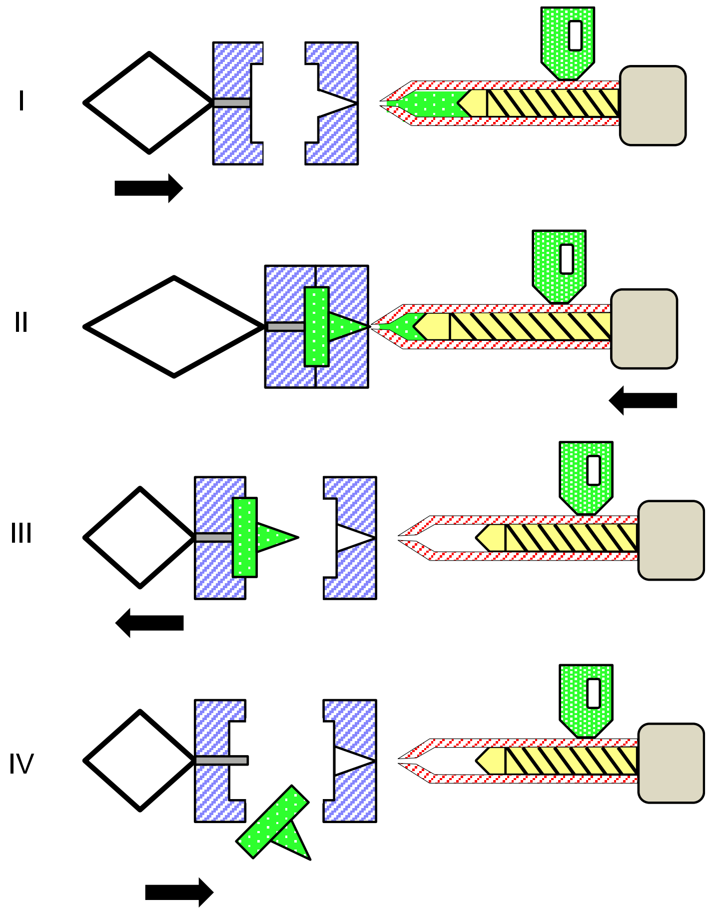
The melting of the material occurs by two ways: heat and shear, whereas the first one is obtained with the rise of temperature inside the cylinder, the second one happens due to viscous dissipation when the plastic is forced to flow through a closed channel, also causing a temperature rise (VALERO, 2020).

This process occurs inside the cylinder, which usually is divided in zones that have their own temperatures. A basic division consists in four zones; however, a higher number can still be used (VALERO, 2020). Similarly, the screw is also divided, usually with three sections: feed, responsible for compacting and pre-heating the material fed by the hopper; transition, where the material is melted for the shot; and metering, the section which the plastic is pumped forward (VALERO, 2020).

The basic stages of an injection molding cycle are presented in Figure 11. It starts with the closing of the mold (I) by the clamping unit and the material being fed (II) by the hopper to the heated cylinder. Then, the screw inside the cylinder transports the material to the nozzle and the plasticization of the polymer granules occurs until the required point for the injection of the melted material into the mold (GOODSHIP, 2004).

On the next stage of the cycle (III), the screw rotates and retracts, metering a specific amount of material for the next shot while the previous shot is cooling in the mold (GOODSHIP, 2004), and, after that, the injection unit moves away from the clamping unit. Lastly (IV), the clamping unit opens the mold and ejects the concluded part, making room for the next one to repeat the cycle, the mold closes, and the injection unit moves forward (GOODSHIP, 2004).

Figure 11 - Injection molding cycle



Source: Adapted from Polyplastics (2022).

Several parameters govern this process, many of them can be changed while the cycle is happening (within certain limits), while others have fixed values. The variables that can be changed during the process are related to temperature, pressure, and time, while the fixed ones are linked to the dimensional capabilities of the tooling and the machine, such as volume, area, and lengths (VALERO, 2020).

Pressure plays a decisive role in part quality (GOODSHIP, 2004) and is one of the most important parameters of the process, it is distributed as injection pressure, holding pressure, clamping pressure and back pressure (PYE, 2018), each one with its particularity in the cycle.

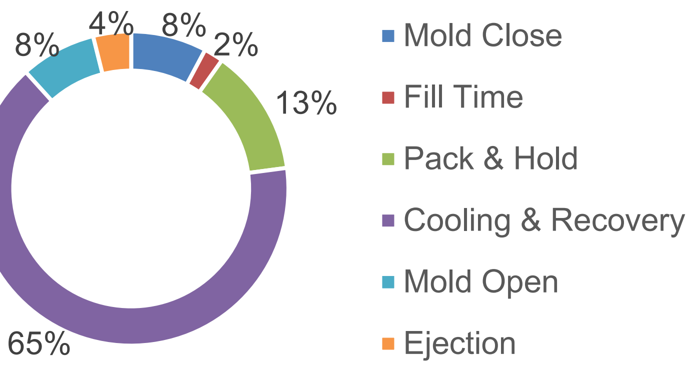
The injection pressure is responsible for filling around 98% of the molten plastic in the mold; holding pressure is used to complete the material in the mold until the component cools; clamping pressure is responsible for keeping the two halves of the mold closed during injection; and back pressure acts during the screw return action for dosing the next cycle, controlling the injection volume and plasticization of the material (PYE, 2018).

Thus, the selection of those pressures should be as high as necessary to fill the cavity sufficiently quickly, completely, and efficiently, but on the other hand, as low as necessary to produce injection molded components with low stress and avoid problems when the components are ejected from the mold (GOODSHIP, 2004).

Regarding the temperatures involved in the process, they are defined as mold temperature, nozzle temperature, cylinder temperature, and drying temperature (VALERO, 2020). All of them are usually given from the supplier of the material and must be settled accordingly to assure a good and fast process (PYE, 2018).

However, another major factor that impacts the whole process is the cooling stage and it can correspond to more than 50% of the total time (Figure 12). The shape and thickness of the part are parameters that affect the cooling; thus, the mold must guarantee a good thermal exchange in that stage (CATOEN; REES, 2021).

Figure 12 - General injection molding cycle distribution



Source: Adapted from Biometrics (2020).

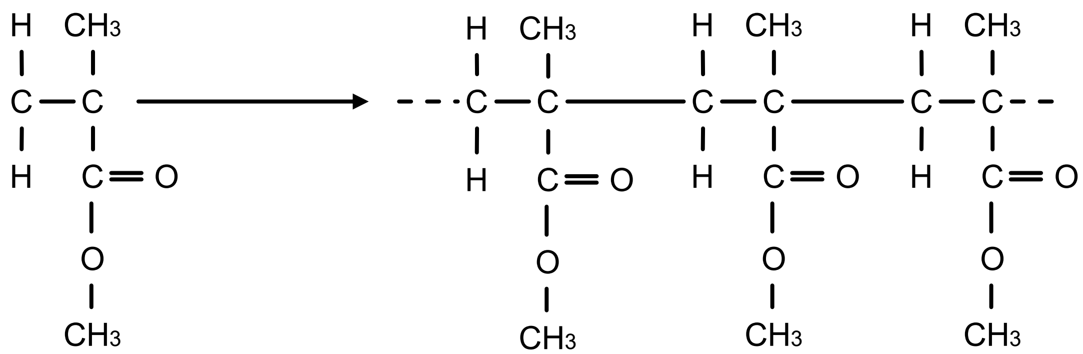
Besides the basic process that was described, some variants of it have been developed. Injection-compression molding, co-injection, over-molding and many others are suitable for specific market applications, whereas to produce optical parts, the variant injection-compression molding is mostly used (GOODSHIP, 2004).

The injection-compression occurs by filling a pre-set amount of material into the mold with it partly closed, then, when the mold closes completely, the whole cavity is filled by the pressing of the material (GOODSHIP, 2004), this additional stroke is either done by the machine or a coining punch in the mold.

This process results in a more evenly distributed pressure over the part surface, which improves the accuracy and dimensional stability of the components, enabling the production of low-stress, thick-walled components, with high contour accuracy, and greatly reducing damage in the inserts. Due to this, this variant is most suitable for optics products since it minimizes the internal stresses and thus influence the optical properties (GOODSHIP, 2004).

As already stated, injection molding uses polymers as raw material, those macromolecules are composed of a repeating chain of smaller molecules, called monomers, where the number of existing connections affect its properties (VALERO, 2020). Figure 13 shows an example of both monomer and polymer.

Figure 13 - Methyl methacrylate and polymethyl methacrylate



Source: Author (2022).

Plastic products have polymers in their chemical structure and may also have other additives that aim to increase their functionality for certain scenarios (VALERO, 2020). They are divided as thermoplastics, thermosets, and elastomers (GOODSHIP, 2004) and has distinct applications.

The main characteristic that differs thermoplastics from thermosets is the thermal behavior. While it is possible to heat, mold and cool thermoplastics infinite times, it is not possible to do the same with thermosets, due to the nature of the chemical bonds, making them able to go through this cycle only once (VALERO, 2020). On the other hand, elastomers are polymers with elastic properties, often called rubber, however, it will not be the focus of the research since the applications do not coincide with the optical parts.

Indeed, for replication processes, only thermoplastic polymers (amorphous and semicrystalline) are usually used, especially the ones with amorphous molecular chains for optical applications, since they are transparent (MICHAELI; WALACH, 2012).

The material has a profound influence on the final characteristics of the parts and the design of the components must take into consideration the physical, optical and thermal properties of it (MICHAELI; WALACH, 2012). Table 2 shows the most used polymeric materials for optical manufacturing via injection molding and lists some of their main properties.

Table 2 - Optical polymeric materials

	PMMA	PC	COC	PA	PMMI	PCC	PES
Refraction Index	1,49	1,58	1,53	1,51	1,53	1,56	1,65
Transmittance (%)	92	88	91	90	91	89	80
Density (g/cm3)	1,19	1,2	1,02	1,02	1,21	1,14	1,37
Injection Temperature (°C)	220-260	280-310	240-310	280-300	260-290	330	340-390
Mold Temperature (°C)	60-90	80-130	95-145	60-80	130	100	120-170

Source: Adapted from Michaeli e Walach (2012).

Among those materials, the ones that stand out are PMMA (Polymethyl methacrylate) and PC (Polycarbonate). PMMA is commonly known as acrylic, it has a high transmittance and the lowest refractive index among the listed transparent polymers. It has good optical properties, high hardness, easy processability and a low price, which makes this material widely used for optical applications (MICHAELI; WALACH, 2012).

Meanwhile, polycarbonate (PC), compared to PMMA, has a higher impact strength, so it can be used in applications where a major shock may occur, and unlike PMMA, it has low fluidity, which leads to the need for high injection speed (MICHAELI; WALACH, 2012).

At last, compared to glass, polymer optics have reduced costs, higher impact resistance, less weight and there are more configuration possibilities to simplify system assembly, however, they have lower resistance to scratches and are more sensible to temperature changes (MICHAELI; WALACH, 2012).

2.2.2. Precision glass molding: process and materials

Glass molding has become a viable alternative for the manufacture of optical components. Compared to conventional processes of manufacturing glass products – such as turning, grinding, and polishing – PGM can have higher precision, shorter production cycle, lower cost, and no pollution in some scenarios, such as for glass optics with complex forms, aspheres, diffractive structures, lens-arrays, or freeform optics. (MING et al., 2020).

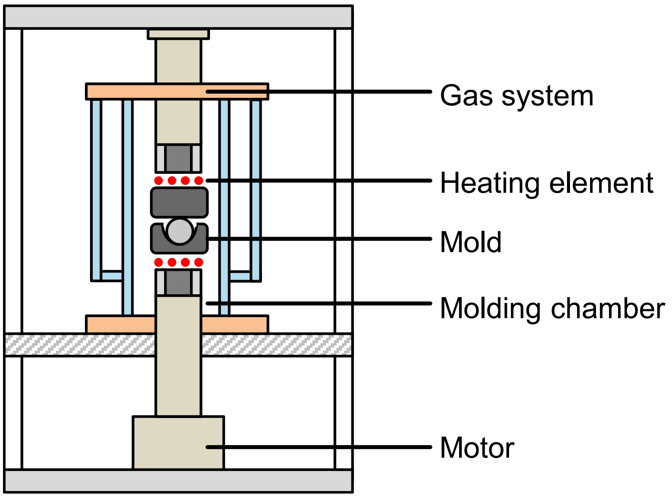
Their applications are diverse: according to a catalog from Rayotek Scientific Incorporated (2021), those components are found in camera and video systems, lighting, imaging and display systems, reflectors for solar power generation, sensors, inspection, monitoring, and optical detection systems.

Glass molding (or glass pressing) as mentioned before, is a production method that uses as basic principle the reshaping of material through a mold assembly that, after heating, pressing and subsequent cooling, results in a component with the desired form (NELSON, 2020).

In general, the machinery used for this process needs to meet the following requirements: heat generation; compressive force generation and control; linear motion control; controlled environment (clean room class 10000 or lower); and cooling control (NELSON, 2020). Figure 14 represents a generic glass molding machine and its main systems.

Infrared lamps are commonly used to heat the mold, increasing the temperature by radiation. The molding chamber is where the two halves of the mold are positioned and when necessary, moves and compresses the glass via a servomotor. The environment control and the cooling are done by introducing inert protective gases (commonly nitrogen) inside the chamber, the goal is to purify the air, prevent oxidation and cool the system (MING et al., 2020).

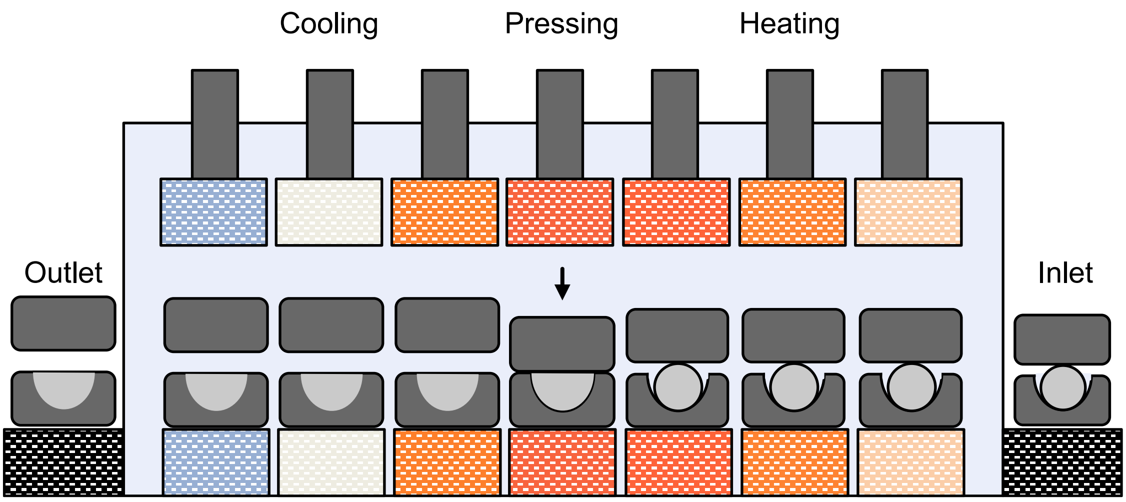
Figure 14 - Glass molding machine (single-workstation)



Source: Adapted from MING et al. (2020).

Moreover, glass molding machines can be classified into two categories: single-workstation (Figure 14) and multi-workstation (Figure 15). The difference lies in the fact that, for the first one, the entire process takes place in the same station, keeping the mold fixed during the process, while the second one runs different steps in different stations within the machine, moving the mold at each stage (MING et al., 2020).

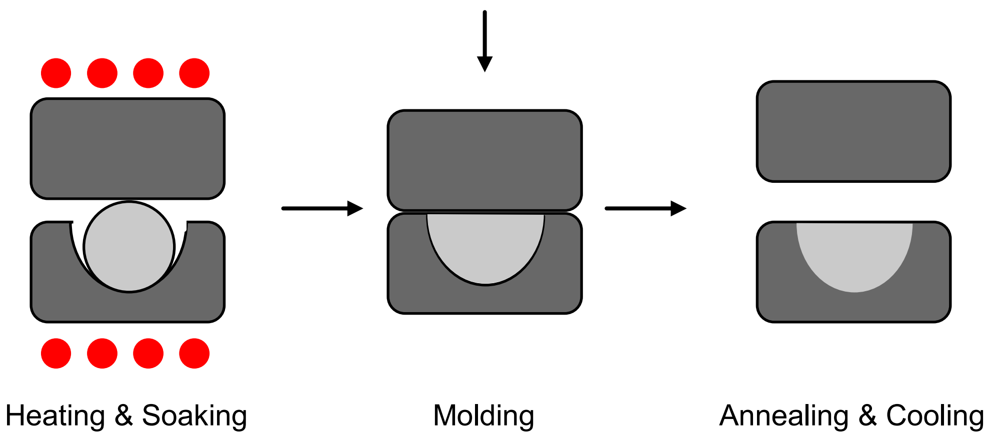
Figure 15 - Glass molding machine (multi-workstation)



Source: Adapted from Zhou et al. (2017).

The production cycle (Figure 16) has three main stages: heating, molding, and cooling. First, the material is placed in the lower part of the mold, oxygen is removed from the working area and nitrogen is filled to purify the molding chamber and then, the mold is almost closed (no contact with the upper half). After that, the heating of the mold begins and goes until the thermal equilibrium between the glass transition temperature and melting temperature of the material (MING et al., 2020). In the heating stage, the glass must be uniformly heated and exceed the molding temperature, otherwise, cracking of the glass preform might happen during the molding process.

Figure 16 - Glass molding cycle



Source: Adapted from GLEASON et al. (2012).

During the molding phase, the upper half slowly presses down the glass while the temperature is kept constant, and when the final thickness of the part is reached, the pressing stops and the two halves are separated again. The cooling stage starts right after, the environment already filled with nitrogen helps the system to cool down until the temperature is at the point of proper handling and removal of the produced part (MING et al., 2020).

It is important to know that if the pressing is carried out at temperatures above the yield point, the glass may stick to the molds, due to the rapid increase of its volume expansion (MING et al., 2020). On the other hand, if the pressing is conducted at temperatures below the yield point, a higher compression load is required, since the material is not enough softened, causing a large residual stress in the glass, which will also shorten the life of the molds (MING et al., 2020).

Lastly, although molding pressure is directly related to the temperature conditions, it must be as high to deform the glass and as low to reduce internal stresses. Thus, appropriate parameters should be selected for the glass molding (MING et al., 2020).

Because of the advancement of this process, it has become necessary to develop special glass formulations to apply in this production method, they are called moldable glasses, which have lower glass transition temperatures (SCHOTT TIE-40, 2011), this facilitates molding and increases the service life of the molds. Those glasses are preforms and might have the shape of globs, balls, discs, or rods.

As example, according to SCHOTT's catalog, a supplier that has been operating in the market of glass production for about 135 years, more than 120 types of glasses are offered for various applications and processes. In the field of glass molding, those materials can be classified in two categories, based on their chemical compositions: oxide glass and chalcogenide glass (ChG) (NELSON, 2020).

Oxide glasses usually work in the visible range of the spectrum and are composed of oxygen along with another element, such as silicon, which make up the traditional silicate glass (SiO4). Other constituents that are part of this category are boron, germanium, selenium, and antimony (NELSON, 2020).

On the other hand, chalcogenide glasses usually work in the infrared range of the spectrum and are made by combining one or more chalcogenides – sulfur, selenium, and tellurium – with a semi metallic element – arsenic, antimony, germanium, and gallium (NELSON, 2020).

Some of the moldable glasses were taken from SCHOTT's catalog, three oxides and three chalcogenides and their properties are presented in Table 3. Because of the large number of glass types due to their various chemical compositions, only a few were selected.

Table 3 - Optical glass materials

	SCHOTT P-PK53	SCHOTT P-SK57	SCHOTT P-LASF47	SCHOTT IRG22	SCHOTT IRG25	SCHOTT IRG27
Refraction Index	1,52	1,58	1,80	2,51	2,61	2,41
Density (g/cm3)	2,83	3,01	4,54	4,41	4,66	3,20
Glass Transition Temperature (°C)	383	493	530	368	285	197

Source: Author (2022).

As seen in Section 2.1, the refractive index and transmittance are important optical properties. In the case of glasses, the transmittance stays above 90% and can reach values close to 100% (SCHOTT TIE-35, 2005), besides that, the refractive index can vary between a greater range, influencing the optical performance of the product (SCHOTT TIE-29, 2005).

The glass transition temperature plays a major role in the molding stage and is the main restriction for molds due to its high temperatures. In fact, when comparing IM with PGM, there is a great difference in temperature values, which makes the requirements for the thermal fatigue resistance of PGM molds to be higher. At last, glass optics in comparison with polymer optics have higher transmission, lower susceptibility to corrosion and scratches, and are more durable in general (NELSON, 2020). Therefore, glass material is most often used in precision optics, prisms and lenses, while polymer can be applied in products that do not require as much high optical properties as glass, aiming to cost-effective and lightweight designs.

2.3. PRODUCTION METHODS FOR MOLDS AND INSERTS

Injection molding and glass molding are ideal processes for mass production and replicative manufacturing, they make use of molds and inserts, which have the capacity to produce several units while maintaining the same characteristics each cycle. However, if the mold is poorly designed regarding its operating requirements, the entire manufacturing process is put at risk. Thus, the correct fabrication of this tool is of paramount importance for the viability of production.

Therefore, in this section, the state-of-the-art of conventional and additive manufacturing of molds are covered: properties, requirements, fabrication methods, technologies, materials, and surface finishing topics.

2.3.1. Molds and inserts: general requirements and materials

A mold (or die), is a hollowed-out block that serve as a base for inserts, also known as core and cavity, of a product to be made. It can be of different materials, the most common of which are steel, aluminum and copper and can have different components, including pins, plates, lifters, ejectors, guides, bushings, and alignment devices (ROSATO et al., 2001).

Molds and inserts can vary its design to meet different product requirements, they can be highly sophisticated tooling with high quality metals and precise machining to meet large production volumes and high specifications, as well as simpler, for prototyping, with fewer particularities for small-scale production, or even a combination of both (ROSATO et al., 2001).

However, they always have the function of shaping the material into a part, assisting the cooling of the molded product and in the case of mass production, long service life (ROSATO et al., 2001). To ensure this, molds and inserts have a group of requirements.

In general, injection molding inserts and precision glass molding inserts require the same basic properties to be utilized. Still, as seen in Chapter 1, they have different design solutions, due to the machinery, raw material, and fundamentals of the processes. As for optical parts, some of the general requirements for the inserts are presented in Table 4.

Table 4 - Inserts general requirements for optical parts

	Injection Molding	Glass Molding
Work Temperature	< 300 °C	< 700 °C
Cooling	Water	N_2
Dimensional Accuracy	< 1 µm	
Surface Quality	Ra < 10 nm	
Cycles	1000 (Soft Metal) 1 Mi (Hard Metal)	5000
Surface Finishing	Turning	Grinding

Source: Adapted from Fraunhofer IPT (2022).

High thermal conductivity is related to the cooling stage of the part and to features such as internal cooling channels that are developed into the tool, having two types of configurations: conventional or conformal cooling. Conventional channels are simpler and involve straight lines and basic shapes generally located in the center of the object (ROSATO et al., 2001).

On the other hand, conformal cooling channels are more complex and follows the shape of the part, allowing greater heat transfer. Which one to use depends on the produced part, however, if a mold cooling system is not done correctly, deformations and defects in the final part might occur (ROSATO et al., 2001).

The tools used for mass production have a service life of thousands of cycles and have properties such as hardness at elevated temperatures and pressures, steel homogeneity, corrosion resistance, easy welding for repairs, easy handling, and thermal fatigue resistance (CATOEN; REES, 2021). Thus, the forces and temperatures present in the cycle must be evaluated to select the correct material to support them.

As already seen, polymer optic parts are fabricated using PMMA, PC, COC, among others. For their properties, steel, aluminum, copper, brass, and nickel silver are commonly used for the mold assembly and inserts, however, it also depends on the component and its function in the tool (CATOEN; REES, 2021). Table 5 presents the distribution of type, AISI designation, DIN material number and the common components made of the specific material.

Table 5 - Common materials for IM molds and inserts

Type	AISI designation	DIN material no.	Used for
Pre-hardened	4140	1.7225	Plates, leader pins
	P20	1.2330	Plates, pistons, stroke limits
Stainless steel pre-hardened	420SS	1.3216	Plates
Carburizing steels	P5	-	-
	P6	1.2735	-
Oil hardening	O1	1.2510	-
Air hardening	H13	1.2344	Cores and cavities
	A2	1.2363	Wear surfaces, lock rings, stripper rings
	D2	1.2379	-
	S7	-	Wear rings
Stainless steel (SS)	420SS	1.2083	Cores and cavities
High-speed	M2	1.3343	Wear surfaces
Beryllium-copper	BeCu25	-	High thermal conductivity inserts

Source: Adapted from Catoen e Rees (2021).

Between them, the prominent ones are: P20, widely known as the general-purpose tool material for injection molding; S7, tight tolerances and high volumes; H13, thermal fatigue cracking resistance and high strength; and 420SS, custom injection molding and maximum corrosion resistance (MENGES et al., 2001).

On the other hand, although PGM can also use tools made of aluminum and steel, carbides such as tungsten and silicon are widely utilized for the molds and inserts (DAMBON et al., 2009). Table 6 presents the most used materials for the molds and inserts for PGM, as well as their working temperatures.

Table 6 - Common materials for PGM molds and inserts

Material	Molding Temperature (°C)
Silicon	400-700
Nickel Alloy	300-800
Silicon Carbide	400-900
Tungsten Carbide	300-700
Glassy Carbon	400-1400

Source: Adapted from Asgar et al. (2021).

Those brittle hard materials have higher thermal fatigue resistance, wear resistance and better behavior in contact with glass, with no adhesion (ASGAR et al., 2021). The most used among them for optics is tungsten carbide (WC), a well-established material, with low thermal expansion and high compressive strength at elevated temperatures (SUN et al., 2022).

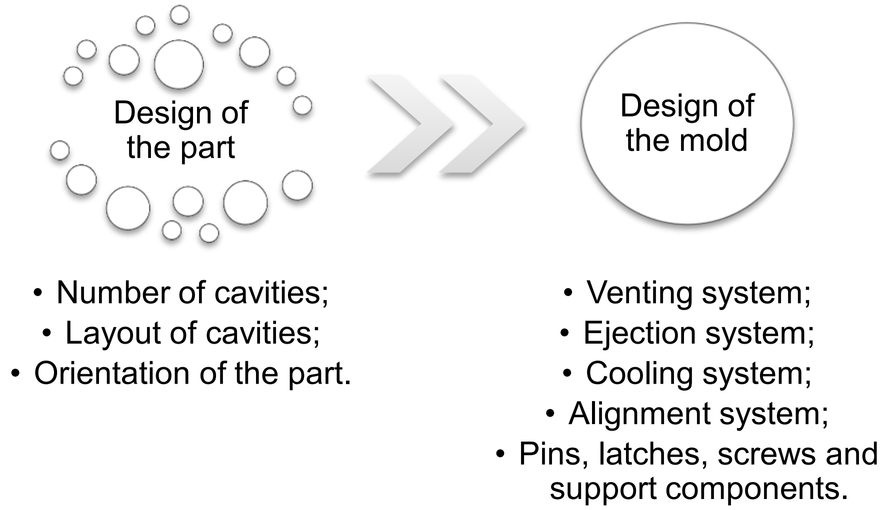
Regarding, the requirements of the inserts, the desired shape of the part is related to the designed application of it; therefore, the inserts must have characteristics such as surface quality, dimensional accuracy, and cleanliness of the faces (avoiding unwanted impurities) to secure the correct molding of the material. Thus, surface finishing processes must be used to accomplish that.

2.3.2. Conventional manufacturing of molds and inserts

As molding processes need complex tooling that allows for production replicability, Catoen and Rees (2021) suggested a few steps for the design of a new mold for injection molding, however, it can also be applied for glass molding, since the general principles are similar. Figure 17 summarizes those stages.

Computer aided design (CAD) is widely used to create the tool and such designs follow a checklist that is verified at the end of each stage, to found for example, if assembly and disassembly is possible, among other details, to assure that the tool is correctly projected. When it finishes, a call for a concept and design review is done, and if all is as planned, the tool fabrication can be initiated (CATOEN; REES, 2021).

Figure 17 - Design stages



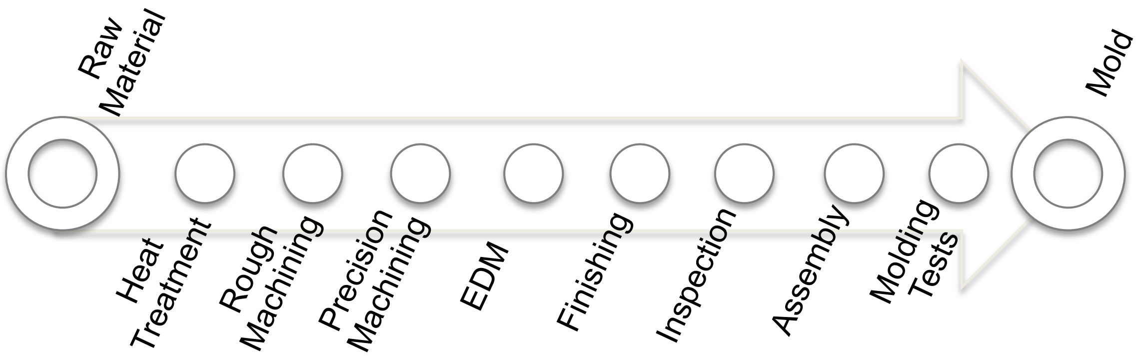
Source: Adapted from Catoen and Rees (2021).

Currently, conventional manufacturing of the mold, cavity, and core plates account for the most widely employed manufacturing method. The conventional manufacturing is usually related to subtractive processes of machining (turning, drilling, and milling), which, depending on the complexity of the tool and number of components, can go through several stages (ROSATO et al., 2001).

Regarding the machining operations, turning is when the workpiece is rotated as the cutting tool travels in a linear motion, producing cylindrical shapes; drilling, produces round holes in the workpiece; and milling, uses multi-point rotary cutters to remove material from the workpiece. They can be carried out either automatically or manually in the production and are often combined (DAVIM, 2008).

With the desired part known and its CAD, the mold can be designed to fulfill its requirements of shape, material, as well as to guarantee the replicability of the process. In the case of IM molds, they are fabricated from steel blocks through two main methods: standard machining and electric discharge machining (EDM). The standard one is the most common along the process, while EDM is used when complex shapes are required (SORTINO et al., 2014). Figure 18 shows a typical IM mold making process.

Figure 18 - IM mold manufacturing



Source: Adapted from Sortino et al. (2014).

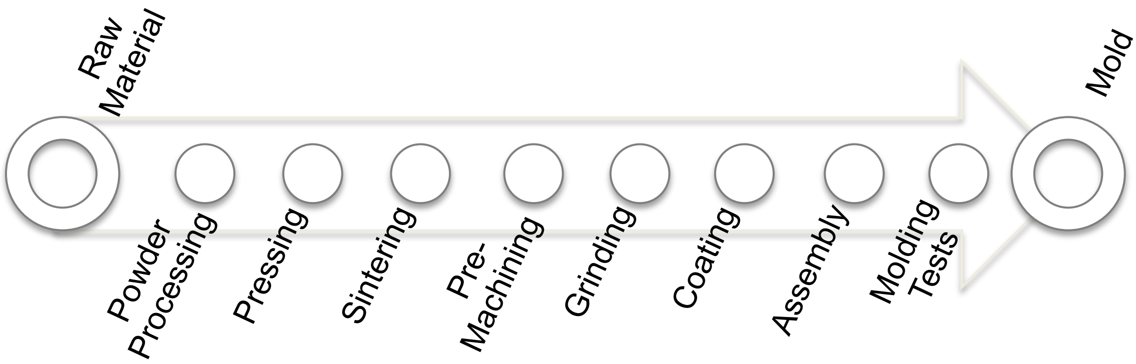
The machining stages are composed of multiple phases that take hours and sometimes days to complete, and the time to produce increase with the complexity of the tool. Within those stages, all the conventional machining methods can be used, commonly with computed numerical control (CNC) machines (SORTINO et al., 2014).

Indeed, with more features to be added, such as cooling channels, the more difficult it is the fabrication, and when conventional machining cannot reach complex shapes, EDM is used as a complement process in its fabrication chain (SORTINO et al., 2014).

For optical surface quality (Ra > 10 nm), the surface finishing stage is of great importance and conventional molds already have modern technologies that facilitate the obtaining of extremely low roughness, although they are costly processes. However, they will be presented in Section 2.3.4.

The process for PGM molds, on the other hand, starts with powder processing to achieve suitable grain sizes; pressing and sintering to obtain the first mold base, as for carbide materials. After that, pre-machining takes place and like the rough machining, the goal is to reach the first form of the tool to finish it later (CHOI et al., 2004). Figure 19 shows the mold making process of PGM.

Figure 19 - PGM mold manufacturing



Source: Adapted from Choi et al. (2004).

For PGM, the mold materials are some of the hardest on earth and can only be machined with diamond-based products. This limits the types of features that can be machined into the tool and therefore the types of features that can be replicated in the optics (NELSON, 2021).

In addition, to ensure high quality standards, inspection steps occur between each process stage. A crucial part of the whole process is the molding tests, where the tool is put into the machine to determine whether the mold can create the specified shape and, if the mold is not suitable, it must be reworked (SORTINO et al., 2014). Since those processes are high cost and time consuming, an error can led to unwanted additional expenses.

Overall, the mold and insert fabrication for injection molding and precision glass molding processes, although uses different materials, have the same sequence: from the base material, a first rough fabrication is conducted, which then can be finished using various processes.

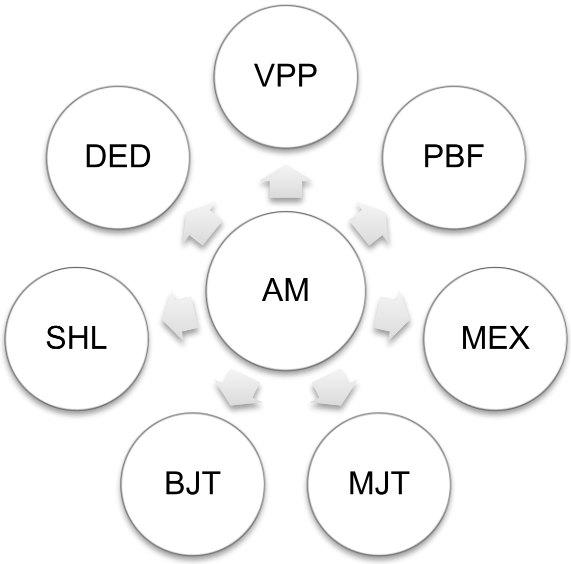
2.3.3. Additive manufacturing: state-of-the-art

Additive manufacturing is the formalized term for what used to be called rapid prototyping and what is popularly known as 3D printing (GIBSON et al., 2020) and is a rapidly expanding technology in various industries. This production method transforms CAD design files into fully functional products (BIKAS et al., 2015), where the key to how AM works is that parts are made by adding material in layers; each layer is a thin cross-section of the part derived from the original CAD data (GIBSON et al., 2020).

The first reported parts produced by 3D printing technologies are dated from 1981 and since then, this field began to grow and create more methods, however, terms such as 3D printing and additive manufacturing were only first used in 1993 and 2000, respectively. Although this process emerged in the 1980s, it was only in the last few years that it has become economically feasible for wider application, as the cost of entry fell and more alternatives for processes and materials appeared (PORSANI; SILVA; HELLMEISTER, 2017).

In total, there are seven categories (Figure 20) of AM processes (GIBSON et al., 2020): Vat Photopolymerization (VPP), Powder Bed Fusion (PBF), Material Extrusion (MEX), Material Jetting (MJT), Binder Jetting (BJT), Sheet Lamination (SHL), Directed Energy Deposition (DED).

Figure 20 - Categories of additive manufacturing



Source: Author (2022).

Polymers, composites, metals, and ceramics are all materials to be used in additive manufacturing and are found in the seven available categories of this production method. As AM technology has grown, specific classes of materials have become associated with specific processes and applications (SHI et al., 2021).

Table 7 lists materials with their respective types of AM technology to show which material is used in which method. Note that “3” represents a widely available process, “2” represents a common available process, “1” represents one that it is on R&D phase and “0” that the process doesn’t exist for that specific material.

Table 7 - Materials and AM methods

	VPP	PBF	MEX	MJT	BJT	SHL	DED
Polymers	3	3	3	3	3	2	0
Metals	1	3	2	1	2	2	3
Ceramics	2	1	2	1	1	0	1

Source: Adapted from Shi et al. (2021).

As can be seen, polymers and plastics are the most widely available material for additive manufacturing, being followed by metals and then ceramics. Due to this, it is natural that there are more materials variety for this same sequence, which is shown in Table 8. Thus, solutions for mold manufacturing will also mostly fall in the most used types of materials.

Table 8 - Materials used in AM

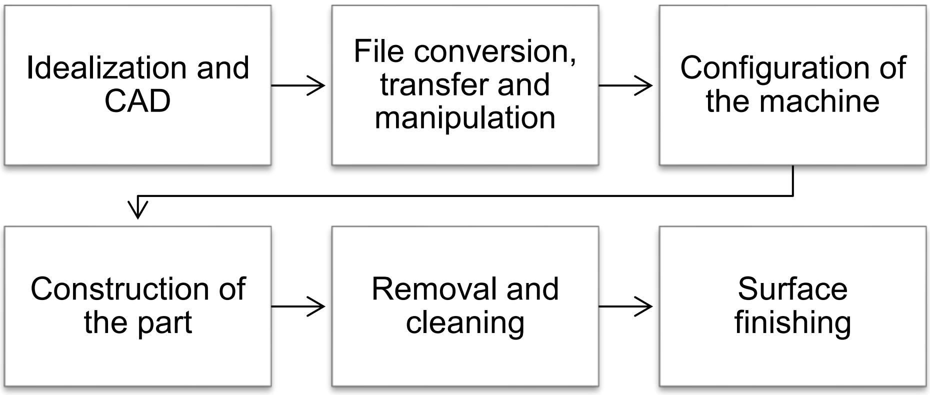
Polymers	Metals	Ceramics
Acrylonitrile Butadiene Styrene (ABS) Polycarbonate (PC) PC/ABS Blend Polylactic Acid (PLA) Polyetherimide (PEI) Acrylics Acrylates Epoxies Polyamide (PA) Polystyrene (PS) High Impact PS (HIPS) Polypropylene (PP) Polyester (PL) Polyurethane (PUR)	Aluminum Alloys Cobalt Chrome Alloys Titanium Alloys Nickel Alloys Ti-6Al-4V Gold Silver Stainless Steel Tool Steel	Glass Aluminum Oxide Tricalcium Phosphate Porous Silicon Nitride Titanium Silicide

Source: Adapted from Bourell et al., (2017) and Shi et al. (2021).

To find if those technologies are viable and suitable to a specific application is a current challenge of the market, especially in fields where this investigation is still in its first steps, as in the optics production. The current processes, their potential in injection molding and glass molding, and the ongoing mold making technologies are all topics that need to be covered in other to better understand this field.

Depending on the part to be produced and the employed technology, AM can have different process chains, as well as conventional methods. Still, a generic process (GIBSON et al., 2020) chain for additively manufactured parts is shown in Figure 21, which covers its main stages.

Figure 21 - AM part process chain



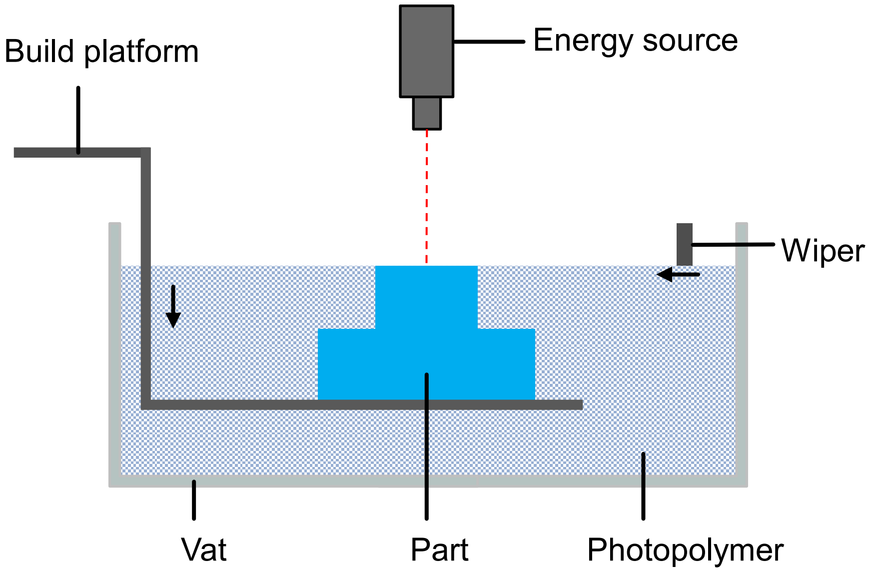
Source: Adapted from Gibson et al. (2020).

The construction of the part is where the main difference between the existing technologies is. All of them are layer-based, however, the way the layers are made, and the used material differs from each other. The correct type of material must be fed into the machine, which can be processed in powder, liquid or solid form (BOURELL et al., 2017).

Vat Photopolymerization (VPP) processes were the first commercialized AM technologies and continue to be widely used. VPP uses liquid polymers into a vat (or tank) that react to repeated radiation patterns corresponding to the cross sections of the desired part, which slowly emerge from the tank (Figure 22).

Subsequent variants of VPP processes involve different radiation sources: Stereolithography (SLA) uses an ultraviolet laser, Direct Light Processing (DLP) and Continuous Direct Light Processing (CDLP) uses a digital light projector. In addition, several types of layering mechanisms can be employed, such as ultrafast VPP, high resolution VPP and multi-material VPP (GIBSON et al., 2020).

Figure 22 - Vat Photopolymerization (VPP)

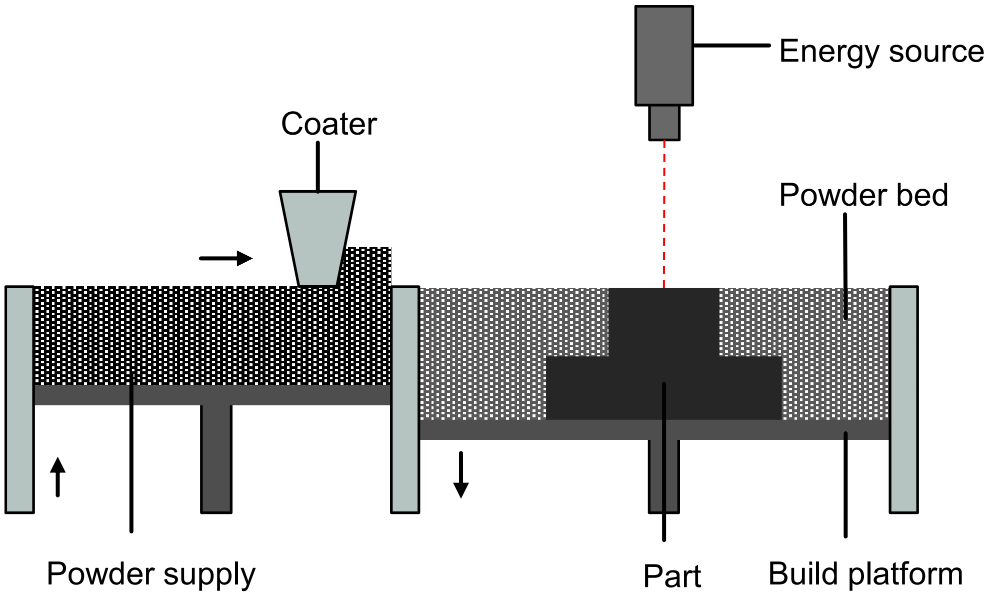


Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

Powder Bed Fusion (PBF) was one of the earliest and remains one of the most versatile AM processes, being suitable for a wide range of materials (GIBSON et al., 2020). The process (Figure 23) consists of thin layers of powders, which are spread and compacted on a platform, the powder in each layer is then fused with the machine heat source and subsequent layers are placed on top of the previous ones and fused together until the final 3D part is built (NGO et al., 2018).

Like the VPP process, the variants of the PBF process differ according to the heating and, the material to be used. Selective Laser Sintering (SLS), typically uses polymers and its heat source is the laser, Selective Laser Melting (SLM), works the same way for metals, Electron Beam Melting (EBM), is another process for metals, which uses electron beams as the heat source (GIBSON et al., 2020).

Figure 23 - Powder Bed Fusion (PBF)

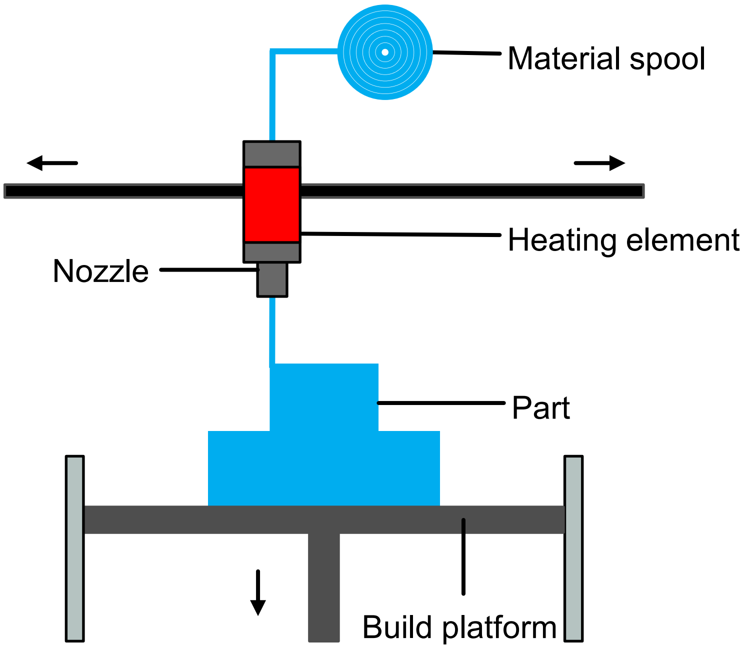


Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

Material Extrusion (MEX), on the other hand, is an additive manufacturing technique that uses a continuous filament of thermoplastic or composite material to build the parts (Figure 24). The filament-shaped material is fed through an extrusion nozzle, where it is heated and then deposited on the construction platform layer by layer (GIBSON et al., 2020).

Its methods can be called Fused Deposition Modeling (FDM) or also Fused Filament Fabrication (FFF), names patented by companies in the market. Both are very similar processes; however, the difference remains in the fact that in FDM there is a heated chamber to control the part temperature, leading to more stable products.

Figure 24 - Material Extrusion (MEX)



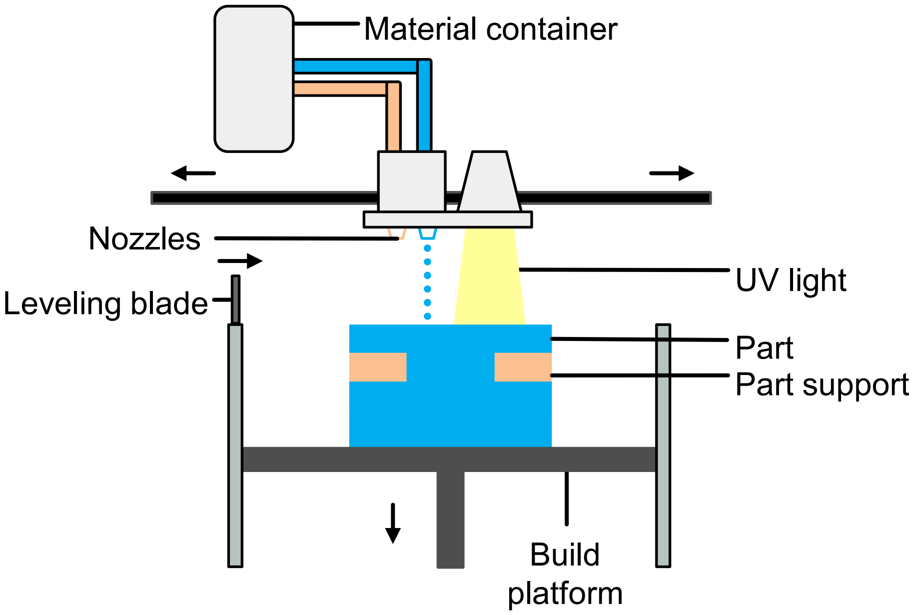
Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

Material Jetting (MJT) process (Figure 25) consists of a printhead blasting material droplets on the construction platform and cured by ultraviolet light or heat to form the final part, the material can be blasted continuously or only, when necessary, i.e., when required to create the parts (GIBSON et al., 2020).

The two most used materials for Material Jetting are photopolymers (in liquid form) and casting wax. Also, support structures are printed simultaneously with the part to ensure its stability during printing, this is due the printhead that allows different heads to dispense different material (GIBSON et al., 2020).

Its variants are PolyJet (PJ), which works in the conventional way, but was the first technology to be developed and had its name patented; Nanoparticle Jetting (NPJ), uses special solid nanoparticles in the mixture of the building material; and, Drop on Demand (DOD), which has a jetting flow on demand, different from the continuous flows of the other methods.

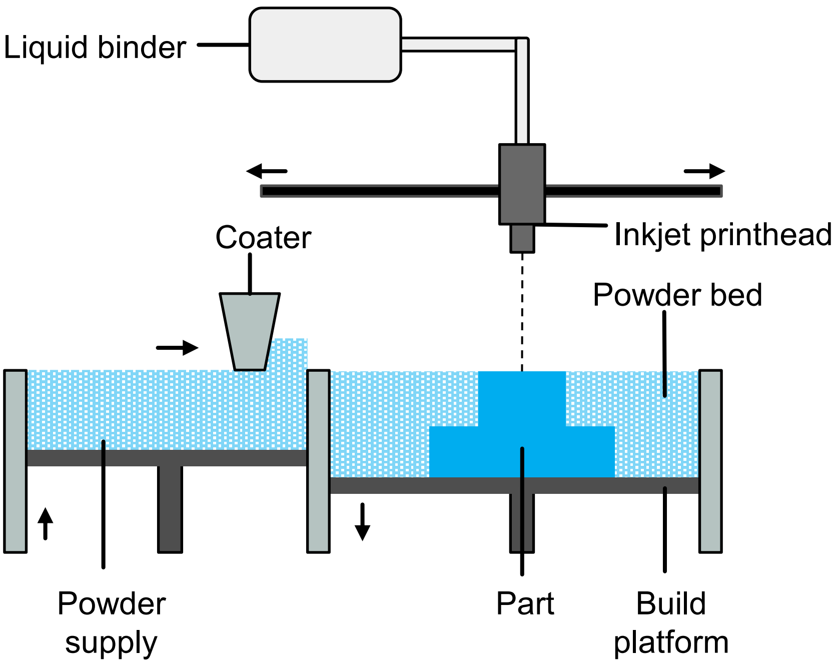
Figure 25 - Material Jetting (MJT)



Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

The Binder Jetting (BJT) process (Figure 26) prints a binder (or adhesive) onto a layer of material in powder form, agglutination occurs in the required areas and then, the process is repeated until the desired part is complete (GIBSON et al., 2020).

Figure 26 - Binder Jetting (BJT)

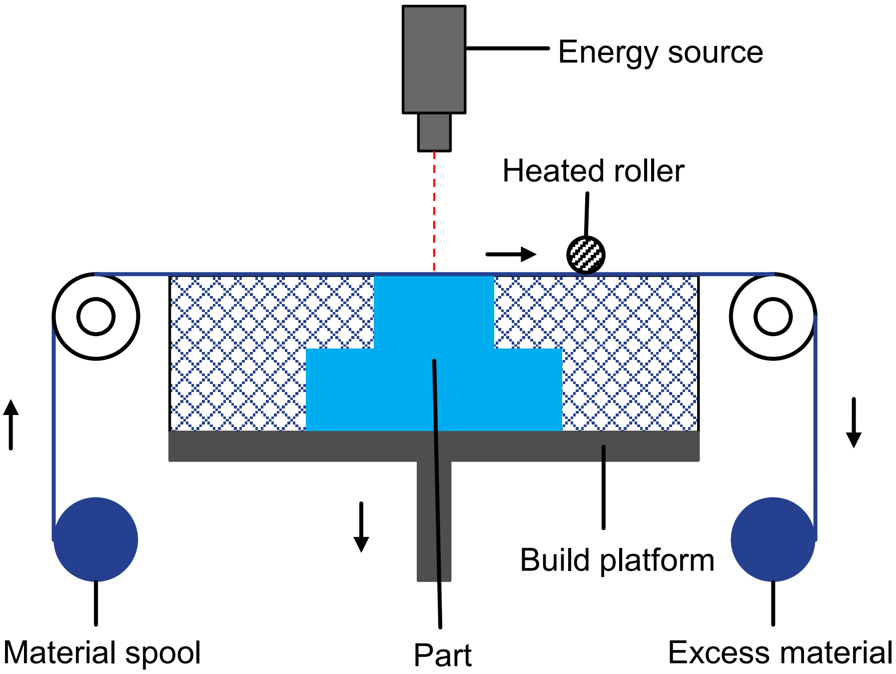


Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

In Sheet Lamination (SHL), sheets (or foils) are cut, stacked, and glued to form an object, this process can be further categorized according to the mechanism used to make the connection between the layers of material (GIBSON et al., 2020). The process starts with the material being positioned on the cutting platform, and if applicable, it is bonded to the previous layer, cut to the required shape, and the sequence is repeated.

The conventional process (Figure 27) is called Laminated Object Manufacturing (LOM) and uses polymeric adhesives along with thermal tools to bond the layers, while the Ultrasonic Additive Manufacturing (UAM) uses ultrasonic welding as the joining mechanism for the material (GIBSON et al., 2020).

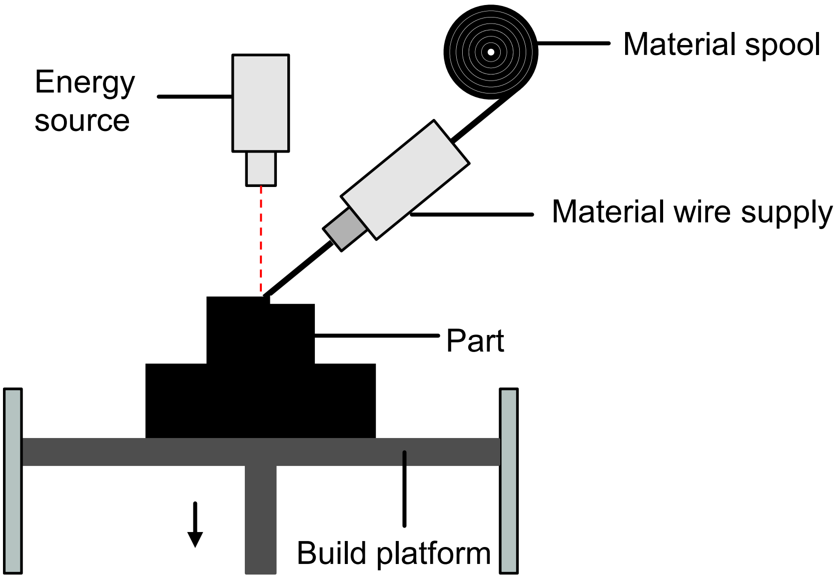
Figure 27 - Sheet Lamination (SHL)



Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

Finally, Directed Energy Deposition (DED) is a process (Figure 28) that melts material in wire or powder form as it is being deposited. While the process is being fed with material, it is also having the necessary energy (laser, electron beam or plasma arc) to melt it, until it forms the final part (GIBSON et al., 2020).

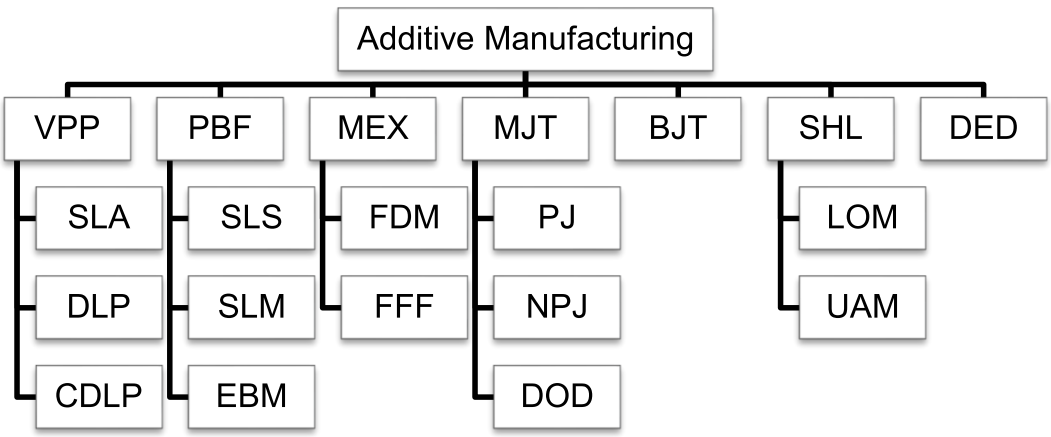
Figure 28 - Directed Energy Deposition (DED)



Source: Adapted from AMRG - Additive Manufacturing Research Group (2022).

As seen, additive manufacturing has several different processes currently available in the market. Figure 29 summarizes the presented AM technologies and their variations within the respective categories. With this number of possibilities of part production, it is important to evaluate and compare each process according to its properties, materials, advantages and disadvantages for better visualization and support in selection criteria. Therefore, Table 9 lists the benefits and drawbacks of each method.

Figure 29 - Additive manufacturing technologies



Source: Author (2022).

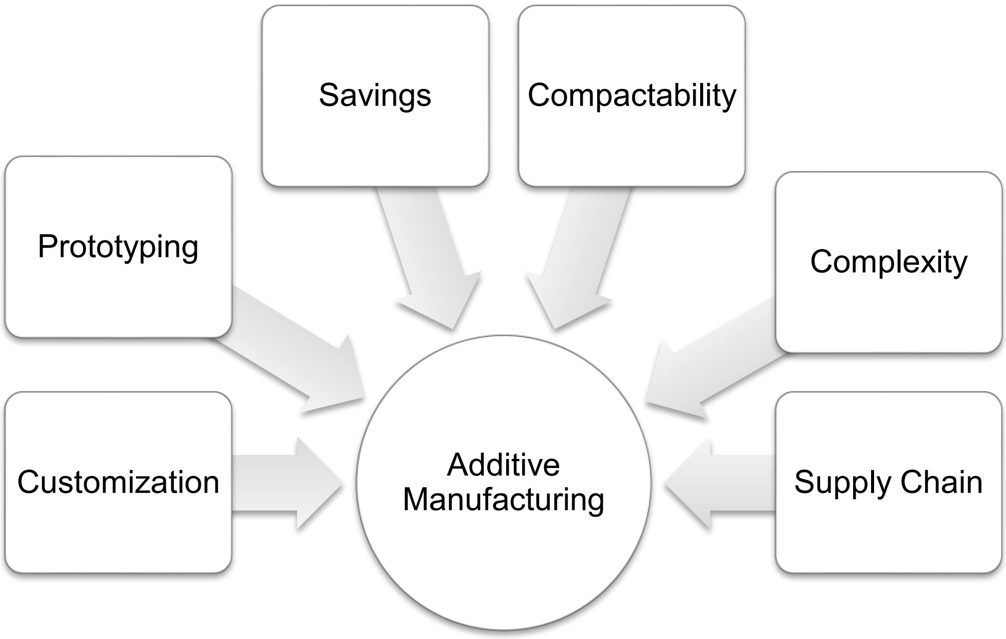
Table 9 - Benefits and drawbacks of AM technologies

Process	**Benefits**	**Drawbacks**
Vat Photopolymerization	High level of accuracy Good finish Quick process	Expensive Lengthy post processing time Limited material use
Powder Bed Fusion	Suitable for visual models and prototypes Broad range of material options	Finishing depends on grain size Size limitations High power usage
Material Extrusion	Wide selection of polymers Ease handling Fast print	Visible layer lines Toxic print materials Poor part strength Delamination issues
Material Jetting	Multi-material printing Fast print Extreme accuracy	High cost Limited material use
Binder Jetting	Assorted colors Range of materials Fast process	Structural parts Surface finishing required
Sheet Lamination	Fast print Ease material handling Low cost Recycle of cut material	Limited material use Surface finishing required
Directed Energy Deposition	High build rates Used for repairing Larger parts Dense and strong parts	High capital cost Low build resolution No support structures

Source: Author (2022).

One of the reasons of the recent rising interest in additive manufacturing is due the benefits that this new technology is capable in the industry, where the direct integration of additive manufacturing in production systems and chains can lead to economies on materials, energy, time, and costs (ELHAZMIRI et al., 2022). Those summarized benefits are presented in Figure 30.

Figure 30 - AM process capabilities



Source: Author (2022).

Due to its digital modeling, the modification of the design of parts and its customization turns additive manufacturing highly design-oriented with greatly creative freedom for customization. Furthermore, combined with this aspect, many prototypes can be created, and its design be optimized before committing to a production run (ELHAZMIRI et al., 2022).

Another important point is the savings that this technology allows, since the process involves layer addition to construct the part, what it is used to create the part is only what is needed, therefore, waste material is reduced. In fact, the energy required is greater for the usual machining methods, what makes additive manufacturing more sustainable, with less energy need overall (ELHAZMIRI et al., 2022).

Regarding the part itself, with the use of AM technology, it is possible to consolidate whole assemblies into just one part, that is, instead of creating individual parts and assembling them at a later point, AM can combine both manufacturing and assembly into a single process, producing parts all together, as all-in-one projects.

AM is even more flexible and can produce complex geometries that it is harder to do it with conventional machining methods, such as internal and external structures with undercuts or cavities for example. Any shape designed in a 3D CAD program can be produced with AM (ELHAZMIRI et al., 2022).

Based on all those capabilities is that AM can establish concepts of on demand production, no over production and stock reduction, highly simplifying the production processes and supply chain of the industry that choses to implement this technology (ELHAZMIRI et al., 2022).

In fact, AM yields a reduction potential of 12% to 60% lead time, 3% to 5% in primary energy, 4% to 7% GHG emissions and 15% to 35% cost over 1 million cycles in the case of injection molding. In the future, AM technologies tends to higher accuracy, advanced materials, increased customization, automatization, and intelligent software in 3D printing smart factories (HUANG et al., 2017; TOSELLO et al., 2018; KAMPKER et al., 2020).

However, AM drawbacks are still hampered by low productivity, inferior quality, and uncertainty of the mechanical properties of the final part. The currently challenges, regardless of the field of application, are to improve surface finish, dimensional control, and size limitations of additively manufactured parts. Also, situations of sudden increases on demand might not be attended due the scalability restrictions (BIKAS et al., 2015). Nevertheless, the current advances of this technology have been making its use in diversified sectors possible, besides being studied as an alternative to replace conventional methods or to support and apply them together (GIBSON et al., 2020).

Ultimately, the usage of additive manufacturing technologies in the replicative optics field can be applied in the mold tool production and can effectively decrease manufacturing costs and lead times (economical factor) and ease the fabrication of complex assemblies and structures (geometric factor), as seen in its benefits (PEÇAS et al., 2018).

Complex internal structures such as cooling channels in the molds, compact design for the mold assemblies and prototypes for testing small batch runs are the key points that AM can bring to the table when using in IM and PGM (PEÇAS et al., 2018). However, optical surface quality and thermal stability are also key points for the advancement of this implementation.

For each type of additive manufacturing, a certain level of roughness is obtained, which vary according to its parameters, such as material feedstock (type, size, and quality), print speed, cooling rates, among others (GIBSON et al., 2020).

Table 10 shows the surface qualities (without post-processes) of the AM methods presented, according to Kumbhar and Mulay (2018) and Huckstepp (2019).

Table 10 - Surface qualities of AM technologies

Process	**Material**	**Surface Roughness (Ra)**
Vat Photopolymerization	Polymers	2 - 40 μm
Powder Bed Fusion	Metals	5 - 35 μm 5 - 30 μm
Material Extrusion	Polymers	9 - 40 μm
Material Jetting	Polymers	3 - 30 μm
Binder Jetting	Polymers	3 - 13 μm 12 - 27 μm
Sheet Lamination	Polymers	6 - 27 μm
Directed Energy Deposition	Metals	15 - 60 μm (Powder) 45 - 200 μm (Wire)

Source: Author (2022).

All the processes have similar ranges of surface roughness, which is not within the optical quality limits. Overall, additively manufactured parts have a natural surface with sand-like, grainy appearance, slightly rough to the touch, and as seen, is not ideal for some applications, needing a finish.

Currently, there are several adopted strategies to treat and enhance the properties of the AM parts. Heat treatments are used to reduce porosity of the part along with other types of post-processing. Some of those techniques are priming, painting, chemical smoothing, blasting, polishing, hydro dipping, epoxy coating, electroplating, depowdering, shot peening, flocking, galvanization, vibratory finishing, and machining in general (GIBSON et al., 2020).

When it comes to machining, it can be categorized as conventional and advanced machining processes. Conventional stands for the already seen turning, milling, and drilling, and others like sawing, lapping, cleaning, and polishing (GIBSON et al., 2020).

The advanced processes are divided in thermal-based, abrasive-based, electrical-discharge-based, laser-based, and chemical-based machining. Some examples of it are laser shock peening, ultrasonic machining, water jet, plasma arc, among others (GIBSON et al., 2020).

Although there are numerous techniques to apply on AM parts, studies comparing one to the other and the roughness levels achieved are scarce in the literature. The company ActOn, through the process of vibratory finishing was able to improve the surface quality of polymeric parts produced by AM and Table 11 presents some of its results.

Table 11 - Polymeric finished parts results

	Average Ra before finishing	**Average Ra after finishing**
Part 1	6,97 µm	1,16 µm
Part 2	13,05 µm	2,46 µm
Part 3	13,25 µm	1,33 µm

Source: Adapted from ActOn Additive (2022).

On the other hand, Witkin et al. (2019) and Bagehorn et al. (2017) conducted some tests on additively manufactured parts produced via selective laser melting with Ti-6Al-4V material and Inconel 625. Table 12 summarizes their results.

Table 12 - Metal finished parts results

Finishing method	**Average Ra before finishing**	**Average Ra after finishing**
Vibratory finishing	6,5 µm	0,46 µm
Abrasive polishing	5,4 µm	0,18 µm
Milling	17,9 µm	0,3 µm
Blasting		10,1 µm
Vibratory ground		0,9 µm
Micro machining		0,4 µm

Source: Adapted from Witkin et al. (2019) and Bagehorn et al. (2017).

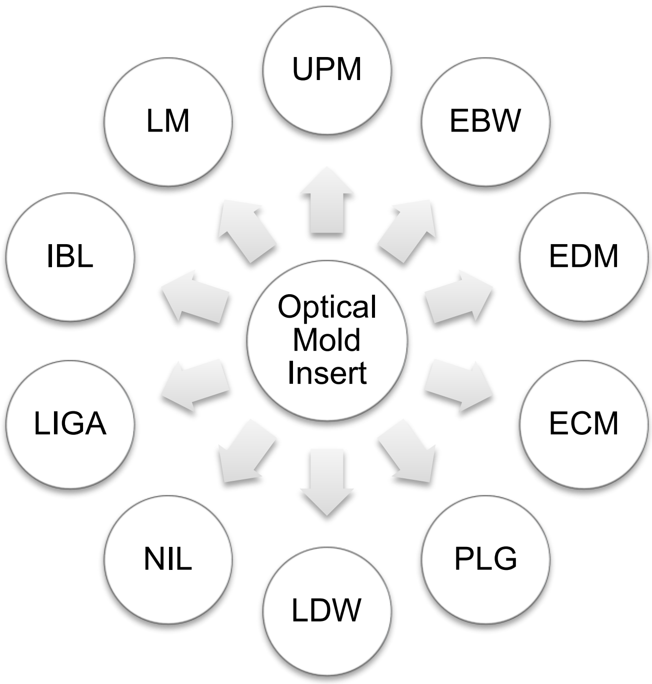
As much as the roughness values have improved, for optical applications it is still not enough, which exemplifies the difficulty of achieving extreme qualities in AM parts. Also, the material used in the process have influence in this capability, being the metals more susceptive to better qualities with finishing than polymer ones.

To know which suits better the mold making, especially for optics production, is currently a challenge, so academia and industry has been continuously taking steps further in this area. It is possible to find companies that have developed their own methods and conducted study cases, in addition, research groups investigate molds produced by AM and their properties in the production of different types of parts. The current state of these studies and their results will be presented in Section 4.1 discussing the results of the literature review on the subject.

2.3.4. Surface finishing of optical mold inserts

One of the most critical points in the fabrication of optics are the surface quality of the inserts, which impact the final part, also, the costs can represent a great amount since high precision processes are necessary to obtain the required characteristics (ROEDER et al., 2019). Figure 31 shows the broad range of technologies currently used in the industry to achieve the desired surface quality and accuracy.

Figure 31 - Surface finishing technologies



Source: Author (2022).

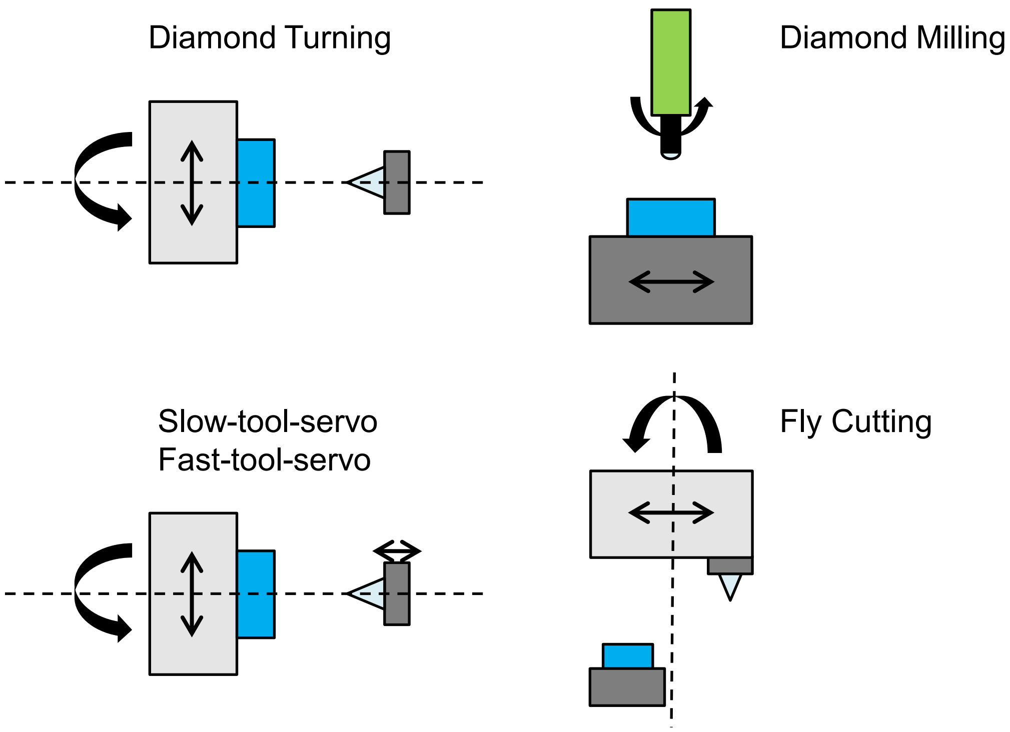
Those methods are: Ultra-precision machining (UPM), E-Beam Writing (EBW), Electric Discharge Machining (EDM), Electrochemical Machining (ECM), Polishing, lapping, and grinding (PLG), Laser Direct Writing (LDW), Nanoimprint Lithography

(NIL), Lithographie, Electroplating and Replication (LIGA), Ion Beam Lithography (IBL) and Laser Machining (LM).

Most of these technologies can be used for form-giving, construction of microstructures or finishing of the part, where the most common method for the fabrication of optical mold inserts is the Ultra-Precision Machining (UPM). It achieves accuracy in the nanometer range, leading to outstanding surface quality and form accuracy, with a roughness smaller than Ra < 10 nm, perfect for the optical application, reaching mirror-like finished surfaces (ROEDER et al., 2019).

However, this process is limited to non-ferrous materials, and due to this, nickel-phosphorus (NiP) coatings became a standard use for the industry onto steel molds to prepare the roughly fabricated mold to the ultra-precision methods (Figure 32): diamond turning, slow-tool-servo or fast-tool-servo, diamond milling or fly cutting (ROEDER et al., 2019).

Figure 32 - UPM methods



Source: Adapted from Roeder et al. (2019).

These processes use diamond tools for the subtraction of the material with a granite block as foundation, high-precision positioning systems, high-speed spindles and accurate fixture and handling equipment, being a state-of-the-art technology, which increases the cost and time for the whole process (ROEDER et al., 2019).

The diamond turning is a standard process to finish optical mold inserts for spherical and aspherical lenses. When this type of machining is not applicable, diamond milling is usually used, such as for non-smooth surfaces (ROEDER et al., 2019). On the other hand, for non-symmetrical, free-form optics, microstructures and large areas, the slow-tool-servo, fast-tool-servo, and fly cutting are more employed, since there are more degrees of freedom and intermittent contact of the diamond tool with the workpiece (ROEDER et al., 2019). These aspects result in UPM processes being used together to manufacture a wide range of geometries for the inserts.

Therefore, Table 13 summarizes the main characteristics of UPM methods and Table 14 of the other mentioned methods, regarding surface quality, dimensional limits for micro-structure construction, advantages, and disadvantages.

Table 13 - Characteristics of UPM

Method	Surface Quality	Micro-Structuring	Benefits	Drawbacks
Diamond Turning	< 5 nm	5 µm	Very high accuracy and surface quality	Limited to symmetrical parts and non-ferrous materials
Slow-Tool-Servo	< 10 nm	5 µm	Fabrication of asymmetrical parts	Geometries are limited due to the slow stroke of the tool
Fast-Tool-Servo	< 10 nm	< 1 µm	Fabrication of asymmetrical parts, fast and accurate positioning of the tool	Geometry must be within the scope of the stroke
Diamond Milling	< 10 nm	50 µm	Fabrication of free-form structures	Long machining time especially when good surface quality is required
Fly Cutting	< 10 nm	< 1 µm	Fabrication of complex microstructures like prisms and pyramids	Limited to flat substrates

Source: Adapted from Roeder et al. (2019).

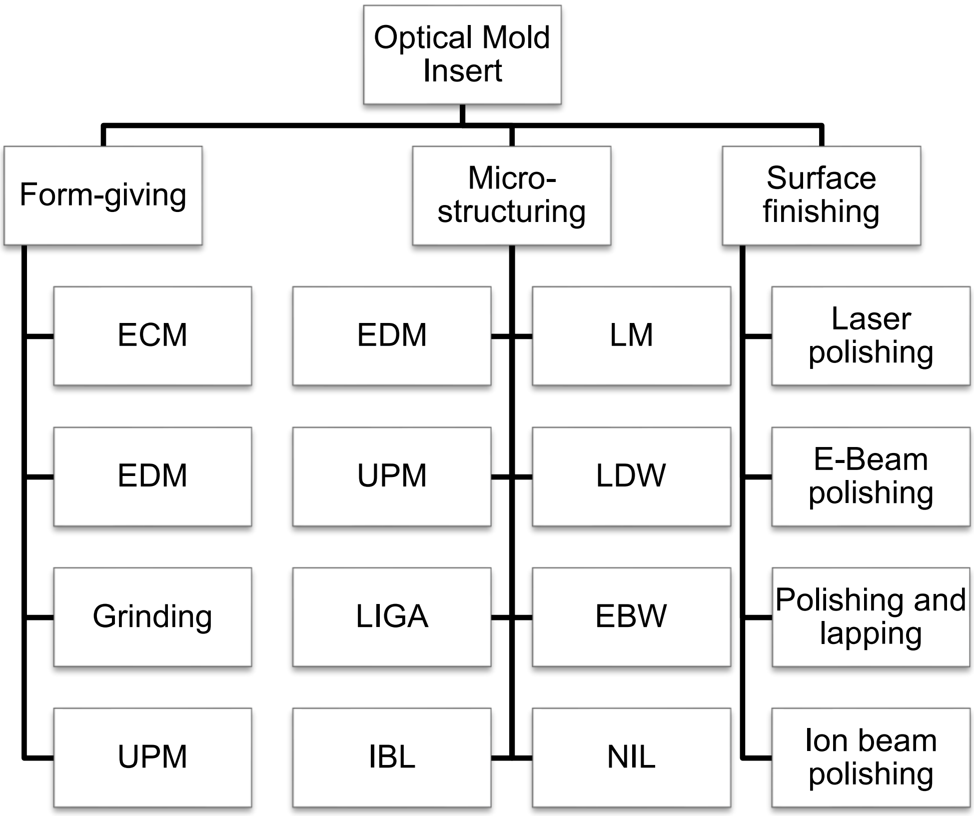
Table 14 - Characteristics of other finishing methods

Method	Surface Quality	Micro-Structuring	Benefits	Drawbacks
EDM	< 0,1 µm	< 10 µm	Large material removal rate	Only conductive workpieces, surface roughness not sufficient for optical applications
ECM	30 nm	Not suitable for micro-structuring	No tool wear, high removal rate also in hardened materials	Only conductive workpieces, electrodes can be complex and expensive
Grinding	< 10 nm	Not suitable for micro-structuring	Machining of hardened steels	Long machining time
LIGA	< 10 nm	< 1 µm	Micro-structures with high aspect ratio are possible, broad range of micro-structures possible	Limited to flat substrates, expensive and complex when multiple lithography steps are necessary
NIL	-	< 10 nm	Fabrication and replication of very small micro and nanostructures, high throughput	Quality is very much depending on the stamp which has to be fabricated by a micro-structuring technology, limited to 2D substrates
LDW	25 nm	1-3 µm	Suitable for curved substrates, fabrication of continuous structures	Limited to structuring of a photoresist
EBW	0,2 µm	< 100 nm	Machining of all materials, suitable for large area smoothing	Limited to small areas due to long process time
IBL	< 1 nm	< 10 nm	Machining of all materials except for magnetic materials, fabrication of micro and nanostructures	Limited to small areas when used as a structuring method due to long process time
Polishing/Lapping	< 1 nm	Not suitable for micro-structuring	Very high surface quality	Limited form accuracy especially in free-form parts

Source: Adapted from Roeder et al. (2019).

This wide range of technologies are related in general to parts made by conventional manufacturing and, commonly, metal materials, which are usually mold inserts configuration. The application of these same processes for AM parts is an area of study that is in its infancy, however, there are already some works in the area, which will be addressed in Chapter 4. In order to facilitate the visualization of these methods, Figure 33 was elaborated.

Figure 33 - Categorized surface finishing processes



Source: Adapted from Roeder et al. (2019).

Another key attribute to mold tools is the material hardness, as it is related to scratch resistance and surface durability. Most of tools will have protective coatings applied to their optical surfaces so that substrate hardness becomes less of an issue (NELSON, 2021).

The use of protective coating is key to extending the life of molds and increasing the surface quality of the produced parts, an important development of coating is to enable precision molded optics that divert the optical industry from conventional, expensive, and time-consuming manufacturing processes by grinding, polishing, and lapping (AKHTAR; RUAN, 2022).

Its application is commonly associated for PGM tools, which have three groups of surface protection coatings that can be used: noble metal coatings, ceramic coatings, and carbon-based coatings. Table 15 shows several existing coatings for the first two groups, which are the most widely used (AKHTAR; RUAN, 2022).

Table 15 - Coatings for glass molding molds

Coating	**Group**	**Characteristic**
PtIr, IrRe, IrReCrN, MoRu, CrRu, TaRu, TiAlN	Noble Metal	Superior oxidation and corrosion resistance and better reliability Easier coating process
CrWN, CrN, CrSiN, ZrSiN, TaSiN	Ceramic	Cost and durability

Source: Author (2022).

3. RESEARCH PROCEDURE

To achieve the general objective and the specific objectives of the research, four different approaches were conducted: literature review, qualitative survey, selection criteria definition, and finally, prototype creation, testing and evaluation. These steps are explained in more detail in this chapter.

3.1. LITERATURE REVIEW

In order to gather academic research on the topic of additively manufactured molds and inserts for optical production, five bibliographic databases with some keywords and variations of them were applied. Table 16 summarizes the used search terms and visited websites.

Table 16 - Literature review approach

Bibliographic database	Search terms
Fraunhofer eLib	Additively manufactured mold Additively manufactured insert Additively manufactured mold tooling Additive manufacture in optics production Additive manufacturing in injection molding Additive manufacturing in glass molding
ScienceDirect	
ResearchGate	
Web of Science	
IEEE Xplore	

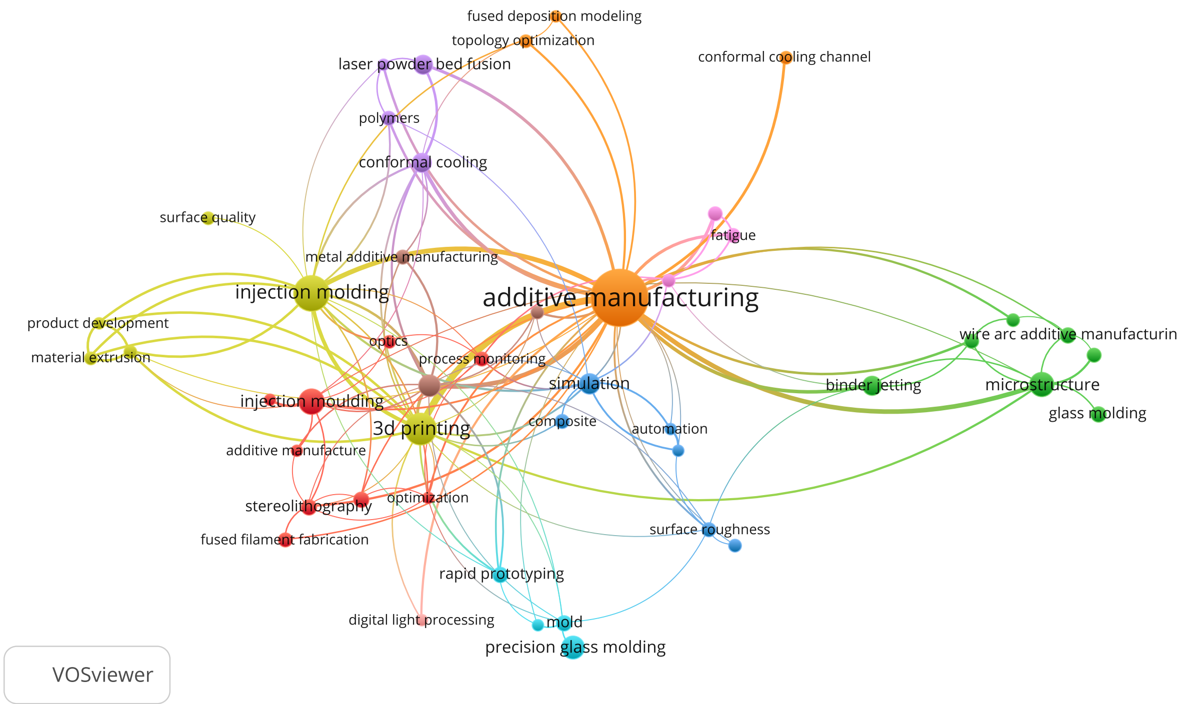
Source: Author (2022).

The search resulted in an amount of more than 100 papers, however, a refinement was conducted to filter the works that better suit the proposal of the research, i.e., additively manufactured molds and inserts, resulting in 15 papers. In addition, a review paper additive manufacturing of metal-mirrors was also selected. Hence, using the RIS files of the selected papers and VOSviewer software, a network map was created.

According to the developer, VOSviewer is a software tool for constructing and visualizing bibliometric networks. These networks may for instance include journals, researchers, or individual publications, and they can be constructed based on citation, bibliographic coupling, co-citation, or co-authorship relations.

In this research, the bibliometric network was constructed based on the co-occurrence of important terms extracted from the body of the papers from five or more appearances. Figure 34 shows the connected keywords, where the size of the circles means the frequency with which these keywords appear in the papers and the colors highlight the occurrence of the terms that are most related to each other.

Figure 34 - Bibliometric network

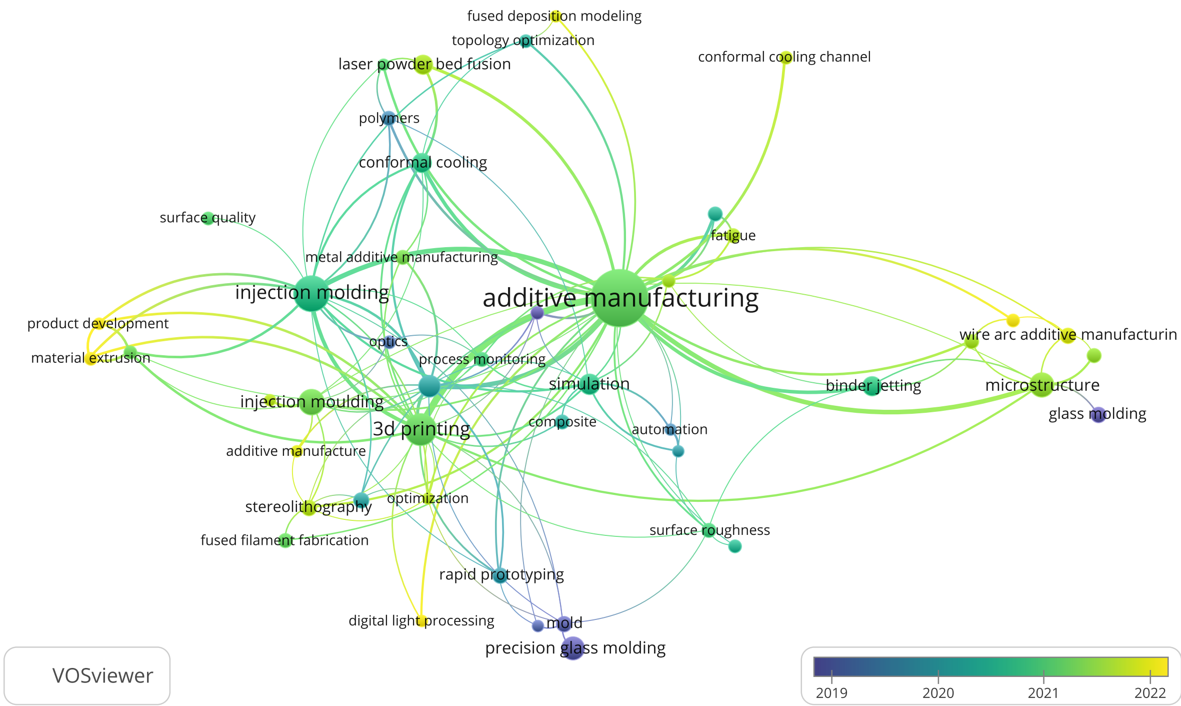


Source: Author (2022).

As can be seen, the central term is additive manufacturing, making the bridge between all of them. It can be noticed as well that this technology is more related to injection molding than precision glass molding process and that the optics is hardly present in this network, due to few works in the literature.

Furthermore, the map was filtered by year of publication, to access how recent were the selected papers to not include outdated works, revealing the year range between 2019 and 2022. Figure 35 shows the filtered network.

Figure 35 - Bibliometric network filtered by publication date



Source: Author (2022).

For the industrial case studies, conventional search tools were used, e.g., Google. Additively manufactured molds in industry and case studies were found, resulting in a total of 13 studies from different companies on the subject.

Those results will be presented and discussed in Section 4.1, regarding class of material, specific material, additive manufacturing method, goal of the produced mold and the respective reference, either company or authors.

3.2. QUALITATIVE SURVEY

Another source for information gathering was conducted through a qualitative survey (see Appendix A). The questionnaire was elaborated using Microsoft Forms online tool with 15 questions varied between open questions, multiple choice, linear scale, and checkbox within the subject of additive manufacturing applied to optical production via injection molding and glass molding.

The survey was sent to external companies and partners of Fraunhofer IPT as well as for internal researchers of the institute that work in the subject area. However, the answers were collected mainly by attending industry trade and exhibition fairs and getting in touch with the companies.

Two events in Germany were visited (Figure 36): Optatec 2022 in Frankfurt, the international trade fair for optical technologies, components, and systems; and K 2022 in Düsseldorf, the world's number one trade fair for plastics and rubber.

Figure 36 - Attended fair trades

Source: Author (2022).

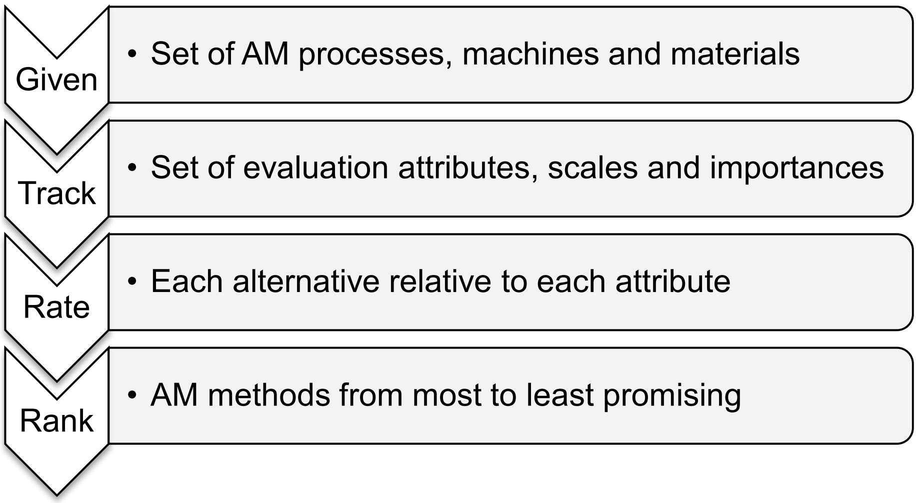
The total number of participants in the survey was 31, however, the number of answers in each question was less, since there was no mandatory question in the survey. The results will be sorted and analyzed in Section 4.2.

3.3. SELECTION CRITERIA

Gibson et al. (2020) propose a preliminary selection decision support flowchart for additive manufacturing technologies (Figure 37) consisting of four stages which was used in this research. The first stage refers to the inputs for the selection, in this case the different AM processes and materials, which must fit a series of attributes for evaluation in the second stage, previously tracked according to the production objective, which has already mentioned, are optical parts.

The third stage deals with rating each input relative to each attribute, in order to obtain a measurement parameter so that in the fourth and final stage, all solution alternatives can be ranked. For this research, the inputs of the first stage are the seven categories of AM technologies and the evaluation attributes are the key properties for molds and inserts in optics production such as thermal fatigue resistance, surface quality and dimensional accuracy.

Figure 37 - Preliminary selection decision support flowchart



Source: Adapted from Gibson et al. (2020).

The rating was conducted using the theoretical background, literature review and qualitative survey results as a base, which then leads to the final ranking of suitable solutions. Lastly, the technology with the highest score was chosen to proceed for the experimental stage of the research, presented in Section 4.3.

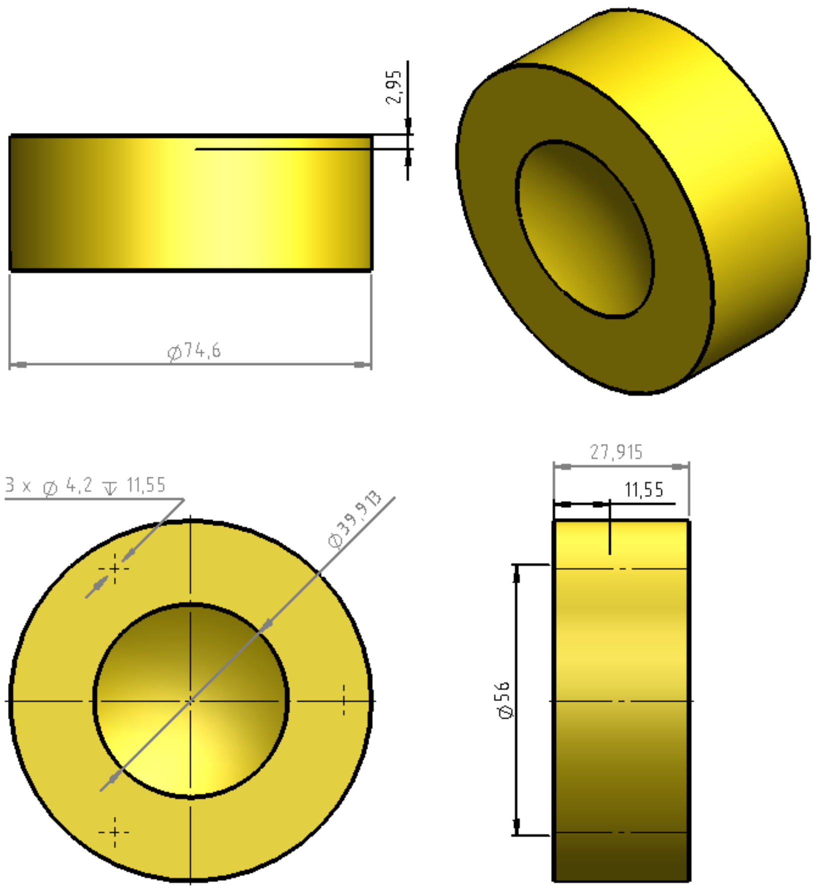
3.4. PROTOTYPE FABRICATION

In order to evaluate the chosen technology from the selection criteria, a mold insert was fabricated using additive manufacturing, which consisted of the core half (maximum diameter of 74,6 mm and height of 29 mm) of an assembly that produce an aspheric optical part via injection molding. The mold insert CAD is shown in Figure 38, the adapted mold insert CAD with cooling channels is shown in Figure 39, and the optical part in Figure 40.

The prototype was fabricated by Powder Bed Fusion technology due to the points explained in Section 4.3 with the Selective Laser Sintering process. The machine used for the manufacturing was an EOS M290, fed with the LPW-316-AAAT (stainless steel) metal powder, since is one of the most used materials for it. However, parameters such as layer thickness, layer deposition speed and laser power for example are not shared for confidentiality reasons.

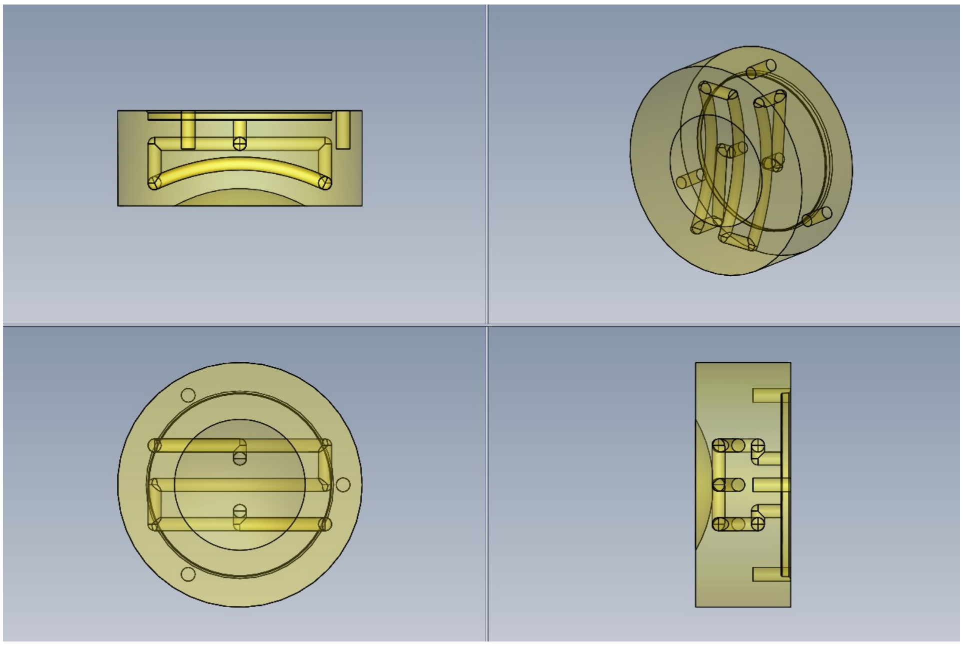
Following the manufacturing stage, surface roughness measurements (Ra, Rz and Rt) were taken from the upper surface of the insert using a Alicona InfiniteFocus optical 3D-measuring device. All production and measuring steps were conducted at Fraunhofer Institute for Production Technology.

Figure 38 – Mold insert of movable side



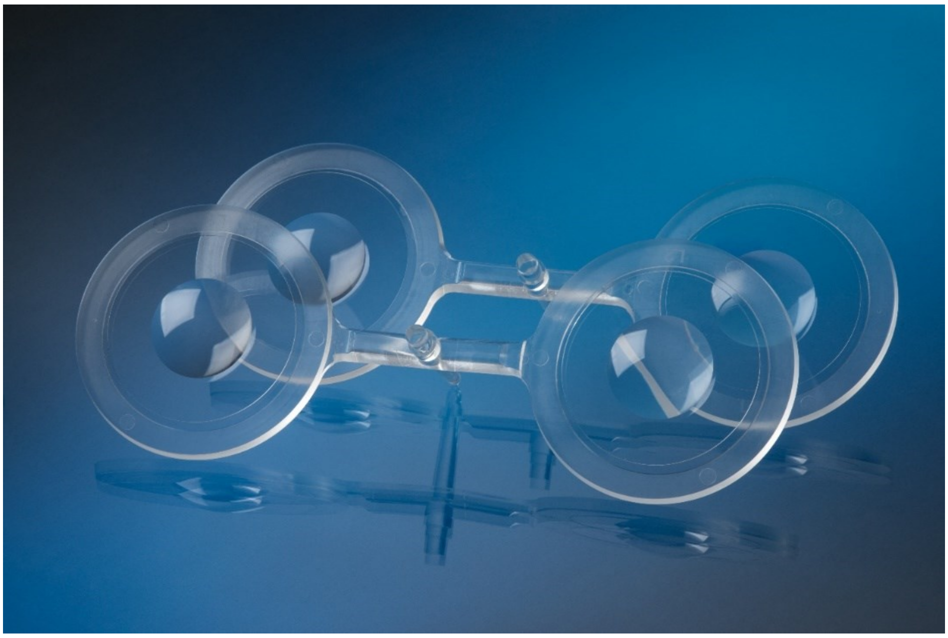
Source: Author (2022).

Figure 39 - Mold insert with cooling channels



Source: Author (2022).

Figure 40 - Aspherical lens



Source: Fraunhofer IPT (2022).

Finally, eventual changes were made using SolidWorks software to adapt the design to AM production, and to test some of its capabilities, such as adding internal conformal cooling channels in the insert (4 mm of diameter). The results of the fabrication are presented in Section 4.4.

4. RESULTS AND DISCUSSION

This chapter presents the results obtained from academic papers, industry case studies, qualitative survey answers, the application of a selection and decision process to classify the AM technologies and materials, and the physical prototype development and evaluation.

Firstly, the results of the company case studies are discussed, followed by the papers on additive manufacturing produced mold inserts and optical level surface finish of AM produced parts. The next results are from the qualitative survey, which are sorted and discussed by questions made using analysis tools.

Finally, with the previous results, the preliminary decision selection support flowchart criteria were applied to rate, rank and identify the most suitable additive manufacturing technology for the mold inserts fabrication, which a prototype was designed, fabricated, and evaluated, comparing the theoretical and practical data at the end.

4.1. RESULTS OF LITERATURE REVIEW

The search for industry studies resulted in 13 cases from 12 different companies. In general, the conducted cases deal with the optimization of the injection molding process using additively manufactured inserts.

Key information was extracted from those sources: the class of material, the specific material used in the manufacturing, the additive manufacturing method employed, the purpose of the mold, i.e., the product that was to be produced, and finally, the company that conducted the work.

It is important to note that a few of the mentioned information could not be collected in some of the cases, leaving the respective field empty, as well as other that are not discussed, such as the surface finishing process used. Table 17 summarizes the results obtained from the industry cases to better understand the current state of additively manufactured molds and inserts used in replicative production processes.

Table 17 - Additively manufactured mold: industry cases

Type	Material	Method	Goal	Company
Polymers	10K Rigid Resin High Temp Resin Grey Pro Resin	SLA	Threaded caps, prototypes, mask straps	Formlabs
Polymers	Digital ABS	PJ	Junction boxes, cord sets, splitters	Turck
Polymers	Digital ABS	PJ	-	Stratasys
Polymers	Iglidur i3	SLS	Plain bearings	Igus
Polymers	-	FFF	Screws	Apium Tec
Polymers	PLASTCure Rigid 10500	DLP	-	Hahn-Schickard
Metals	Xirodur B180	SLM	Ball bearing cages	Igus
Metals	-	SLM	-	VEM Group 3D
Metals	1.2709	SLM	-	SLM Solutions
Metals	-	SLM	Polymer optic part	Toolcraft
Metals	BÖHLER M789 Uddeholm Corrax	SLM	Syringes, bottle caps, test tubes	Voestalpine
Metals	-	SLM	-	EOS
Metals	1.2709	SLM	-	Nonnenmann

Source: Author (2022).

Powder Bed Fusion stands out compared to Directed Energy Deposition method for the additive manufacturing of metal molds and inserts, with the Selective Laser Melting process being used unanimously among the companies. On the other hand, there is not a clear technology that is being used for polymeric inserts, the founded study cases show a diverse range of possibilities, with Vat Photopolymerization, Material Extrusion and Material Jetting as the attempted methods.

In addition, when it comes to the parts produced by the companies, a preference for simple products that do not require high surface qualities to perform their function, such as mask straps, screws, and bottle caps, was noted. However, there was one exception of a polymeric optical component produced by an SLM insert, but information about its roughness was not found.

Similarly, Table 18 summarizes the information of 15 academic papers. For these results, it can be observed that the Material Jetting method is the chosen one when it comes for polymer inserts, and again, Powder Bed Fusion for the metal ones. There is also, an example of a ceramic mold, produced by additive manufacturing, showing its early stages of development for this material.

Table 18 - Additively manufactured mold: academic papers

Type	Material	Method	Goal	Reference
Polymers	Polyamide 6	MEX	Sample part	Gohn et al. (2022)
Polymers	RGD 450	PJ	Battery cellframe	Schuh et al. (2020)
Polymers	Visijet M3X Digital ABS	PJ	Sample part	Bagalkot et al. (2021)
Polymers	Methacrylic Photopolymer	DLP	Sample part	Davoudinejad et al. (2019)
Polymers	Digital ABS	PJ	Sample part	Bogaerts et al. (2021)
Polymers	Rigur	PJ	Sample part	Burggräf et al. (2022)
Polymers	Visijet M3X Digital ABS	PJ	Sample part	Bagalkot et al. (2022)
Polymers	Formlabs Resin ABS	SLA FDM	Sample part	Dizon et al. (2019)
Polymers	-	SLA	Chess piece	Whlean and Sheahan (2019)
Metals	EOS MS1 Steel	SLS	Sample part	Kanbur et al. (2022)
Metals	ER70S-6	DED	Sample part	Hassen et al. (2020)
Metals	Stainless Steel 17-4PH	SLM	Automobile piston	Heogh et al. (2022)
Metals	Ti-6Al-4V	SLM	Sample part	Park et al. (2022)
Metals	Stainless Steel 316L	SLM	Optical part	Schneckenburger et al. (2020)
Ceramics	Refractory Fused Silica Powder	SLA	Sample part	Bae et al. (2019)

Source: Author (2022).

In the same way as seen for the industry study cases, the parts researched in the academic papers have simpler requirements regarding its surface. Also, most of them were samples, that is, without specific functionality, only for example purposes, to evaluate mold characteristics and process properties, such as thermal fatigue resistance, hardness, and service life. In fact, mechanical and thermal properties are better in the metal additively manufactured inserts, when comparing with the polymer ones, which leads to a more stable and replicative process.

Among the papers on metallic AM molds and inserts, Schneckenburger et al. (2020) researched on optical parts and evaluated properties such as surface quality and dimensional accuracy. In its work, the goal was to fabricate a mold insert via selective laser melting to produce miniature size lenses.

To accomplish this, a process chain to generate the optical surfaces on additively manufactured tool inserts was proposed. After the AM step, four surface finishing methods were used to improve its quality: milling, laser polishing, milling again and abrasive polishing. Table 19 summarizes some properties of those stages.

Table 19 - Process chain of AM mold

Process	**Machine**	**Surface Roughness (Ra)**
Selective Laser Melting	TruPrint 1000 Multilaser	5,82 µm
Milling I	RÖDERS RXP500 DS	0,16 µm
Laser Polishing	TruDisk4002	0,325 µm
Milling II	RÖDERS RXP500 DS	0,1 µm
Abrasive Polishing	-	0,09 µm

Source: Adapted from Schneckenburger et al. (2020).

As can be seen, optical quality was not reached (Ra < 10 nm), although the surface finishing steps did improved the overall condition of the part. However, Zhang et al. (2021) conducted a review about the design and fabrication technology of metal mirrors based on additive manufacturing, which are components used in optomechanical applications that require low surface roughness and its challenging to machine, thus, comparable to the mold insert for optical production.

Table 20 summarizes the results of a review on the additively manufactured metal mirrors. It is shown that the Powder Bed Fusion processes are most used for those applications than DED for example, and the surface accuracy vary between a wide range (255 nm to 1,5 nm). Although the majority are still not within the optical limits, the values are suitable for optical parts in two of the cases.

Table 20 - Results from AM metal mirrors

Material	Method	Surface Accuracy (RMS)	R&D Unit
$AlSi_7Mg_{0.3}$	SLS	1,5 nm	Corning
$AlSi_{10}Mg$	SLS	43,2 nm	General Dynamics
$AlSi_{10}Mg$	SLS	255 nm	University of Arizona
Ti-6Al-4V	EBM	-	University of Arizona
$AlSi_{10}Mg$	SLM	-	Lockheed Martin
$FeNi_{36}$	SLM	-	Optimax Systems
$AlSi_{12}$	SLM	12,5 nm	Fraunhofer IOF
$AlSi_{40}$	SLM	7,3 nm	Fraunhofer IOF
$AlSi_{10}Mg$	SLS	16 nm	UKAT
$AlSi_{10}Mg$	SLM	58 nm	CIOMP

Source: Adapted from Zhang et al. (2020).

On the other hand, Atkins et al. (2019) conducted research where they compare six additively manufactured metal mirrors with six different technical routes for the surface finishing, changing machining processes, materials, and coating deposition. Table 21 summarizes its results and Figure 41 exemplifies those routes.

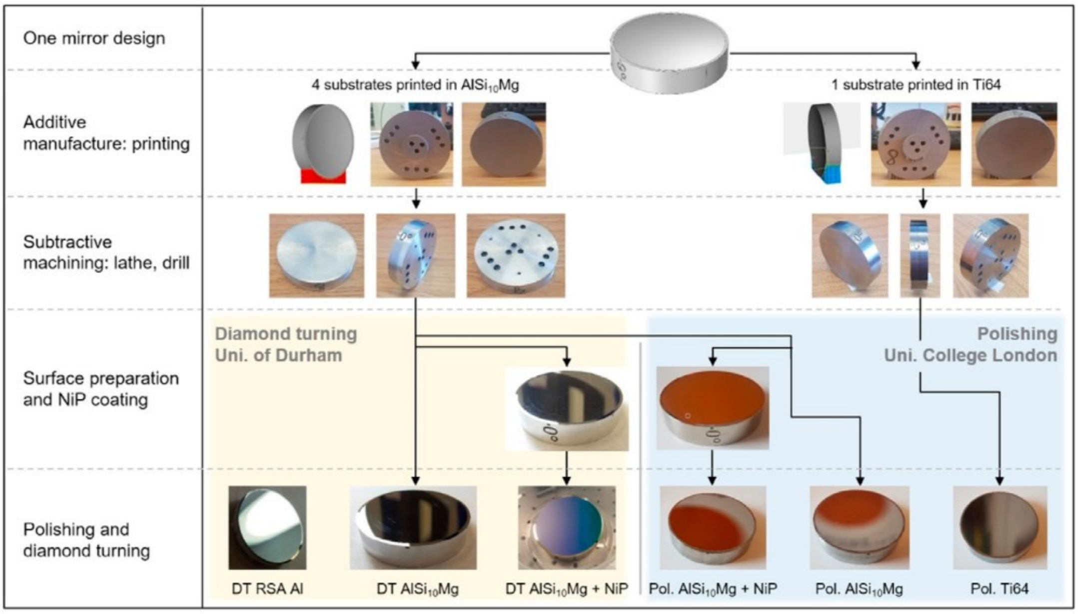
Table 21 - Experimental methods and results

Route	Material	Surface Finishing	Roughness (Ra)
1	$AlSi_{10}Mg$	Diamond Turning	5,64 nm
2	$AlSi_{10}Mg$	Diamond Turning	4,85 nm
3	RSA 6061	Diamond Turning	4,96 nm
4	$AlSi_{10}Mg$ + NiP	Polishing	2 nm
5	$AlSi_{10}Mg$	Polishing	15 nm
6	Ti-6Al-4V	Polishing	2 nm

Source: Atkins et al. (2019).

Therefore, except for route 5, all the other production chains managed to achieve roughness below 10 nm, ideal for optical applications, so it is expected that, when using such processes with similar material for the surface finishing of metallic inserts produced by AM, similar roughness can also be obtained.

Figure 41 - Schematic diagram of several experimental methods



Source: Atkins et al. (2019).

In conclusion, several examples of molds made by AM were presented, although the majority are concentrated to produce products that do not require a high degree of surface quality, some works with optical application were found, besides the supposed compatibility of production of metal mirror surfaces for optomechanical application, which already has more advanced works for high qualities.

A few mold inserts were able to be finished to qualities below 10 nm with some effort, however, most of the acquired surface qualities are higher than 10 nm, varying between 10-100 nm. Although this is not the desired value for ultra-precision optics, it is already possible to fabricate optical parts with this surface quality, such as products for lightguide applications.

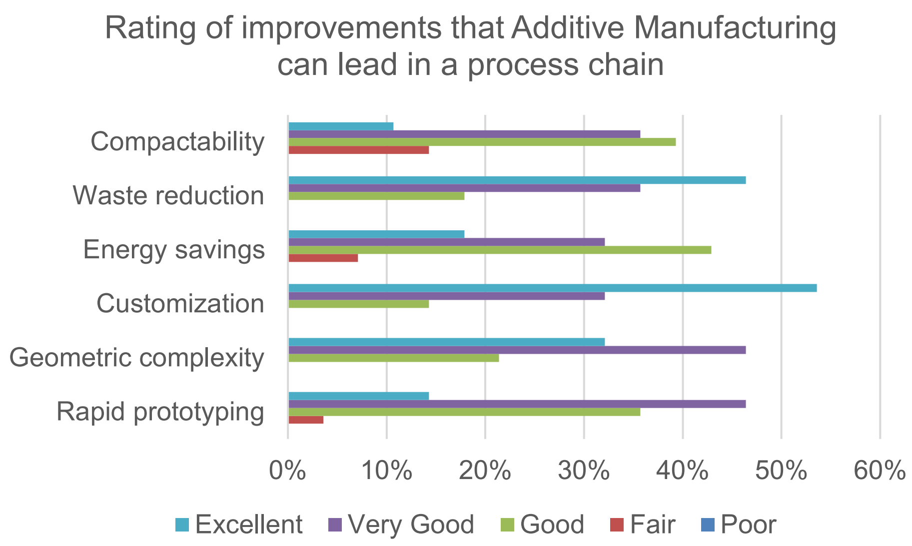
As seen, the most consolidated additive manufacturing process for optical production is Powder Bed Fusion, more specifically Selective Laser Melting, being widely used and indicated to achieve better mechanical and thermal performances.

4.2. RESULTS OF QUALITATIVE SURVEY

The qualitative survey resulted in 31 answers from different companies (see Appendix B) in the field of optics, photonics, injection molding, glass molding and mold manufacturing. The roles of the interviewees are distributed between sales, founder, owner, optical engineer, mechanical engineer, research assistant, consultant and managing director.

All of them answered that they are familiar with AM technologies and regarding the AM categories, 31 have previous knowledge about PBF processes, 28 on VPP, 27 on MJ, 26 on MEX and 1 on BJT. Also, 80% of the answers were positive about if additive manufacturing could lead to improvements and 20% weren't sure. Figure 42 summarizes the rating of the capabilities of AM processes.

Figure 42 - Survey results I



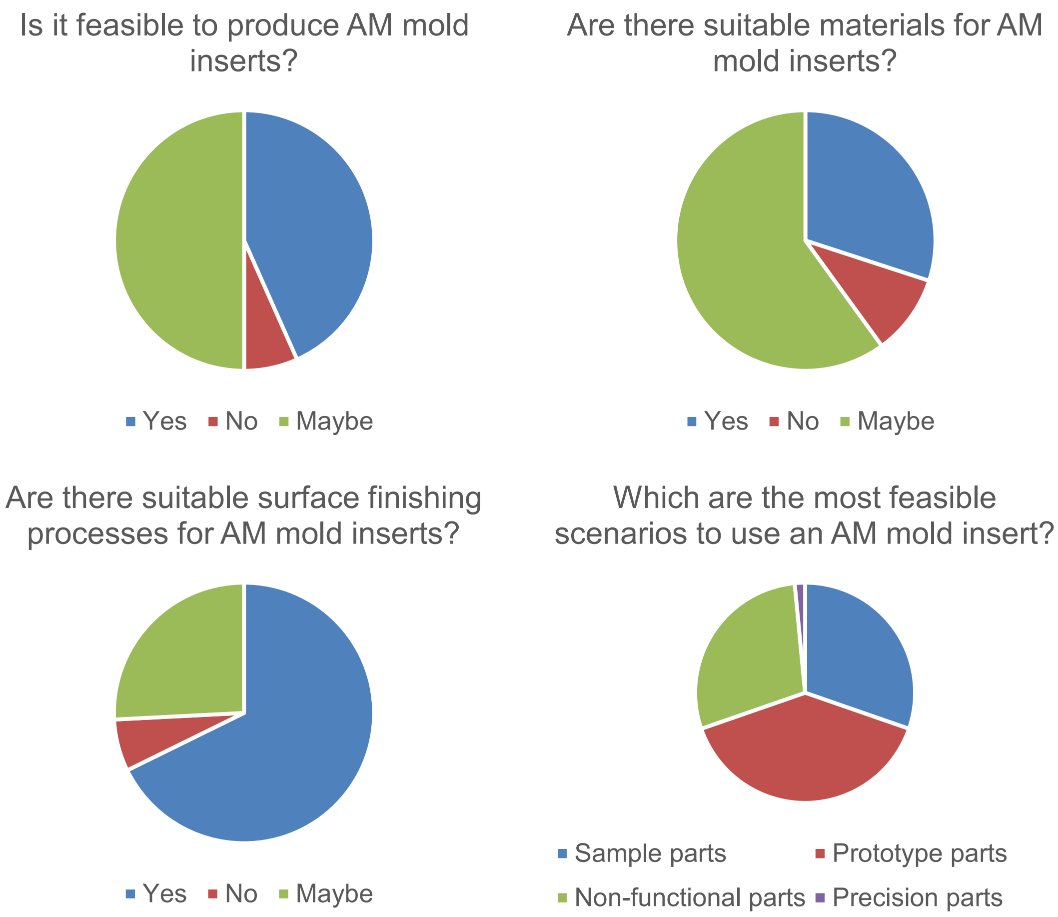
Source: Author (2022).

Customization, waste reduction and geometric complexity were the most rated improvements with the implementation of AM in a process chain, and followed by them are energy savings, rapid prototyping and compactability. In fact, the top 3 rated ones are what draws the most attention to this technology and leads to studies into the feasibility of implementing it in the production of a product.

Regarding the specific application to fabricate mold inserts via AM, Figure 43 illustrates 4 graphs with results of direct questions. It covers the topic of feasibility, suitable materials, surface finishing processes and what type of parts are the best scenarios to use AM mold tools to produce.

Most interviewees are not sure whether are suitable materials or if is it possible to produce mold inserts via AM, however they are more positive answers than negative for those questions. In fact, it was expected to have this level of uncertainty, since it is a new field for the market. On the other hand, more than 50% of the answers pointed out that suitable finishing processes for AM mold inserts are available now.

Figure 43 - Survey results II



Source: Author (2022).

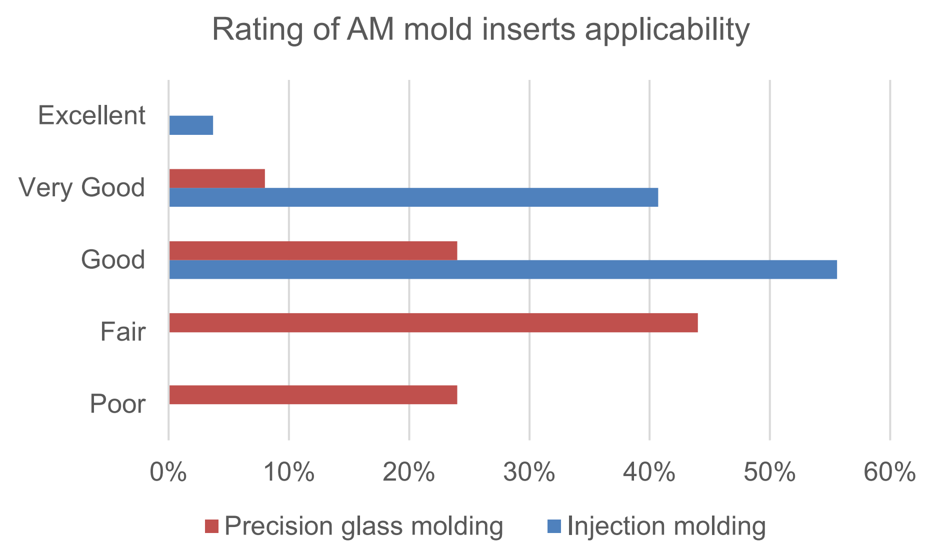
When comes to the producing scenarios for those AM mold inserts, 4 were made as an option for the answers: sample, prototype, non-functional and precision parts. As mentioned before, sample parts correspond to study reasons only; prototype to a first version of a product; non-functional to roles that are not crucial; and precision to optic applications or that require high specs.

The first three had almost the same percentage of answers, showing that the companies don’t see, at least for now, a viable production of precision parts via AM mold inserts. Indeed, as concluded from the industrial cases and academic papers, simpler parts are targeted now for production using AM tooling.

Additionally, the interviewees were also asked which additive manufacturing technologies they think are the best to produce molds for optical production, and the answer was unanimous: the Powder Bed Fusion process.

This is in accordance with what was seen in the previous Section 4.1 and throughout the research, the powder metal additive manufacturing process can obtain better characteristics needed from a mold and insert in general, as well as having easier machining to achieve the optical quality requirements. The application of those tools either in IM or PGM were also rated, as shown in Figure 44.

Figure 44 - Survey results III

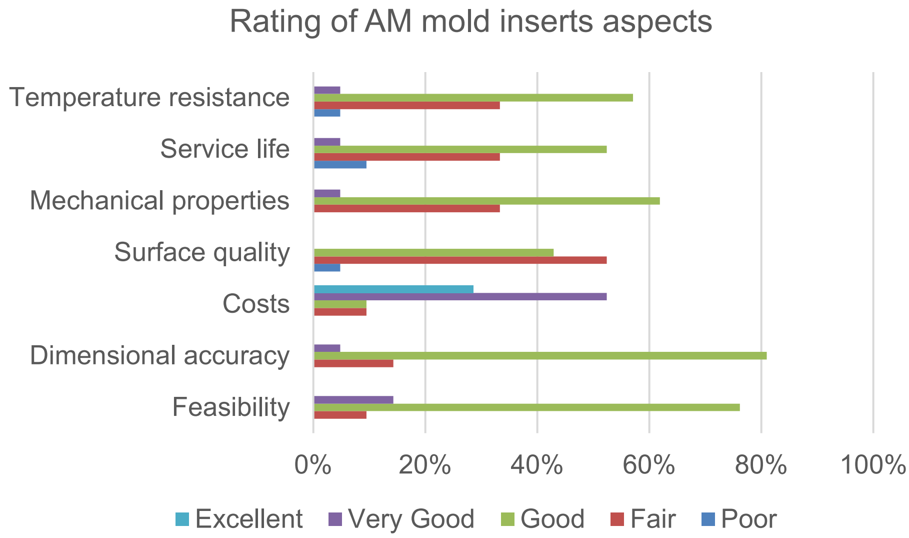


Source: Author (2022).

The best scenario rated for AM mold tooling is for injection molding, comparing with precision glass molding that doesn’t have that much of good perspectives so far, with the rating being more accentuated at the Poor and Fair levels, while injection mold is in Good and Very good levels. This mostly is due the requirements (see Section 2.3.1) that are much higher for PGM than IM, which makes easier to test on IM first, as seen as well in the industry studies and academic papers that were all based on injection molding tooling.

Lastly, Figure 45 shows the rating expectations of some of the aspects of mold inserts if they were produced via additive manufacturing. Overall, the costs were classified as being Excellent, however aspects such as feasibility and dimensional accuracy were rated most as Good, mechanical properties, service life and temperature resistance have a close range between Good and Fair, while surface quality has the worst rating, with the Fair level being the most answered.

Figure 45 - Survey results IV



Source: Author (2022).

This summarizes all the advantages and disadvantages of additively manufactured molds and inserts that were discussed so far. Although the costs, feasibility and dimensional accuracy are promising inputs for the implementation of those tools, there is still a lot of concern regarding its temperature resistance, service life, mechanical properties, and surface quality, which are crucial characteristics for the correct and safe operation of molding tools in the replicative processes.

The final and open question got less answers than the overall questionnaire, however, some interesting thoughts were shared about additively manufactured mold inserts for optics parts. The interviewees mentioned that this is a good approach for the future of production, it moves along with the current worldwide efforts to reduce waste and energy consumption and a greener process. However, most of them pointed out that it might not be good for the specific precision optics market at the moment, but rather for the packaging, for example.

It can be concluded that, with the literature review and qualitative survey, a good knowledge base was constructed to better understand the current state of additively manufactured mold inserts in the industry and academia. Besides understanding the main benefits and challenges associated to this innovation, with this content, it is possible to assist the decision-making process of technologies.

4.3. RESULTS OF SELECTION CRITERIA

Using the preliminary selection decision support flowchart (Figure 37) presented in Section 3.3 along with the results obtained from the theoretical background, literature review and qualitative survey, it was possible to elaborate a rank of the material types and additive manufacturing processes for the fabrication of mold inserts for the optic parts production.

The given set of AM technologies and material types were the initial inputs for the decision-making. Therefore, the seven categories (Vat Photopolymerization, Powder Bed Fusion, Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination, Directed Energy Deposition) and three material types (polymers, metals, and ceramics) were evaluated.

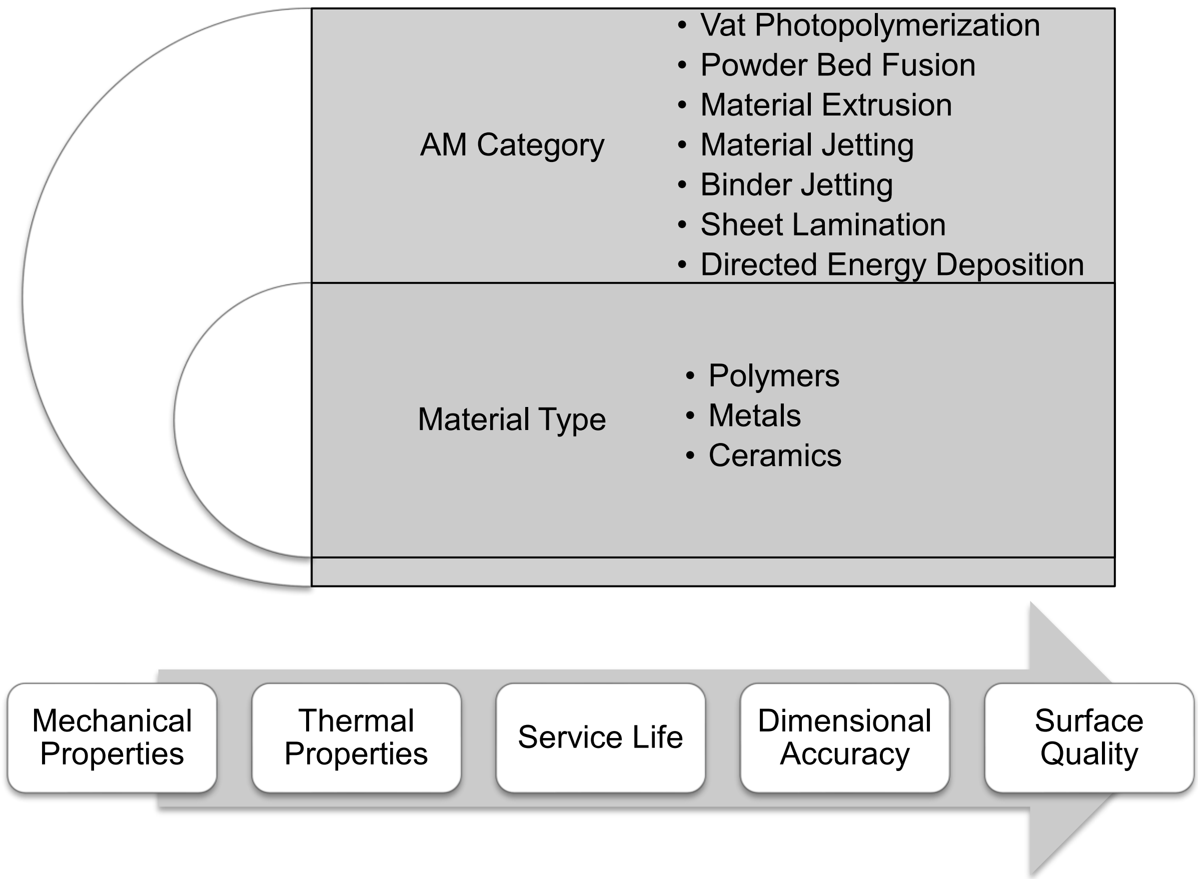
The assessment of these processes and materials was conducted based on the attributes needed to achieve the optical requirements of the parts, i.e., mechanical properties (machinability, hardness, pressure resistance), thermal properties (conductivity, fatigue resistance, temperature resistance), service life, dimensional accuracy, and surface quality. Those inputs and attributes are shown in Figure 46.

The next stage of the decision-making process rates each input relative to each attribute and then rank them from most to least promising solution. For this, it’s interesting to present the conclusions and rating factors taken from the results.

From the theoretical background, the described AM methods, advantages, disadvantages, and surface roughness comparison showed that for simple applications all of them can be used. However, when costs are a determining factor, the polymer-based ones are the best, on the other hand, if high endurance is a requirement, metal ones suit better, as they have more strength and resist to more cycles.

Although the collected data regarding surface roughness showed that polymer and metal AM processes are almost at the same range, the metal ones have more room to improvement in comparison with polymer ones after surface finishing processes, thus, if surface quality and machinability are essential, as for optical application, metal-based processes (PBF and DED) are the right choice. This guarantees a better qualification for processes based on metallic materials compared to the others in the rank.

Figure 46 - Inputs and attributes



Source: Author (2022).

In fact, when looking to the industry cases and academic papers that focused on the fabrication and implementation of additively manufactured mold inserts, the same logic is repeated.

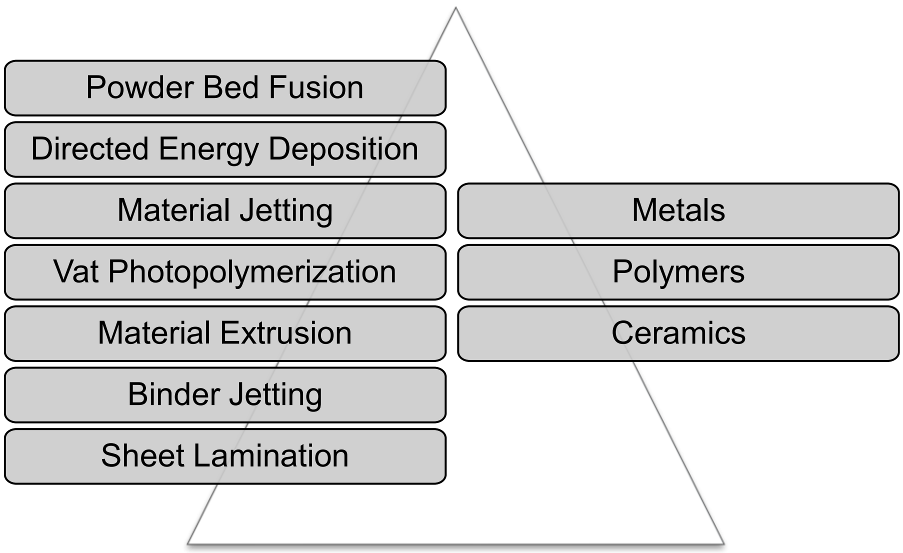
The companies that conducted study cases prioritized specific characteristics sought in their production chains: for simple products, initial tests and cost reduction in short-term small-scale production, molds made of polymer were the most applied, since they can meet these demands. In this manner, the most used processes were Vat Photopolymerization and Material Jetting, whose main difference lies in the level of accuracy and coverage of materials – higher in the PJ process.

However, even the best polymer-based AM technology cannot lead to higher endurance performance or outstanding surface qualities after finishing, which then make it necessary the use of metal-based processes, as already described. Therefore, when the production demands a greater number of cycles or higher precision in its parts, the Powder Bed Fusion was unanimously applied, with one of them having as a goal a polymeric optical part, already giving a hint of the implementation of AM in this product process chain.

The same was observed for the academic papers: MJ and VPP were the most used for the polymeric inserts while PBF for the metallic ones due to the already described characteristics. In fact, when comes to high quality surfaces, a review of additively manufactured metal mirror-like parts showed that the SLM and SLS processes were the most suitable due to their ability to improve to required roughness levels after finishing.

These results from the literature already allow the classification of the AM methods for the manufacturing of inserts for optical production, however, the qualitative survey complement the carried-out analyses. For the interviewees, the category of AM that best suits the replication process of optical parts, was unanimously the PBF, finalizing the data collection for the classification of technologies, which are ranked from most to least promising in Figure 47.

Figure 47 - Final ranking of AM methods and materials

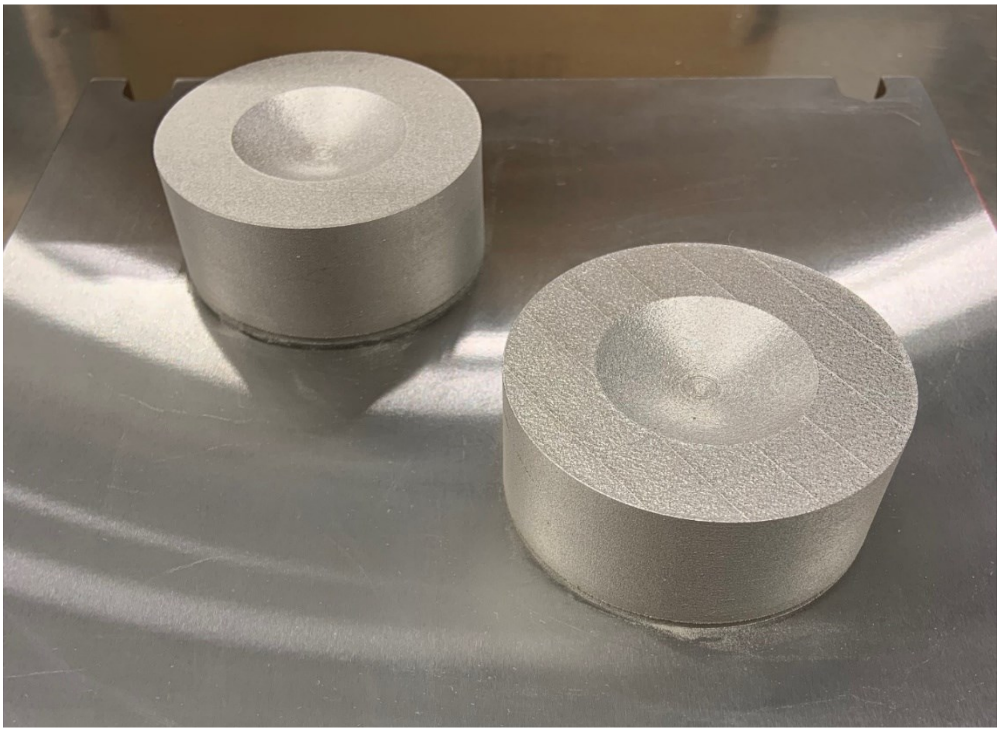


Source: Author (2022).

4.4. RESULTS OF PROTOTYPE FABRICATION

A mold insert model based on an existing one was produced to evaluate its properties in comparison with the theoretical results obtained. Two sample parts were fabricated as described in Section 3.4, with a total time of 21 hours. Figure 48 illustrates the additively manufactured mold inserts on the building plate.

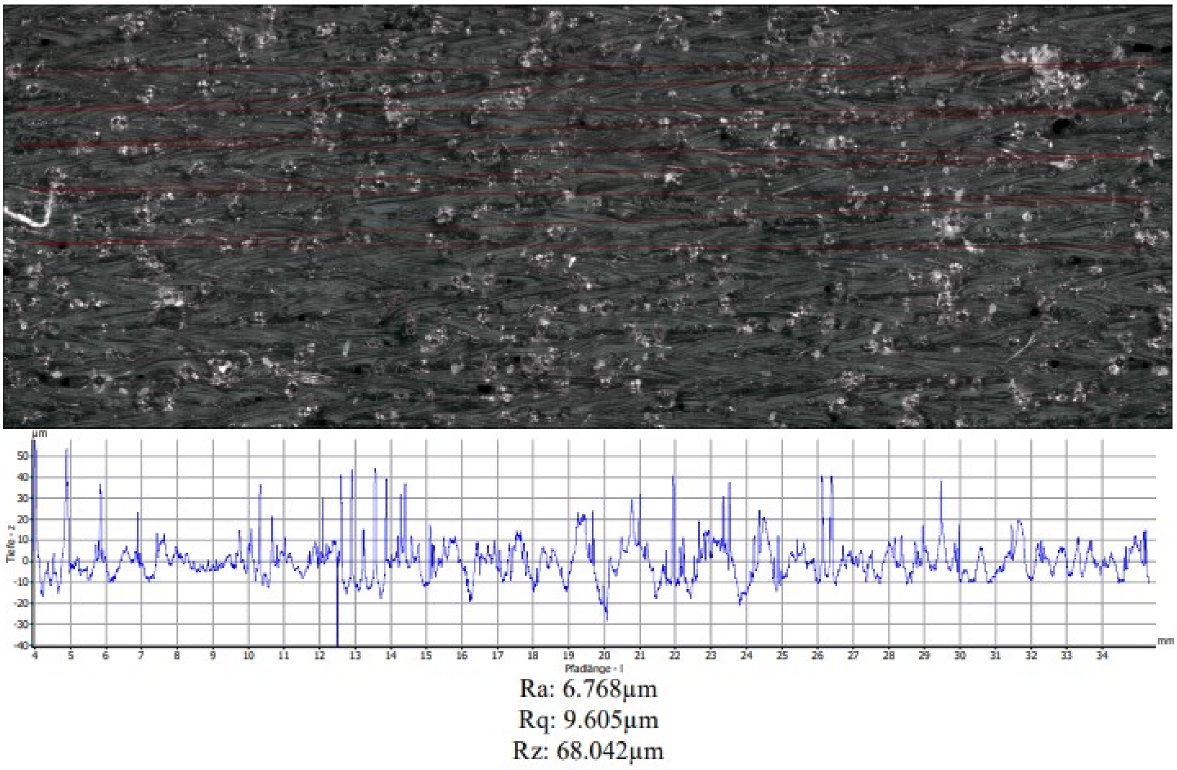
Figure 48 - AM prototype



Source: Author (2022).

The insert (see Appendix C) as built from the additive manufacturing process has a grainy sand like texture and porous surface, with irregularities in it. When compared with similar inserts that were fabricated via conventional manufacturing the AM ones are behind in overall surface quality. Values of Ra, Rq and Rz roughness's were measured, as described in Section 3.4, as well as other parameters, in order to assess these qualities. The full results report for one of the samples are available in Appendix D, however, a snapshot of it is illustrated in Figure 49.

Figure 49 - Mold insert prototype roughness



Source: Author (2022).

The prototype got an Ra of 6.768 µm, and as seen in Table 10, the roughness value fell in the same range (within 5-35 µm) from the literature. Although far from the optical quality of Ra < 10 nm, lower values are expected to be obtained with the adoption of surface finishing processes in the prototypes, to acquire the mirror-like appearance, improvement that would be lower if conducted in polymeric surfaces.

Lastly, some of the additive manufacturing capabilities proved to be successful, such as the implementation of cooling channels, reduction of waste material and boost of the fabrication lead time, it is also expected that more savings will be reached if production trials are conducted.

5. CONCLUSION

The optics and photonics market are in constant grow, with a total value of 593,7 billion USD in 2020, being found in a variety of products in the industry and everyday life. Therefore, it is important to seek for the implementation of new technologies, materials, and strategies in order to optimize the production chain of these components. In that regard, this research presented the development of a feasibility study on mold inserts fabricated by additive manufacturing to produce optical parts via injection molding and precision molding processes.

To map possible solutions in this context, the research was divided into 3 main fronts of information gathering: academic papers, industry study cases and qualitative survey answers of companies and experts in the field, with the final objective of ranking and classifying the studied technologies from most to least viable.

A database about additive manufacturing technologies and materials applied for the insert fabrication was elaborated through the analysis of the 3 information gathering sources. The obtained insights showed a good performance of additively manufactured mold inserts, using polymer-based technologies, mainly PolyJet and Vat Photopolymerization to produce simple plastic parts, such as bottle caps and packaging.

On the other hand, to produce precision parts, such as optical components, Powder Bed Fusion and Directed Energy Deposition processes have proven to be more suitable, since its metal-based and are more susceptible to thermal-endurance and surface quality improvement, characteristics that are crucial to produce optical parts. In fact, works done in the literature and industry corroborates the idea of good fulfilling of requirements for those parts using metal-based additive manufacturing methods.

In general, the results of the qualitative survey showed agreement with the literature data, the interviewees had the unanimously choice of Powder Bed Fusion processes for the manufacturing of mold inserts when asked in comparison with other technologies. It also became clear from the responses that the optical market is interested in additive manufacturing technologies, due to their broad capabilities and advantages when implemented correctly in the production system.

Therefore, with the acquired information, it was possible to apply a selection criterion to classify the additive manufacturing technologies considering their advantages and disadvantages regarding optical production. The final ranking had the Powder Bed Fusion as most suitable and Sheet Lamination as the least for the proposed application. In addition, it is considered that the most recommended surface finishing techniques to subsequent stages of the production were ultraprecision machining processes, such as diamond turning.

A prototype mold insert was designed and manufactured, based on an existing tooling used in the production chain of an aspheric lens via injection molding at Fraunhofer IPT. The prototype was modified to be compatible with 3D metal printing and internal cooling channels were added, features that do not exist in the original insert. As result, the surface quality values fell within the expected ranges before surface finishing processes (5-35 μm), moreover, the implementation of cooling channels proved to be successful in the design.

Thus, from the results presented it is now possible to conclude that the objectives of this work were achieved, having determined the technologies and materials most suitable so far for the fabrication of mold inserts by additive manufacturing with the gathered information on the subject.

Lastly, in order to proceed with the feasibility study activities, it is suggested as future work that the following tasks be conducted:

- Conduct surface finishing processes in the prototype mold inserts.
- Fabricate a mold insert by Directed Energy Deposition and compare the surface quality results with the literature.
- Compare additively mold inserts fabricated via Directed Energy Deposition and Powder Bed Fusion.
- Test different additively manufactured mold inserts made of distinct metallic materials.
- Conduct production trials with additively mold inserts in Injection Molding of optical parts.
- Conduct production trials with additively mold inserts in Precision Glass Molding of optical parts.

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APPENDIX A – Qualitative Survey

Additive Manufacturing in Mold Making

Additive Manufacturing (AM) has been growing in the last years, due to its innovative capabilities, increasingly gaining space in the industry and academia, with new technologies and methods for the fabrication and application of parts in the most diverse areas.

Regarding Injection Molding (IM) and Precision Glass Molding (PGM), an alternative for the use of AM in those processes is on additively manufactured mold inserts.

Hence, this survey aims to obtain informations, opinions and thoughts of specialists in such theme, in order to better understand the possibilities of 3D printed inserts and the feasibility of its application.

Estimated time to complete: 4 minutes.

1

What is your company name?

Ihre Antwort eingeben

2

What is your role in the company?

Ihre Antwort eingeben

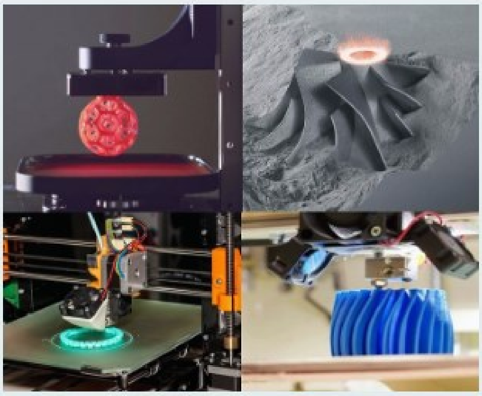
3

Are you familiar or have experience with Additive Manufacturing (3D Printing)?

- ◯ Yes
- ◯ No

4

What are the Additive Manufacturing technologies that you are familiar with?



- [ ] Vat Photopolymerization (SLA, DLP, CDLP)
- [ ] Powder Bed Fusion (SLS, SLM, EBM)
- [ ] Material Extrusion (FDM, FFF)
- [ ] Material Jetting (PJ, NPJ, DOD)
- [ ] None
- [ ] Sonstiges

5

Do you think Additive Manufacturing can lead to improvements in product process chains?

- ( ) Yes
- ( ) No
- ( ) Maybe

6

Rate the improvements that Additive Manufacturing can lead in a process chain.

	Poor	Fair	Good	Very good	Excellent
Rapid prototyping	○	○	○	○	○
Geometric complexity	○	○	○	○	○
Customisation	○	○	○	○	○
Energy savings	○	○	○	○	○
Waste reduction	○	○	○	○	○
Compactability	○	○	○	○	○

7

Do you think it is feasible to produce additively manufactured mold inserts?

- ○ Yes
- ○ No
- ○ Maybe

8

Do you think there are suitable materials for additively manufactured mold inserts?

- ○ Yes
- ○ No
- ○ Maybe

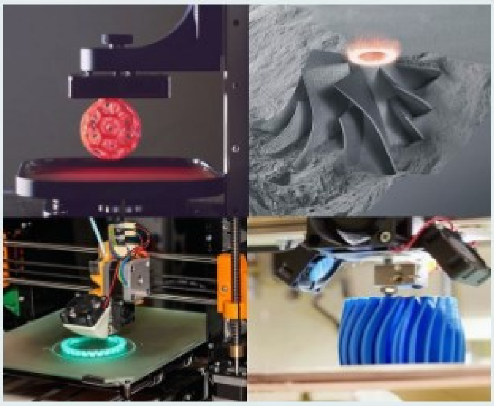
9

Do you think there are suitable surface finishing technologies for additively manufactured mold inserts?

- ◯ Yes
- ◯ No
- ◯ Maybe

10

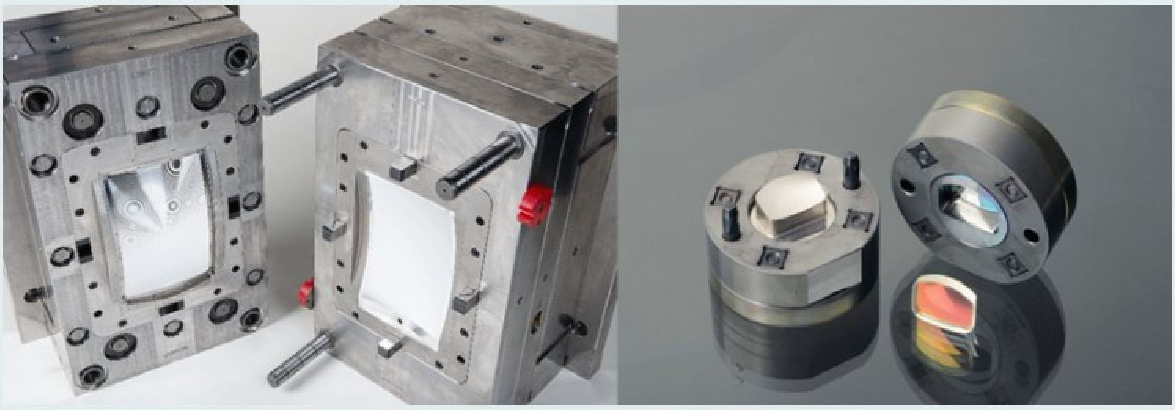
In your opinion, which are the Additive Manufacturing technologies that could be the best for mold making?



- ☐ Vat Photopolymerization (SLA, DLP, CDLP)
- ☐ Powder Bed Fusion (SLS, SLM, EBM)
- ☐ Material Extrusion (FDM, FFF)
- ☐ Material Jetting (PJ, NPJ, DOD)
- ☐ None
- ☐ Sonstiges

11

Rate the applicability of additively manufactured mold inserts in the following processes.



	Poor	Fair	Good	Very good	Excellent
Injection Molding	○	○	○	○	○
Precision Glass Molding	○	○	○	○	○

12

In your opinion, which scenarios are the most feasible to use an additively manufactured mold insert?

- ☐ Sample parts
- ☐ Prototype parts
- ☐ Non-functional parts
- ☐ Precision parts
- ☐ Sonstiges

13

Rate the aspects of additively manufactured mold inserts.

	Poor	Fair	Good	Very good	Excellent
Feasibility	○	○	○	○	○
Dimensional accuracy	○	○	○	○	○
Costs	○	○	○	○	○
Surface quality	○	○	○	○	○
Mechanical properties	○	○	○	○	○
Service life	○	○	○	○	○
Temperature resistance	○	○	○	○	○

14

What are your thoughts about using additively manufactured inserts for the production of precision optic parts?

Ihre Antwort eingeben

15

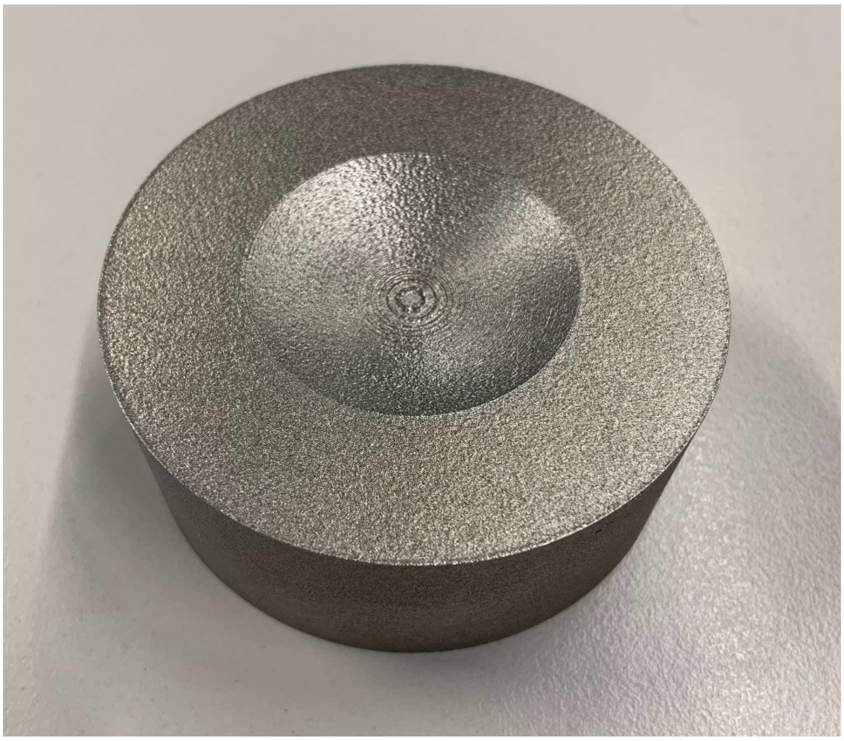
Your contact for further questions.

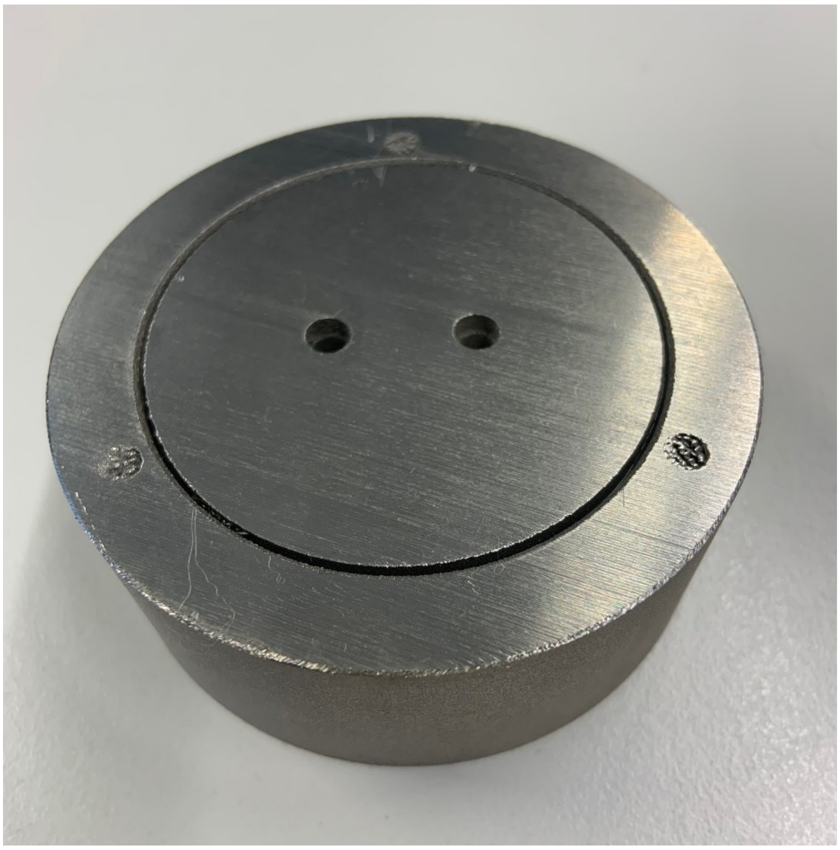
Ihre Antwort eingeben

APPENDIX B – List of Companies

Amstog
QED Technologies
Fraunhofer IPT
Innolite
Himax IGI Precision
3D AG
Röders
Kerdry
Opticoelectron Group
Sill Optics
Moulded Optics
Ametek
Bazigos
Wittmann
Brink
VBF Mould Production
ARBURG
Fraunhofer IFAM
Fraunhofer IOF
HWANG MOLD
Precision Moulds
EOS Electro Optics Systems
GODE Mold
Dioma
Erwes Reifenberg
Mold Masters
Oerlikon
Esistampi
Meusburger
Freeform Aspac

APPENDIX C – Mold Insert Prototype





APPENDIX D – Roughness Measurement Report

Alicona Imaging GmbH
Dr.-Auner Strasse 21a
A-8074 Raaba/Graz

alicona

Measurement Report

Profilmessung

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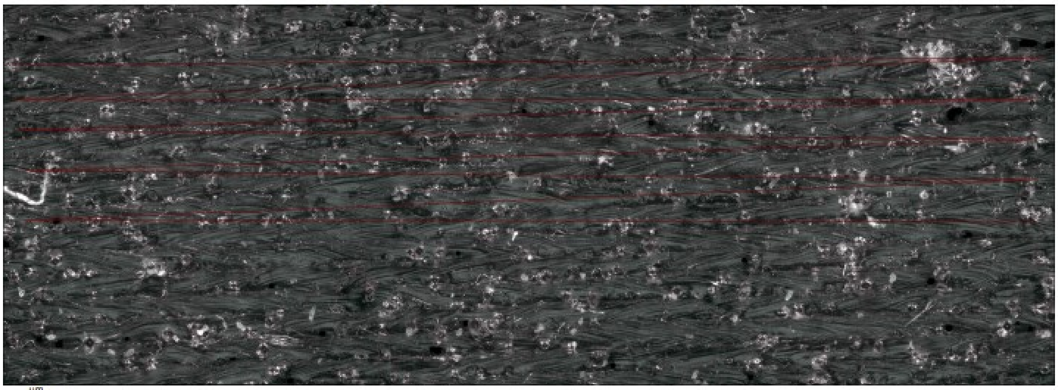
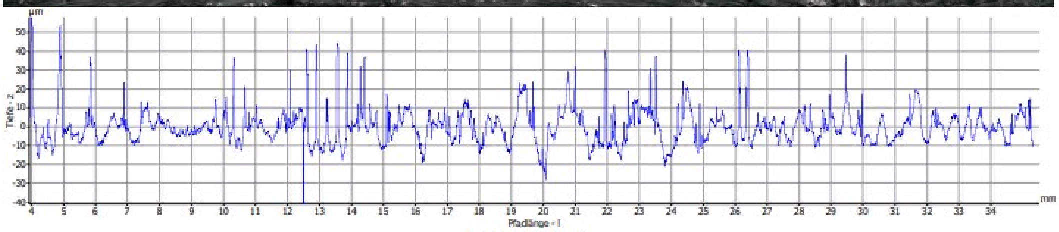
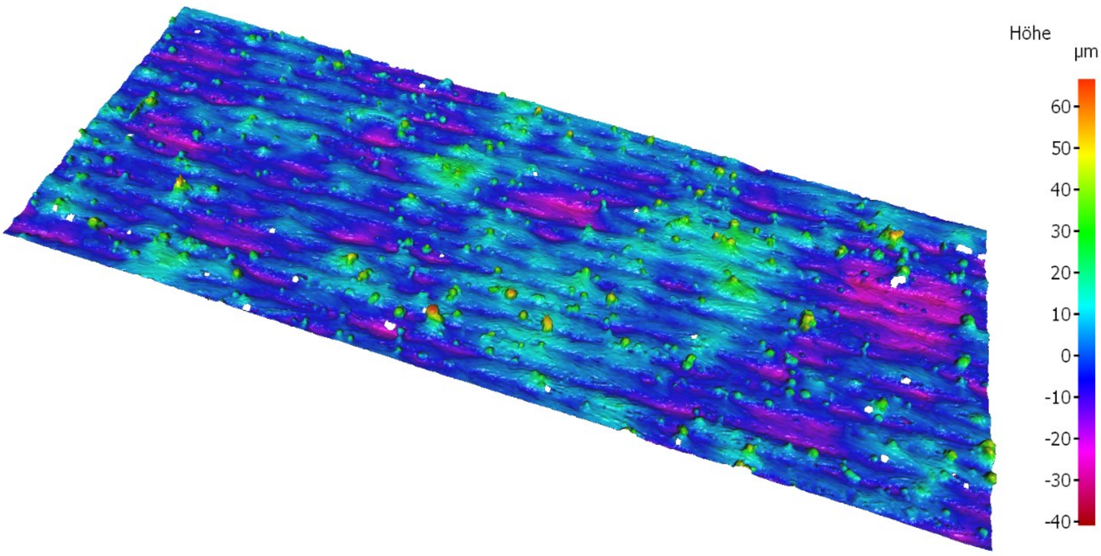




Ra: 6.768µm
Rq: 9.605µm
Rz: 68.042µm

Filter: Hochpass - Rauheitsprofil
Lc:= 2.500mm



Alicona Imaging GmbH
Dr.-Auner Strasse 21a
A-8074 Raaba/Graz

alicona

Measurement Report

ProfilRauheitsMessung

Parameter des Rauheitsprofils

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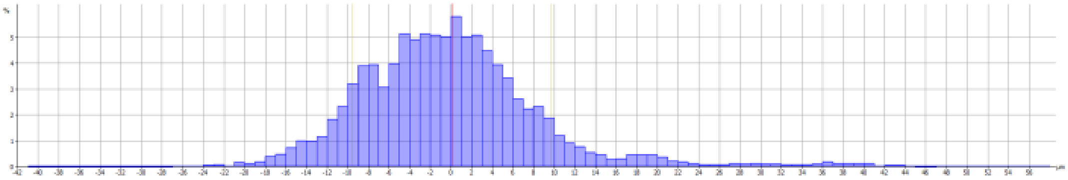

Histogramm Histogramm Einstellungen

Klassenanzahl: 99
Minimalwert: -41.004µm
Maximalwert: 57.996µm
Klassenbreite: 1.000µm

Statistiken

Name	Wert	Einheit	Beschreibung
Elemente	52430		Anzahl von Datenpunkten
Klassen	99		Anzahl von Histogrammklassen
Durchschnittswert	0.114	µm	Mittelwert der Datenpunkte
Standardabweichung	9.604	µm	Mittelwert der Standardabweichung

Parameter

Name	Wert	Einheit	Beschreibung
Ra	6.768	µm	Mittlere Rauheit des Profils
Rq	9.605	µm	Quadratischer Mittelwert der Rauheit des Profils
Rt	98.781	µm	Gesamthöhe des Rauheitsprofil
Rz	68.042	µm	Gemittelte Höhe des Rauheitsprofil
Rmax	85.315	µm	Maximale Höhe des Rauheitsprofil innerhalb einer Einzelmessstrecke
Rp	57.777	µm	Höhe der größten Profilspitze des Rauheitsprofil
Rv	41.004	µm	Tiefe des größten Profiltales des Rauheitsprofil
Rp5	44.388	µm	Mittlere Höhe der größten Profilspitzen des Rauheitsprofil
Rv5	23.653	µm	Mittlere Tiefe der größten Profiltäler des Rauheitsprofil
Rc	41.927	µm	Mittlere Höhe der Profilunregelmäßigkeiten des Rauheitsprofil
Rsm	1.089	mm	Mittlerer Abstand der Profilunregelmäßigkeiten des Rauheitsprofil
Rsk	1.543		Schiefe des Rauheitsprofil
Rku	8.297		Steilheit des Rauheitsprofil

Name	Wert	Einheit	Beschreibung
Rdq	0.468		Quadratischer Mittelwert der Profilsteigung des Rauheitsprofil
Rt/Rz	1.452		Extreme Kratzer/Spitzen-Wert von Rauheitsprofil, (>=1), höhere Werte bedeuten größere Kratzer/Spitzen
l	39.246	mm	Profillänge
Lc	2.500	mm	LambdaC: Grenzwellenlänge

Alicona Imaging GmbH
Dr.-Auner Strasse 21a
A-8074 Raaba/Graz

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Measurement Report

FlächenTexturMessung

Oberflächentextur des Rauheitsdatensatzes

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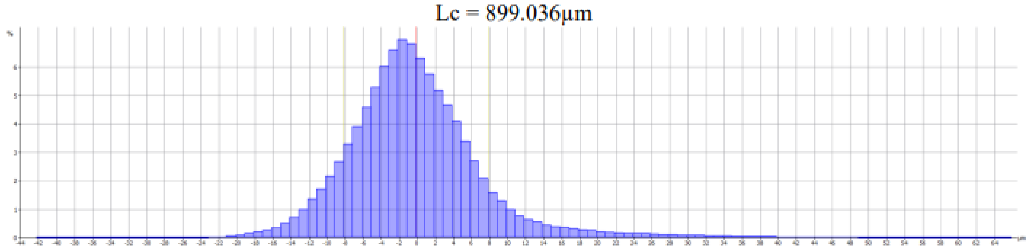
Lc = 899.036µm



Histogramm Histogramm Einstellungen

Klassenanzahl: 108
Minimalwert: -42.184µm
Maximalwert: 65.816µm
Klassenbreite: 1.000µm

Statistiken

Name	Wert	Einheit	Beschreibung
Elemente	9361031		Anzahl von Datenpunkten
Klassen	108		Anzahl von Histogrammklassen
Durchschnittswert	-0.131	µm	Mittelwert der Datenpunkte
Standardabweichung	8.057	µm	Mittelwert der Standardabweichung

Parameter

Name	Wert	Einheit	Beschreibung
Sa	5.663	µm	Arithmetischer Mittelwert der Höhen der ausgewählten Fläche
Sq	8.058	µm	Quadratischer Mittelwert der Höhen der ausgewählten Fläche
Sp	64.865	µm	Größte Höhe der ausgewählten Fläche
Sv	42.184	µm	Größte Tiefe der ausgewählten Fläche
Sz	107.048	µm	Maximale Höhe der ausgewählten Fläche
S10z	100.532	µm	Zehn-Punkt-Höhe der ausgewählten Fläche
Ssk	1.479		Schiefe der gewählten Fläche
Sku	8.756		Kurtosis der gewählten Fläche
Sdq	0.808		Quadratischer Mittelwert der Steigungen

Name	Wert	Einheit	Beschreibung
Sdr	23.881	%	Verhältnis des Überschusses der wahren Fläche zur projizierten Fläche
FLTt	107.048	µm	Ebenheit mittels Referenzebene der kleinsten Fehlerquadrate
Lc	899.036	µm	LambdaC: Grenzwellenlänge