3D-printing of plastic optical components & comparison to traditional manufacturing methods

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3D-printing of plastic optical components
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Abstract

Optical components used in industrial, commercial and military imaging systems are commonly made out of various glass materials, which offer a range of suitable properties for optical usage. However, manufacturing components from glass is a complex and slow process, generally leading to high expenses of individual imaging components. Polymer materials, such as thermoplastics and thermoset plastics, are therefore introduced as more cost-effective alternatives. The manufacturing methods of plastic optical components are presented and compared, and special emphasis is put on manufactureability and open communication between the parties involved in the process chains.

Focusing on manufacturing of plastic optics, four copies of an aspheric lens designed by Senop Oy are fabricated with a novel 3D-printing method, and the surface qualities of the whole lens studied with a tilted wave interferometer. The results of the full-area measurements show surface roughness values in single micrometers and form deviation values in the tens of micrometers, suggesting that the lenses are not sufficient for imaging usage. On the other hand, the lenses were printed in relatively little time and had no post-processsing or iterative methods attempted, and yet they still are not far from adequate considering plastic components.

It is therefore proposed that more research and development should be conducted on improving the methods and processes. Ultimately, raising awareness of the possibilities of additive manufacturing is deemed vital, as 3D-printing has potential to become a viable choice for rapid optical prototyping in the future.

Preface

This manufacturing-themed thesis is carried out in collaboration with the Department Physics and Mathematics of the University of Eastern Finland in Joensuu and Senop Oy in Lievestuore, Finland. The thesis is supervised by Research Director Petri Karvinen from the UEF, and R&D Specialist Jyrki Pikkarainen from Senop Oy.

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Joensuu, the 9th of December 2019 *Juuso Uusimäki*

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Chapter I

Introduction

Optics as a science studies the physics of light, describing the laws and phenomena related to its propagation and interaction with the atoms and electrons of regular matter. Optics is often aimed towards practical usage in the form of optical components, which are the heart of all optical systems found in diverse sections of modern technology: each time a picture is taken with a camera, a data packet sent and received via the internet or the night sky observed with a telescope, various forms of optical components (lenses, mirrors, waveguides) are utilized in guiding light in some desired manner. [1, 2] Optical components are commonly made from different types of glass due to its excellent optical properties for visible light (high of refractive indices of over 1.5, great transmissive capabilities) and beneficial mechanical attributes, such as structural stability (rigidity, scratch resistance) and tolerance of environmental conditions (e.g. temperature & humidity changes), making it the most popular material for imaging optics. [3]

However, the manufacturing of glass components usually comes with a relatively high price and has limited geometrical possibilities (spherical surfaces are favoured [4]), restricting their usage in e.g. mass-manufactured products that would not necessarily require such high quality components or have a strict weight limit. This has driven a search for more cost-effective and versatile materials that could be at least partially used to manufacture replacements for certain glass components in optical systems, or come up with innovative design solutions resulting in the usage of glass being completely unnecessary in various imaging products. [4, 5] As a result, carbon-based plastic polymers have risen to become a competitor to glass products,

and components from plastics have already been utilized in various applications, such as medical arthroscopes, military-grade night vision devices and mobile camera systems. [6] Plastics tend to be cheaper, lighter and offer more freedom in their optomechanical capabilities, and manufacturing of plastic optical components has many advantages in e.g. repeatability and creation of freeform surfaces. [4] Plastic imaging optics of are possible to manufacture with various different methods, commonly by utilizing injection moulding (IM) and diamond turning (DT) technologies, of which the former has been originally designed for mass-manufacturing various plastic products from packaging to mechanical assemblies, and the latter for precision machining metal parts and components. [4] Moreover, as additive manufacturing (AM) has become increasingly popular during the last decades, special 3D-printing (3DP) methods have been developed with having fabricating macroscale (diameter in centimeters) imaging optics in mind. [7] Utilizing one of these technologies to print an aspheric lens for Senop Oy and characterizing its surface qualities on the whole aspheric area is the research topic of this thesis, aiming to provide a clear picture on the actual quality of the printable components and how the novel technology compares to readily available manufacturing methods.

The voyage to understanding plastic optics starts from chapter two, where the fundamentals of optics and related phenomena are shown to be widely applicable in the form of common optical components, which have specific surface requirements to fill if desired to be used in imaging applications. Additionally, optical-grade plastics, meaning plastic materials that fit some sort of optical task, are described with a comparison to glass materials, and the various manufacturing methods of AM, IM and DT are introduced. The methods are then compared with an intention to provide guidance for parties wishing to participate in manufacturing of plastic optics. It is essential to keep in mind that, if not otherwise specified, solely macroscale lenses are the focus of the study. The research-part of the thesis is presented in the next two chapters, starting from describing the technology and the process behind the printing as well as the interferometric metrology setup in chapter three, whereas the fourth chapter visualizes the results of the surface measurements. Chapter five is reserved for analyzing the results and discussing their importance, with conclusions of the study presented in chapter six. All in all, an extensive comprehension of plastic optics and its manufacturing methods is sought.

Chapter II

Plastic optics

The requirements for high-grade optical components, such as high transparency and a high refractive index, are properties common plastics tend not to inhibit due to their molecular structure and absorption properties, which render many of the materials with otherwise useful structural properties opaque. However, development in plastic materials has lead to solutions that can be utilized in efficient manufacturing of plastic optical components. [4] The theoretical properties and requirements of such materials are described in this chapter, though starting from the basic theories and concepts of optics. Several different manufacturing methods of plastic optical components are also presented, with discussion on their advantages and shortcomings, ending with a brief material overview.

2.1 Basics of optics

The physical nature of light (electromagnetic radiation) and its properties are classically modelled with Maxwell's equations of electrodynamics, which with four partial differential equations describe the theoretical framework of electric and magnetic fields in free space, binding them together as electromagnetism. Maxwell's equations also enable modelling how light interacts with the physical world. [1, 8] However, even though it is beneficial to be familiar with the highly theoretical background, the basics of light and related phenomena are more appropriate to review in this manufacturing-themed thesis, starting from the propagation of light and interfaces.

2.1.1 Propagation of light & interfaces

Discovering how light propagates through the vacuum of space requires finding a solution to the differential wave equation

$$\frac{\partial^2 \Psi}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 \Psi}{\partial t^2}, \tag{2.1}$$

where Ψ is a wavefunction describing the propagation of the wave (one-dimensional, for the sake of simplicity), x the displacement, v the velocity and t the time. [9] In vacuum, a common solution is the harmonic plane wave with a wavelength of λ, presented in a complex exponential form as

$$\Psi = A \exp\left[i(kx - \omega t)\right], \tag{2.2}$$

where A is the amplitude, $k = 2\pi/\lambda$ the propagation constant and $\omega = 2\pi\nu$ the angular frequency (ν is the frequency of the radiation). [9] A wave of this form propagates in the x-direction in vacuum with a constant velocity, the speed of light, defined as

$$c = 1/\sqrt{\epsilon_0 \mu_0}, \tag{2.3}$$

where ϵ_0 is the electric permittivity and μ_0 the magnetic permeability of free space [1]. Permittivity ϵ in general describes how an electric field behaves in the medium, whereas permeability μ depicts the medium's interaction with magnetic fields [8]. A single quanta of light, a photon, has an energy of

$$E = h\nu, \tag{2.4}$$

where h is Planck's constant. [1] Therefore, the higher the frequency (and shorter the wavelength), the higher the energy of the photon.

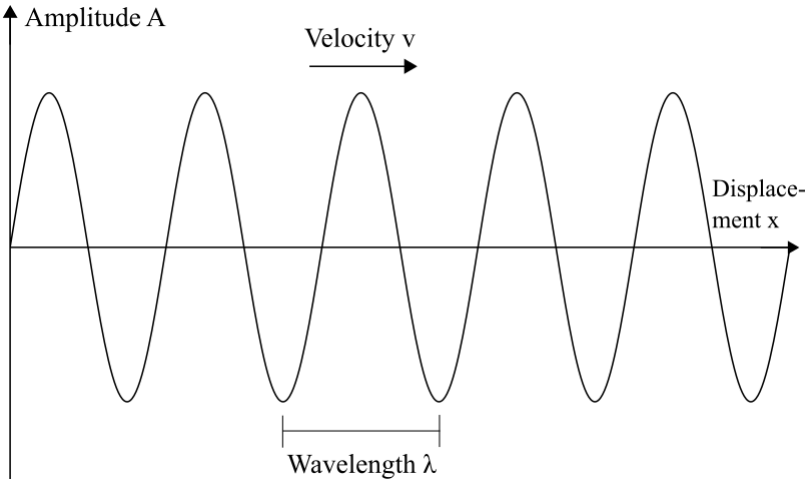

Figure 2.1: Propagation of a harmonic wave.

Even though the speed of light in vacuum is a constant, the velocity of an electromagnetic field changes as it propagates to a dielectric medium, such as air or glass (molecules made of atoms with electrons). The velocity of propagation changes because of the different properties of the media in the atomic scale, leading to dissimilar responses to the propagating electromagnetic fields. This change of propagation velocity is described with the refractive index n, which is defined as the ratio between c and the velocity of the electromagnetic wave in the propagating medium v: [1]

$$n = c/v, \tag{2.5}$$

and since

$$v = 1/\sqrt{\epsilon\mu}, \tag{2.6}$$

the refractive index becomes

$$n = (\pm)\sqrt{\epsilon\mu/\epsilon_0\mu_0}. \tag{2.7}$$

When a propagating field faces a boundary between media, an interface, with different propagation velocities (and therefore refractive indices), two phenomena can occur if no absorption is present: a part (or all) of the incident wave can be reflected off the interface or transmitted through to the second medium. In the case of transmission, the wave experiences a change in the direction of propagation inside the

medium: refraction. Refraction is a cornerstone of optics, and it is usually described with either Fermat's or Hyugens' principles, which both lead to the law of refraction, also known as Snell's law: [9]

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{2.8}$$

where n_1, n_2 are the refractive indices of the media, and θ_1, θ_2 the angles of the incident and transmitted waves. Snell's law can be applied in e.g. calculating angles of refraction at an interface: when light enters a medium with a higher refractive index than that of the incident one, it bends towards from the normal of the interface ($\theta_1 > \theta_2$), and the larger the refractive index of the refracting media, the closer to normal the light bends. In the opposite case, when propagating from a medium with a higher to one with a lower n, light bends away from the normal, as illustrated in figure 2.2. This behaviour leads to some special phenomena, such as total internal reflection and the Brewster angle, which are useful in many optical applications. [10]

Moreover, in a case of no absorption all light must be spread between reflection and transmission, leading to a simple relationship between reflectance R and transmittance T:

$$R + T = 1, \tag{2.9}$$

in which case reflectance and refractive index are related by [1]

$$R = \frac{(n-1)^2}{(n+1)^2}. \tag{2.10}$$

Similarly, for transmittance [9]

$$T = \frac{4n_1 n_2}{(n_1+n_2)^2}. \tag{2.11}$$

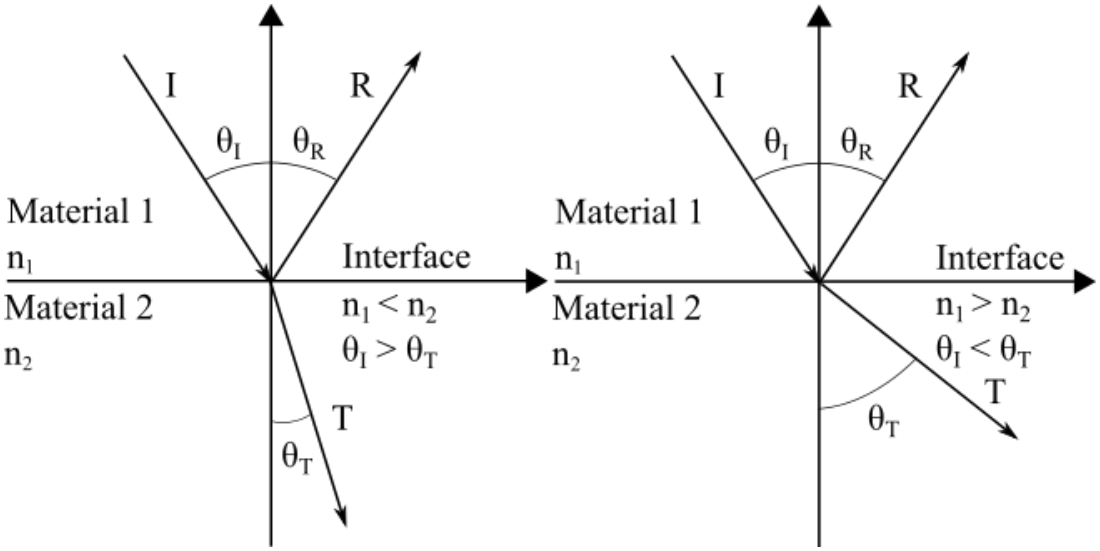

Figure 2.2: Reflection (R), transmission (T) and refraction of incident (I) light at an interface. Depending on the refractive indices of the materials, light is refracted at different angles.

2.1.2 Dispersion & Abbe number

The index of refraction, even though generally considered a constant for a material, is in reality dependent on the wavelength of the propagating radiation, meaning shorter wavelengths refract in a different angle than longer ones - this phenomena is called dispersion. Theoretically, dispersion arises from the interaction of the electromagnetic field and the atoms (electrons) of the matter, and is an important property of an optical material, as it can lead to e.g. chromatic aberrations in the imaging system: due to refraction being dependent on the wavelength of light, and the wavelengths of visible light being perceived as different colors by humans, various colours may be focused on different areas of the detector or not focused at all. [1]

Dispersion can be approximated with the empirical Sellmeier equation:

$$n(\lambda) = \sqrt{1 + \sum_{i=1} \frac{B_i \lambda^2}{\lambda^2 - C_i}}, \tag{2.12}$$

where B_i, C_i are material-specific Sellmeier coefficients [1,11], and a numerical value for dispersion and the dispersive effect of a material can be given with the Abbe number:

$$V = \frac{n_d - 1}{n_F - n_C}, \tag{2.13}$$

where the n_d, n_F and n_C are defined as the material's refractive indices at wavelengths 587.6 nm, 486.1 nm and 656.3 nm, corresponding to blue, yellow and red colors, also known as Fraunhofer's D-, F- and C-lines. A larger Abbe number corresponds to a lower refractive index and lower dispersion and *vice versa*. [4] The refractive index of a material and therefore its Abbe number can also change due to phenomena such as thermal expansion, which with other heat-related issues of plastics are discussed in section 2.2.

2.1.3 Optical components

As has been presented, the refractive properties of transparent materials and the phenomena that are caused by the refraction of light are utilized with optical components, of which the most common are lenses. Lenses are used to focus light in a certain manner, either to converge or diverge the incident wavefront, essentially altering its propagation direction or wavefront curvature. Lenses often have at least two refractive surfaces, of which usually one or both are curved in a spherical or aspherical (near-spherical) manner, though the surfaces can even be freeform, meaning any geometrical shape that refracts light in a desired way. [1,12]

Lenses also have certain properties, such as the focal length f (how far the lens focuses the light) and diameter D (how thick the lens is), and their ratio is called the f-number $N = f/D$. [1,13] Lenses can be used to, for example, magnify or decrease the size of the image of an object, and multiple different lenses can be set up as an optical system, leading to creation of devices such as telescopes, microscopes and cameras. Figure 2.3 showcases dispersion of a plano-convex lens, whereas 2.4 shows a ray-tracing simulation for certain lens types.

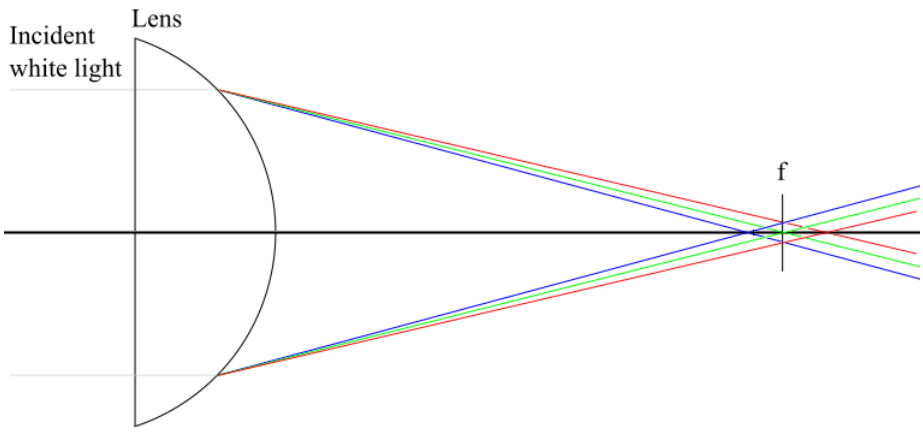

Figure 2.3: Dispersion of white light through a plano-convex lens. Blue and red wavelengths do not focus exactly on the focal point (f), whereas green does.

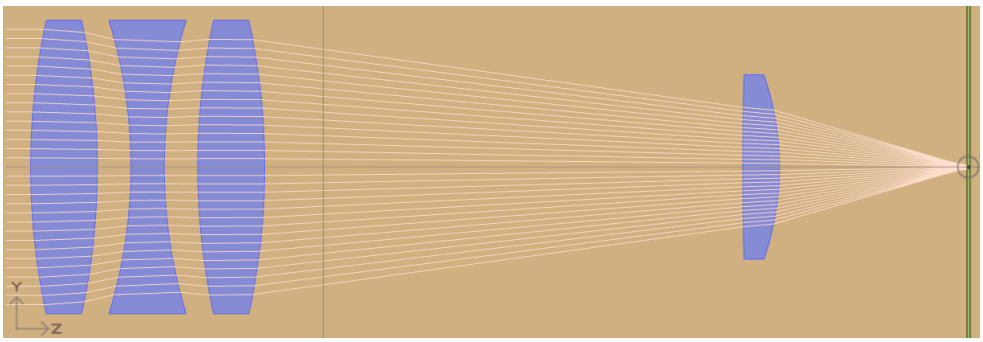

Figure 2.4: A ray-tracing simulation showcasing how common lenses refract light. Independently created using Synthrays. [14]

A purely spherical lens design is actually a simplification of sorts, as its properties are mostly described by its radius of curvature. Aspheric lenses, on the other hand, make use of the dispersive effects of the material, and have more freedom in the design phase: aspherics can be described with

$$Z(s) = \frac{Cs^2}{1 + \sqrt{1 - (1+k)C^2 s^2}} + A_4 s^4 + A_6 s^6 + A_8 s^8 + ..., \tag{2.14}$$

where Z is the sag of the surface parallel to the optical axis, s the radial distance from the axis, C the inverse of radius, k the conic constant and the A_n terms the orders of aspheric coefficients. [15] Aspheric lenses can also be designed to eliminate issues that riddle systems that use spherical lenses, two of those issues being spherical aberration and astigmatism. However, aspheric lenses tend to be harder to design and manufacture due to their more complex surfaces geometries, leading to higher costs per component. What is more, measuring their properties with the tools and techniques used for spherical lenses can be troublesome, and post-processing (e.g. grinding, polishing) can turn out very demanding, as real-world lenses always suffer from issues caused by roughness and form inaccuracies. [16]

2.1.4 Surface roughness & form deviation

Even though any degree of precision can be reached in the design phase of optical components, no produced lens can ever be manufactured perfectly. During the process chain of manufacturing, surface errors always emerge in each step, and these stacking errors need to be taken in to account during and after production. This is handled with tolerancing, and in optics it requires that manufactured components have their properties specified, as both the material used and the component created need to be within set error ranges. These ranges can be percentages of the designed value, or tolerancing standards used in the industry.

Components are often analyzed based on how good their surfaces are for optical usage, meaning how smooth the surfaces are (roughness) and how close to the original design the manufactured form is (form deviation). Manufactured surfaces are never complately smooth, as micro- and nanoscale peaks and valleys tend to materialize during manufacturing, and issues with e.g. diameter and focal length can be appear. [4, 6, 11, 17]

Measurements of surface roughness can be conducted with a contact profilometer and interferometric measurement systems. A common parameter to describe surface roughness is the arithmetical mean roughness value

$$Ra = \frac{\sum_1^N |Z_i|}{N}, \tag{2.15}$$

where Z_i are the measured heights of the profile and N the amount measurements. Similarly, surface roughness can be evaluated with the root mean square (RMS):

$$Rq = \sqrt{\frac{\sum_1^N Z_i^2}{N}}. \tag{2.16}$$

The difference between the two descriptions is that even though they use the same data (measurements of the heights of the peaks and valleys in the optical surface), the RMS value tends to react stronger to single higher peaks or valleys than the R_a value. Therefore, larger-scale imperfections, such as cracks and scratches, can more strongly affect the RMS value. [18] In general, the higher the values for Ra and Rq, the rougher the surface is, and therefore worse for optical usage: as the wavelengths used in optics are often in the nano- and micrometer range, roughness levels of 10-20 times smaller are required for the component to be usable in high-end devices (even down to 5 Ångströms or 0.5 nanometers for high-quality components [17]). Otherwise, light can be diffracted and scattered in unwanted ways, potentially ruining the whole optical system. [4,6,11] Figure 2.5 visualizes a surface roughness measurement result.

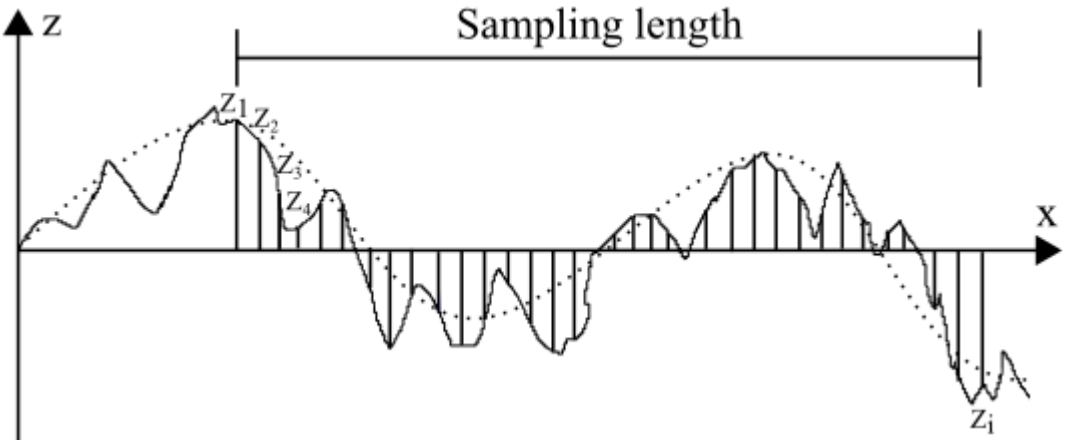

Figure 2.5: An illustration of a surface roughness measurement. The height of each point Z_i is measured, and the chosen method then applied in calculating the roughness of the profile. The dotted line represents larger-scale form deviation (waviness).

Even if the nanometer-scale surface quality of a component is deemed sufficient, the micrometer-scale geometrical form needs to be in order as well: geometrical form deviations in e.g. lens diameter and center thickness can cause issues with mounting the lens and its focal length, and the looser the tolerances, the less probable it is for the system to perform as required. A common method for describing the form deviation of a lens is peak to valley (PV), which is the difference between the highest and the lowest point of a measured surface. As is often the case with industries of all sorts, varying tolerancing standards are applied by manufacturers, and the most suitable one to follow should be chosen by the potential customer. [6, 11, 17]

2.2 Optical-grade plastics

Research in carbon-based polymer materials has enabled the manufacturing of efficient optical components out of polymers that can compete with traditional glass-based optics in many applications. [5, 19] This section focuses on giving a clear impression on which sort of plastics are usable in optics, and their general properties, which are then compared to those of optical glass materials.

2.2.1 General properties

Plastic materials used in optics can be divided to two main groups: thermoplastics and thermoset plastics. The key difference between the two groups is that thermoset plastics cannot be easily reused, as the polymerization reaction (described in section 2.3.1) happens during the manufacturing of the part and cannot be reversed, whereas the pre-polymerized thermoplastics can be recycled via melting and re-forming. Some optical components require the use of thermoset materials, as maintaining the shape and structure of a component in varying enviromental conditions is highly important (such as opthalmic lenses for e.g. eyewear), whereas thermoplastics are used in e.g. injection moulding techniques to create components in medical disposables and military optics. [3, 4]

Common plastic materials used in optics include polymethyl methacrylate (PMMA), polycarbonate (PC), polystyrene and cyclic olefin polymer (COP) (an overview of a multitude of materials is presented in section 2.3.5). Some come in liquid form, such as photopolymeric resins used in 3D-printing of optics (see section 2.3.1), whereas

some are solid pellets or sheets, and are e.g. melted for injection moulding (IM) (described in section 2.3.2) or pre-machined for diamond turning (DT) (section 2.3.3). [4] Each material has its advantages, disadvantages and use cases, and the field of polymer materials is constantly developing towards materials with more exquisite properties. [5]

The usage of plastics in optics requires that the transparency of the material is high in a desired wavelength range, which of course varies between applications: visible light (400-700 nanometers) and near-infrared (NIR, 700-2000 nanometers) [13] are common ranges for plastic components in everyday and military applications. Transparency, in general, is related to the molecular structure of the material, with molecular conformation playing a part as well - it is necessary that the molecular chains of the polymer are random in their nature, and crystallization kept to a minimum, as it can increase scattering (absorption and emission of light in random directions) inside the material. Additionally, Rayleigh scattering can appear due to density fluctuations in the medium. Impurities, such as ultraviolet absorbers, tend to color the material, meaning reflection of certain wavelengths increases, further lowering the total transparency. Ultraviolet (UV, 10-450 nanometers [3]) and visible light absorption are related to electron transitions between energy states in the atoms, whereas infrared radiation is absorbed as thermal energy. [4]

If absorption is non-trivial in the medium, it might be beneficial to take it in to account by invoking a complex refractive index

$$\bar{n} = n + ik, \tag{2.17}$$

where i is an imaginary unit and k the index of absorption. However, k tends to be negligible in the visible range of light for many optical polymers [4], which is why this treatment may be unnecessary in the case of plastic optics.

Moreover, as discussed in section 2.3, the refractive index of a material is dependent on the wavelength of light, and is also affected by various factors, such as molecular polarizability and density fluctuations (homogeneity), which are described by the

Lorentz-Lorenz equation: [20]

$$\frac{n^2-1}{n^2+2} = \frac{4}{3}\pi N a, \tag{2.18}$$

where N is the number of molecules per cm^3, and a is the polarizability. Furthermore, by using molecular refraction $[R]$ and molecular volume V, the refractive index of a material can be written as [4]

$$n = \sqrt{\frac{1+2[R]/V}{1-[R]/V}}. \tag{2.19}$$

To summarise, optical-grade plastics are divided in to two categories, both having various different materials available, and describing the refractive index of a material might require taking in to account several atomic and molecular factors that can cause absorption, which the transparency of a material and therefore requires extra attention during manufacturing. [4] Describing the refractive index of a dielectric medium has many options, and the most suitable one should be chosen depending on what information of the material is available.

2.2.2 Comparing plastics with glass materials

To provide a baseline for the properties of optical plastics, comparing them to those of glass materials used in optics is carried out next. In general, plastics are less dense (0.83-1.4 g/cm^3 versus 2.3-6.3 g/cm^3) and much softer than their glass counterparts, meaning plastic components can get damaged and scratched easier. They also have worse maximum service temperatures (usually 60-85°C versus 400-700°C) and absorb (as well as retain) moisture easier: up to 2% of the weight of a plastic optical element can turn out to be water, which causes changes in the transmissive capabilities and the geometry of the component. Similarly, plastics are hardly ever pure of other contaminants, as they tend to contain substances (e.g. stabilizers, colorants) that produce outgassing and changes in the absorption spectrum, again lowering transmissive capabilities of the product. Some plastics can also be fluorescent, and suffer from crosslinking (discoloration) in certain UV and ionizing spectra. Having a higher linear coefficient of expansion than glass and suffering greatly from

changes in ambient temperature and pressure, local variations can be caused in the refractive index of a plastic component, which is already generally lower for plastics than glass materials (1.3-1.73 versus 1.5-4.0). [3, 17, 21]

What is more, depending on how a plastic optical component is manufactured, various issues can come up afterwards. These issues include shrinkage during cooling in methods that require melting of the material, possible creation of microplastic particles in post-processing (grinding, polishing), usage of toxic chemicals in e.g. photopolymer printing and, in some cases, requirements for special coatings. An issue related to mechanical stress appearing in compression-related methods is the double refraction of light (birefringence), in which the refractive index is dependent on the direction of polarization of light, causing a beam splitting in to two components, which also is a reason for discarding an optical component. [4]

Plastics also experience increasing prices and lack documentation of the properties of high-end and specialized materials, and suffer from general cataloging shortcomings: more and more materials are being developed in research and industry, but finding a source of information which could be used for easily browsing through their properties can prove to be gruesome, and instead many articles, proceedings and books might need to be reviewed for discovering the desired information. To add to that, many materials are simply not commercially available. [3]

On the bright side, even though plastics clearly have certain issues and cannot (currently) reach similar levels of stability and reliability as their glass counterparts, utilizing plastics in optics has many advantages. For instance, as plastics weight less, they can be better for applications that have a tight budget on the weight of the components. Plastics components are, in general, cheaper to mass-manufacture, opening possibilities for technological advances otherwise economically nonviable, such as one-time use without the need for sterilization [5]. They also offer more freedom in the design phase, as they allow more complex geometries than their glass counterparts due to more sophisticated manufacturing methods: varying levels of freeform, multisurface and micro- & nano-optical components are made possible with plastics. [3, 4, 22]

Furthermore, the usage of plastics allows creating custom optical components inside other parts and systems - so called structures within structures [23], further clearing room for new inventions. Another certain advantage of plastics is that an optical component can be manufactured to include a mount or a housing, making the assembly of an optomechanical system cheaper and easier. Less time and resources are needed in assembly and packaging in general, as components can be designed for plug-and-play assembly and sent in simple tape and reel packaging. [4,24] Additionally, the usage of plastics has allowed novel innovations, such as creating fully printed LEDs, combining macro- and nanoscale features in a single component (multiscale printing) and manufacturing with multiple materials at once (multimaterial processing), though further development is still required for efficient mass production with these solutions. Other future possibilities include specifically architected materials and graded components, which could allow for e.g. actively self-tuning lenses with capabilities of reacting to the enviromental conditions automatically, as well as out-of-plane nonplanar manufacturing of optical systems. [24] Keeping in mind that the lens studied in this thesis is a relatively simple aspheric singlet, manufacturing methods of common plastic lenses are presented in the next section.

2.3 Manufacturing methods of plastic lenses

Modern manufacturing of plastic optical components is focused on moulding and precision machining techniques, which have lead the production of plastic optics for several decades. [6] However, development in additive manufacturing technologies has made it possible for optical components to be manufactured relatively cheap, easy and fast, at least with prototyping and testing in mind. [25] This section focuses on presenting various methods of manufacturing optical components out of plastics, starting with an introduction to additive manufacturing technologies.

2.3.1 Additive manufacturing

Additive manufacturing methods rely on building a three-dimensional, computer aided design (CAD) model layer-by-layer with a set layer height usually in the micrometer scale. Digital models of the desired object are designed on a CAD software, and prepared for printing with a slicing software, which essentially generates the layers and instructions for the printing machine to follow. [26] The sliced file is then

moved or uploaded to the manufacturing system, and the fabrication process started after configuring the machine with correct parameters for the specific material and model.

There are several techniques of general plastic additive manufacturing, of which the most common method is fused deposition modeling (FDM). Its operating principle lies in heating a spool or grains of plastic printing material (thermoplastics such as PC, ABS) until it melts, and then extruding it through a nozzle, which is moved in two or three dimensions, depending on the geometry of the device. This way, a 2D-layer of a slicing of a CAD model is drawn using molten plastic as the material, which then cools and solidifies, creating a ready surface for the next layer. Drawing layers on top of each other leads to the creation of the desired 3D model in a cost-efficient, fast and simple manner. Other methods that make use of a non-liquid building material are powder bed fusion (PBF) techniques, such as selective laser melting (SLM) and selective laser sintering (SLS), in which a layer of polymer powder in a chamber is simply heated (SLM) or completely melted (SLS) with laser irradiation. After irradiation of a single layer, the powder chamber is lowered and more material is applied, and the process continues towards a full model. [27,28]

Unfortunately, these traditional additive manufacturing methods are not really suitable for creating optical components, as the surfaces produced are riddled with high levels of roughness and the components with inhomogeneities, causing scattering and opaqueness. In FDM, issues arise from relatively large nozzle sizes in (hundreds of micrometers) and the thermoplastic materials used - heating and then extruding a molten material on top of a cooler one may leave an interface between the two, and not all materials are transparent in the first place. SLM and SLS suffer from similar issues. [28, 29] However, additive manufacturing of optical components is made possible with different 3D-printig techniques, such as those grouped under stereolithography (SLA), which rely on photopolymerization of UV-curable resins in a resin-filled vat. [27, 30].

Photopolymerization, as a broad term, refers to a group of light-induced polymerization reactions, in which monomers (small molecules) in liquid form absorb incident light (e.g. UV radiation) with the help of photoinitiators, causing monomers to bond

and form longer chains of solid polymers. Some of these polymers have optically suitable properties, and can therefore be used in manufacturing optical components. A photopolymerization reaction in its simplest form can be depicted as [31]

$$\text{Monomer} \xrightarrow{h\nu} \text{Polymer}. \tag{2.20}$$

Resins suitable for photopolymerization have five main components: [30]

1. Precusors, such as monomers and oligomers.
2. Photoinitiators, which initiate the polymerization reaction.
3. Additives, such as diluents and stabilizers.
4. Absorbers, which define the curing depth.
5. Fillers, such as glass particles for special properties.

Various mixtures of these main components lead to resins with different properties, and again keeping optics in mind, high transparency, neutral color and low surface roughness are some of the most wanted qualities from the solid end-product. Curing resins via photopolymerization requires a source of radiation, and SLA technologies rely on irradiation methods of either laser or digital light processing (DLP), [27] or sometimes a liquid-crystal display (LCD) [30]. Laser-related SLA technologies create 2D-slices of the model by shining a UV-laser on the wanted areas, sometimes point-by-point with single photon polymerization (pinpoint solidification), or only at the focal point (two-photon polymerization), which both only cure the area or voxel (volume pixel) near the focal point of the beam [24, 30]. LCD SLA, on the other hand, cures a 2D-image at once [30].

Two methods are commonly used for the application of the curing radiation: free surface approach (FSA) and constrained surface approach (CSA). [32] Essentially, FSA refers to a top-down incidence with the build platform lowering further to a resin vat in each step, with a mechanical sweeper coating the to-be-cured surface with a new layer of resin. CSA, on the other hand, is a bottom-exposure method that relies on rising a suspended build platform higher after curing the newest layer through a transparent screen or film, building the object upside down. [30, 32] The approaches and a general layout of an SLA system are depicted in figure 2.6.

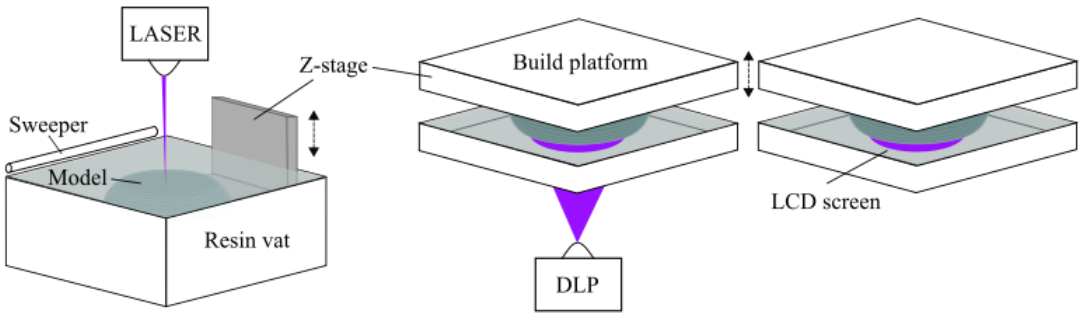

Figure 2.6: Illustrations of free- and constrained surface approaches in laser-, DLP- and LCD-SLA. The model is built layer by layer, though upside down on the two latter methods.

Both approaches have their advantages and disadvantages: FSA might not be able to reach single-micrometer accuracies of CSA, and requires a mechanical sweeper, which of course increases the possibility of malfunction and printing time. However, CSA requires a solution for pulling the latest cured layer off the vat floor as the platform rises. Solutions, such as a hydrophobic layer on the vat floor [32], application of shear forces [30] or printing only to the middle of the vat floor, so that the vat floor bends as lifted and releases the cured layer more easily, can be attempted.

Conventional SLA methods, in general, are relatively cheap and easy for quick prototyping, but the printed objects tend to require post-processing techniques, such as polishing and coating, before they are ready for optical usage. This is because while printing a curved surface layer by layer, visible edges can appear in the object, and impurities in the material as well as machine inaccuracies may create imperfections in the product. [28] What is more, a fundamental issue with layered manufacturing is also present in SLA methods: curing a layer of resin atop another layer can, in addition to visible edges, create an interface of sorts between them, as the two layers may blend together imperfectly. A "step profile" can appear in the micrometer scale, and can cause issues in optical usage, such as birefringence and dispersion, which no amount of post-processing can fix. [28] These issues are depicted in figure 2.7.

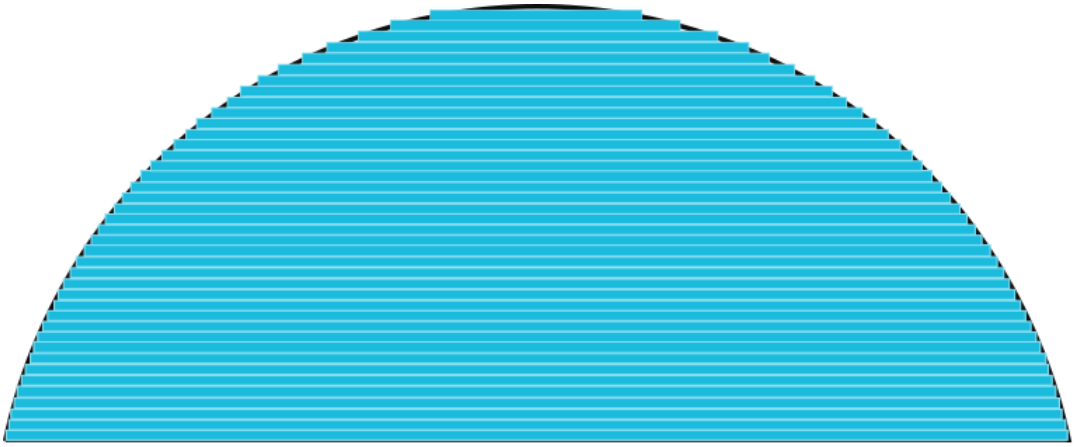

Figure 2.7: The designed lens surface profile (black) and the printed, real profile (blue). Steps are easily visible in especially the top part of the lens, as well as the interfaces between layers inside.

The issues related to the common layer-by-layer techniques could possibly be combated with methods such as continuous liquid interface production (CLIP), which abstains from layers or attachment to the printing window by utilizing a continuous pull during the construction of the model. [33] Also, high optical clarity and nanometer-scale surface resolution can be achieved by utilizing ultrafast (femtosecond) laser technologies, such as multiphoton stereolithography (MPS), which can create a smooth-enough surface for optical usage. MPS has been used to manufacture microlenses with diameters of under 20 micrometers with great surface smoothness, [28] though creating such lenses is time-consuming, and a lens in the size of millimeters might take days to manufacture.

Completely different approaches for AM of plastic optical components are polyjet ink droplet methods, such as direct inkjet writing or inkjet printing. In these methods, droplets of liquid acrylic resin or ink are jetted through a print head, and the droplets either cured by a UV lamp or let solidify on their own, further merging together with the previous droplets and leaving no layer structures. [28] One of these drop-based printing methods is the Printoptical® Technology by Luxexcel, which can print optical-quality transparent products from UV-curable acrylic inks. [34,35]

In fact, Printoptical® Technology was used in manufacturing the aspheric lens of this study, and the process is further discussed in chapter 3.

In short, AM of plastic optical components is a quickly-developing field of optics, engineering and material science, and has shown great promise for prototyping and creating new, innovative concepts with old and new materials. However, to reach the mass production rates and stability of the common manufacturing methods that are presented in the next subsections, more work and research needs to be done and conducted, and knowledge of the possibilities made more widespead and easily accessible for the industries and academia.

2.3.2 Injection moulding

Injection moulding is a traditional machining technique for accurately replicating parts out of plastics, thereby having extensive opportunities for manufacturing plastic optical components, [36] and several different variants of the technology exist. Conventional IM consists of several steps, which are briefly described next. First, making sure that the optical design is manufactureable with the geometries and materials proposed is essential - not all shapes and forms are possible to create with moulding, as parts with both thin and thick sections cause issues with cooling times and lead to uneven shrinkage. Round geometries are preferable compared to rectangular ones for optimal mould flow, which might not matter when lenses are considered, but can cause issues if complete optomechanical systems are moulded at once. These are valid reasons for when considering IM, the designer and the manufacturer should openly communicate and work together from the start to minimize the amount of back-and-forth sending of unmanufactureable designs and general missconceptions. [4, 6]

After the optical design phase is finished to a degree satisfying both sides, the second step to consider is designing a mould with one or more cavities and a number of optical inserts (a "negative" of the optical component) depending on production needs, with the third step being manufacturing them out of e.g. corrosion resistant mould steel. Filling the cavities and inserts inside the mould requires creating sprue channels in the mould as well. If a suitable mould can be created and measured, next up comes the actual IM process with a large and heavy IM machine. The pro-

cess begins with configuring the machinery, setting up the mould halves and inserts, and starting the moulding cycle: the two halves of the mould are carefully aligned and then pressed together with a high clamping force (up to hundreds of tons [6]). [4]

Next, a plasticizing unit heats up and feeds the viscous, hot plastic material to the injection system, which subsequently fills the cavity through the sprue channels, which must happen fast to minimize thermal gradients in the process. Fourth, some compression of the mould halves might be required to combat cooling effects, such as the shrinkage discussed earlier. A shrink rate for an optical thermoplastic can be up to 1% of the volume of a manufactured component, though the smaller the component, the less shrinkage occurs. [6] After cooling the material down to solid form, the fifth and final step is to open the mould and eject the manufactured component for further cooling. The IM process is then repeated for as many times as necessary to reach the desired amount of components, while keeping in mind, as always, that metrology of the manufactured parts is required for guaranteed quality, and optimization of the process most likely needed in all steps. [4]

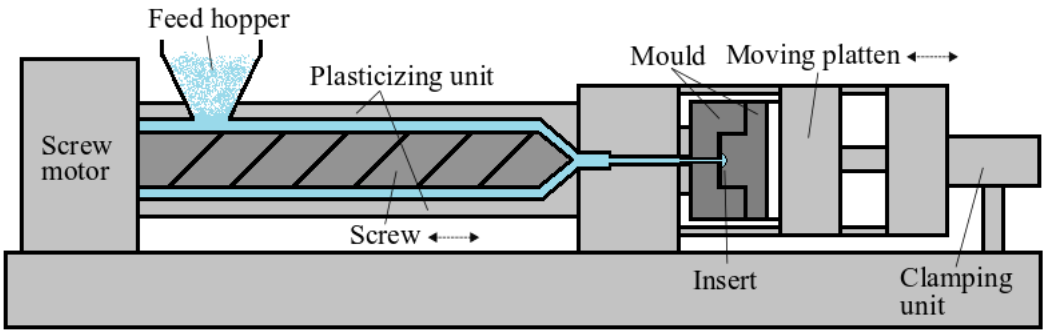

Figure 2.8: A schematic of an injection moulding machine.

Even though relatively fast, simple and reliable for producing components in masses, fundamental issues emerge with the traditional IM process when manufacturing of optical-quality components is considered: internal stress and warpage created by the high-pressure process can render the component unusable, as they cause birefringence and can even result in a component spontaneously breaking, and the surface quality might not be good enough for imaging usage. Therefore, IM techniques have

been developed further, and one of the methods is injection-compression moulding [36], also called injection coining (IC). [4]

IC differs from traditional IM by having dynamic cavity of sorts: the volume of the cavity varies during the operation, as it starts somewhat open in the beginning of the injection, and is constantly pressed more shut during, and totally closed when the cavity is completely filled. This way, the cavity pressure can be held more constant, and less stress is inflicted on the created component, and issues with e.g. wall thickness and voids in the material reduced. However, the technique does require even more sophisticated moulds and machinery than its traditional counterpart, and is split in to many different variations. [4]

As has become evident, all the IM processes consist of various steps that require highly-skilled manufacturers and well-toleranced, accurate machinery: the mould needs to be delicately designed and precisely manufactured to match the optical design as accurately as possible, simultaneously taking in to account the limited possibilities of geometries the moulding process can create - manufacturing a mould relies on precision technologies as well, such as DT (discussed in 2.3.3), and a fault in the mould will replicate in all the manufactured components, meaning there is little room for error in the whole process chain.

What is more, the IM machinery needs to be configured exactly, having the material and mould parameters carefully set for each design, as optical components require minimal deviation from the original design to be of value. Advanced metrology techniques are also required for making sure that the mould and the end-product fit the set tolerances, which can be the most pressing issue of moulding technologies - various different methods are required to measure different shapes and surface geometries, and in some cases, custom measurement systems are required to be built. Also, in each step of the manufacturing chain some amount of error is generated and as they stack, the end result might turn out useless if even measurable. This is why it is preferable that manufacturability is kept in high priority during the optical design phase of a component. Automatization and clean room level surroundings help with possible quality issues during production - dust in the mould can damage and cause the disqualification of batches of components until the issue is noticed. [4]

However, if the required steps are performed correctly, the process can be continued for extended periods of time, and an amount of production cycles may reach millions with a single well-made mould [4,37]. Therefore, though constantly developing, IM techniques are usually best set for mass-production of components instead of quick prototyping and producing small batches that e.g. DT methods excel in. [4]

2.3.3 Diamond turning

DT refers to a group of subtractive ultra-precision manufacturing methods, of which some can reach surface roughness levels of single nanometers, if preparatory processing is carried out properly. Single point diamond turning (SDPT) is often used in manufacturing components requiring high precision, such as the moulds used in injection moulded optics, but it can also be used for creating plastic optical components. Essentially, SDPT is a computerized numerical control (CNC) method that makes use of a very fine diamond-tipped blade and a one- or even five-axis configuration for moving the work piece (turning) and in some cases the tool (milling). A diamond-tipped tool is used to carefully remove material from the work piece line by line on a computer pre-prepared tool path, and as the tip is miniscule, the material is very slowly chipped away. The tiny tool is also the reason why preshaping of the work piece (a blank) is necessary - turning nanometers or micrometers at a time is not overly effective if the surface is not close to the desired shape beforehand. [4,38]

DT processes are very beneficial for optical prototyping, as the surfaces produced can reach single nanometer surface roughness levels and form accuracies in the tens of nanometers for metals, and slightly higher for certain plastics. [39–41] The quality of a diamond-turned surface largely depends on the accuracy of the setup of the machinery and the edge sharpness of the tool, meaning the radius of its edge, which in itself is an approximation of sorts: waviness is always present on the tool radius, which gets reflected on the turned surfaces. Also, the tool edge radius effect is something to consider when choosing the tool for the task, as the larger the edge radius, the rougher the surface finish tends to be. A tool with a 100 micron radius cannot be expected to reach sub-micron surface roughness levels.

These issues can, due to their consistensy, be combatted with computer-aided compensation methods, such as tool radius compensation (TRC). Unfortunately, the surface roughness of a work piece is also affected by many other factors, such as depth of cut, tool wear and material properties as well as similar workplace-related issues as in IM. Even floor vibrations and temperature variations can ruin the turning process, as the size of the metallic machinery parts varies with temperature, meaning they are no longer cutting in the right place or depth. [4, 39]

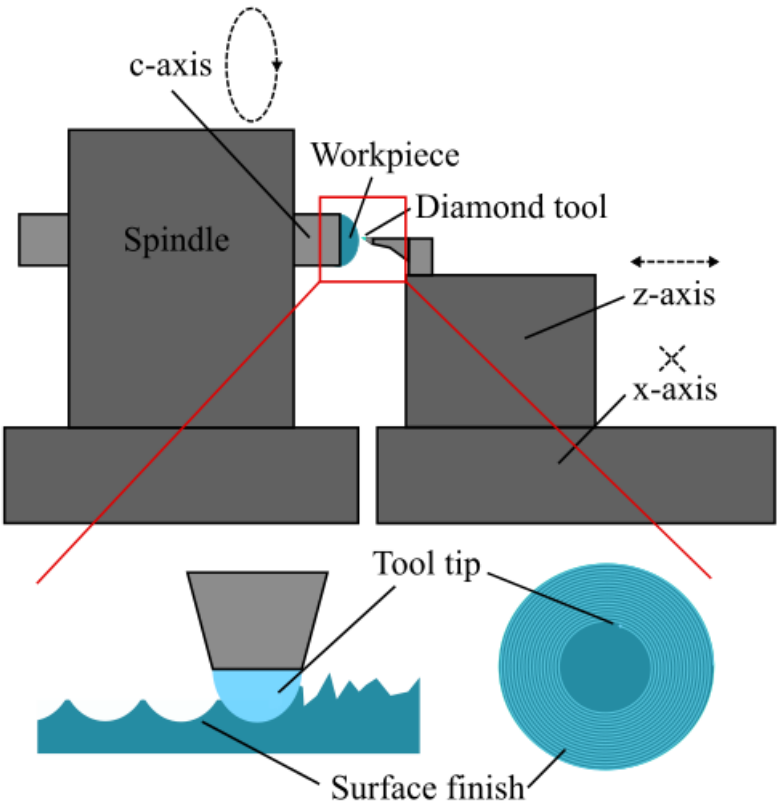

Figure 2.9: A simplified schematic of a DT system and an exaggerated view of the surface finish.

Even though the toughest material available, a side effect of using a diamond as a cutting tool is that it cannot turn all sorts of materials. Considering plastic optics, only certain thermoplastics can be diamond turned, such as PMMA, polystyrene,

PC and COP. Many other common materials are simply too soft for reaching optical surfaces with SDPT, whereas others are too brittle. These issues could be overcome with additives that change the properties of the material, such as using glass fillers, but this often leads to the component being unusable in optics. A possible solution for increasing the amount of diamond turnable materials is the High-Refraction Diamond Turning (HRDT) method by Syntec Optics, which deals with the issue of nonsuitable surface energy charasteristics of softer and more brittle materials. [5]

To sum up, SDPT, HRDT and related technologies are getting more and more common in creating high-quality plastic optics, and is especially useful for those geometries that IM and glass manufacturing cannot handle. Being an ultra-precision technique, much work needs to be put in setting up and tolerancing the expensive machinery as well as pre-machining the work pieces, and again, the whole process should start from a discussion between the manufacturer and the customer. If done correctly, state-of-the-art quality components can be manufactured for imaging usage especially in the infrared range. [38]

2.3.4 Quality, cost and availability of the methods

Now that the various manufacturing methods of plastic optical components have been introduced, drawing a conclusion regarding their possibilities and usefulness in creating high-quality macroscale imaging components out of plastics is carried out next. Discussion on levels of surface roughness and form accuracy that can be reached and where the manufacturing costs lie is brought up with short summaries of the availabilities of the methods. This aims to provide guidance in choosing the best solution for the varying needs of companies, be it producing a single component in prototyping or hundreds of thousands in large-scale mass production.

As discussed in the previous sections, surface errors (form deviation, surface roughness) are present in all manufactured real-world components, and these errors can greatly affect the image quality of an optical system, as unwanted scattering and loss of focus can occur as the errors increase. [11] There is some variation between the surface quality of the methods: in the case of moulding, various techniques have been shown to be capable of RMS values between a large range of single and thousands of nanometers by research groups [42–44], though tolerances of only single and

tens of nanometers are often brought up in literature [4, 6] and by companies [36], with form deviation of single micrometers in state-of-the-art processes [36, 42, 45].

For DT, single-nanometer RMS levels have been claimed possible by both companies [40, 46] and researchers [41, 47], with Chen *et al.* presenting sub-micron surface form accuracy for a plastic contact lens [47] and Khatri *et al.* showcasing nanometer-scale form deviation with SDPT for a polycarbonate aspheric lens [48]. 3DP, on the other hand, has seen promising results provided by Assefa *et al.*: a 10 ± 2 nanometer RMS value with $\pm$ 40-100 nanometer surface profile variation has been reached for a centimeter-scale 3D-printed lens with PrintOptical® Technology by Luxexcel [49]. Similarly, Gawedzinski *et al.* succeeded in printing lenses somewhat comparable to moulded quality glass lenses, though only if smaller apertures were used in measurements. [25] On the other hand, Debellemanière *et al.* suggested that the technology was not yet ready for printing an intraocular lens due to surface roughness issues, though bringing up the method's possibilities in the future. [50]

Disparencies between scientific and corporate results might originate from the fact that the companies producing optical components likely spend more time and resources on perfecting their methods and parameters for customer satisfaction, whereas research groups and thesis workers might have limited time and equipment available, and cannot therefore always reach the highest surface qualities. The differences in roughness values between moulded and turned optics is to be expected, since as has been brought up, the moulds used in moulding techniques are usually created with DT technologies, and therefore produce, by default, lower quality. In any case, it can be concluded that turning technologies can produce the highest quality surfaces for optical components, though moulding methods can produce great optical quality products as well, and modern printing techniques are not far behind.

However, merely reaching imaging quality surfaces does not guarantee the manufacturing method is viable for lens production, since the cost of manufacturing and availability of the method need to be taken in to account as well when considering real-world applications. Producing custom plastic lenses is no easy feat, and companies utilize their own tools for estimating manufacturing costs in each case, which can start from an intuition of a seasoned professional or from a similar earlier

case. The true price is then approximated and updated during the back-and-forth discussion between the client and the manufacturing company, and various parameters affect the final sum, such as the amount of components ordered (prototyping *versus* mass-production), quality requirements (yield; how many components are discarded during production), geometrical size and complexity of the component and, of course, the chosen manufacturing method.

In IM, the estimated price per component includes design costs of the ordered mould and insert(s), and in some cases modifications to the lens design as well, as it might be required to alter the original lens design to make it truely manufactureable. Tooling costs of the mould and the insert(s) are also to be estimated. The actual manufacturing costs, e.g. moulding process and possibly post-processing (coating), need to be rated too. Further estimations can include parameters such as material price (usually 5-30€/kg [36]), machine rate and labour costs.

Commonly, optical components are usually somewhat small and have quite low production volumes, lowering both mould and insert costs, which are then risen back up by the requirement of high surface quality. Due to the requirements of many levels of machinery, skill, planning and cleanliness involved in IM processses, using them in manufacturing plastic optical components can quickly become staggeringly expensive, as the mould itself might cost thousands of euros to manufacture [37,51,52], and high-quality machinery be priced in the tens of thousands [52], without even bringing up the requirements for the talent of precision engineering in all stages. In many cases, only a true expert can give even a directional quote to a potential customer. [4]

Still, if enough skill and starting capital is involved, IM can be used to create very cheap high-quality components: even though each case is unique and therefore the prices can vary wildly, Mäkinen showed in a simplified cost modelling that for a batch size of 50000 lenses of Zeonex E48R for viewfinder optics, a total cost of 1.17€/piece can be reached. This includes estimates of tooling (0.0460€/piece, 33 000€ for design & manufacture of mould and insert), IM process -related costs (0.9176€/piece) and coating (0.2104€/piece). A relation between production volumes and cavity count in the mould was also shown, and it was found that a single piece might end up costing anywhere from single tens of thousands to almost 80 000

euros, whereas if a million lenses are produced, the costs can go as low as 0.9€/lens with an eight-cavity mould. [37]

Though merely a cost-modelling exercise, this gives a hint of the costs related to IM as a manufacturing method for plastic lenses, and it can be deducted that, in general, the more lenses produced, the cheaper the whole process of IM is. Also, IM is a widely-used method for manufacturing all sorts of products from plastics, meaning the equipment required for manufacturing plastic optics is relatively easily available and numerous companies with skillful labour exist around the world, increasing the popularity of IM as a technology for mass-producing plastic optical components.

Next up in discussing manufacturing costs and availability is DT, which has similar requirements for expertise and machine costs as IM, though the ultra-precision machinery can even end up pricier due to tighter enviromental requirements and stricter tolerances on the machine setup itself. [38] Furthermore, instead of mould design & manufacturing, the extra costs of DT come from (1) the diamond-tipped tools used in cutting, as a single high-quality tool can cost thousands of euros [51], and (2) multi-level machining steps: pre-machining, precise machining and ultra-precise machining, which all require time and resources. Also, DT techniques are definitely not meant for mass production, as a single lens might take days or weeks to manufacture, meaning replication rates are very low. [5, 46]

DT is, however, widely useful in optical prototyping and creating small batches of high-quality components, as depending on the configuration of the machinery, it can be used to create lenses with various geometrical possibilities, such as aspheric and diffractive components and even freeform lenses [46]. Simultaneously, the price of testing complex solutions can be greatly reduced, as the realization of prototype and proof-of-concept components can be driven down to 5000$ [5] and significantly faster (e.g. 2-3 *versus* 12 weeks) [53] with DT technologies than with IM. Moreover, the required machinery is available worldwide, but qualified work force specialized in optics manufacturing might be harder to come by, and as was the case with IM, the high-end machinery, extensive planning and workload costs can still make a customer hesitate ordering just a single component made with DT - this is where 3DP has its advantages.

3DP of optical components is, at the moment, meant for researching optical prototyping, as production is slow compared to IM, the machinery costs high and material selection still limited. However, the ease of manufacturing (design, upload, print) and fast production even compared to DT make it a good candidate for manufacturing single lenses or very small batches in merely hours, simultaneously creating savings in e.g. planning, designing, tooling and premachining phases the other methods tend to require. Unfortunately, the 3DP techniques capable of producing any sort of optical quality are not very widely available yet, and much more effort needs to be put in to their scientific, industrial and economic development to make them more cost-effective and available to lens manufacturers. Currently, only Luxexcel provides the technology for 3DP optical quality macro-scale products, though as was briefly discussed in the end of section 2.3.1, various technologies exist for AM of micro-scale optics.

It can be thereby concluded that if high volumes of relatively simple plastic optical components are desired, injection moulding is probably the best fit for the task. More high-end and complex optical components are presumably worth diamond turning, and additive manufacturing still developed further until ready for industrial needs. Hybrid processes might offer benefits of all methods, e.g. moulding components and then finishing the surfaces with turning. In any case, skillful engineers, prime machinery and experts of plastic manufacturing are essential for reaching optical quality plastic products from the variety of available materials.

2.3.5 A brief overview of available materials

Polymer materials used in manufacturing optical components have wildly varying structural and optical properties. Some of the materials might have originally been designed for a completely different use-case than optics, and, obviously, not all materials fit all manufacturing methods, causing confusion when trying to decide on the best available material. [4] This subsection aims to provide a clear picture of which materials fit which methods, and what optical properties they inhibit.

First off all, IM technologies utilize only thermoplastic resins, as the process requires the material survives a melting-cooling cycle. The resins usually come in

small small pellet or grain form, though cast boards and sheets are also available. [4] Common materials for IM of optics are polycarbonates, acrylics, styrenes, cyclic-olefin polymers, cyclic-copolymers and polyesters [54] with each having their own properties and trade names. Since IM is usually utilized in mass-production, the materials are often bough in bulk.

DT methods, on the other hand, for obvious reasons cannot use small pellets or grains in manufacturing, and require larger blocks of starting material for the pre-machining steps. As was discussed in 2.3.3, only some thermoplastics inhibit the required structural properties (hardness, pliability) for regular DT: PMMA, polystyrene, polycarbonate and cyclic olefins are good for SDPT, whereas high-refractive index ($n > 1.60$) materials (e.g. polyetherimide and polyethersulfone) require special methods, such as the aforementioned HRDT or an extended annealing process. [5,55]

Lastly, 3DP of optical components using PrintOptical® Technology relies on Luxexcel's own Lux-Opticlear™ material, which is a liquid UV-curable thermoset polymer. Luxexel also offers another material for its successive VisionClear™ Technology: Luxexcel VisionClear™. [56] Research is being conducted on increasing the amount of available materials, and possibilities of e.g. mixing SiO_2 and TiO_2 with optical polymers might enable 3DP of glass optics. [7]

To conclude, plastic optical components can be manufactured from a multitude of different polymers, and the correct material needs to be chosen based on the method at hand and the requirements of the product. Table 2.3.5 offers a summary of the general optical properties of currently available optical plastics. Known useability in manufacturing is again marked with IM, DT and 3DP. Depending on the suppliers and sources, each material may have several versions under different trade names and, therefore, varying optical properties.

Table 2.1: Properties of common optical plastics gathered from literature sources and internet catalogues. [5, 7, 12, 22, 56, 57]

Plastic	Trade name	Method	n_d	V	Advantage
Acrylonitrile butadiene styrene (ABS)	Acrylon	IM	1.538	-	Durable
Allyl diglycol carbonate	CR-39	IM	1.498	53.6	Suitable for opthalmic products
Copolymer styrene acrylonitrile	Lustran	IM	1.569	35.7	Tough, good chemical resistance
Cyclic olefin polymer (COP)	Zeonex	IM, DT	1.682	55.8	Low water absorption
Cyclic olefin copolymer (COC)	Topas	IM, DT	1.682	58.0	Low birefringence
Methyl methacrylate styrene copolymer	NAS	IM	1.533-1.567	35	Good n range
Photopolymer resin	OptiClear	3DP	1.53	45	No post-processing needs
Polycarbonate (PC)	Lexan, Merlon	IM	1.586	29.9-34	Commonly used
Polyetherimide (PEI)	Ultem	IM, DT	1.682	18.94	High max. temperature
Polyester	OKP-4	IM	1.6070	27.6	Low birefringence
Polymethylpentene (PMP)	TPX	IM	1.463-1.467	51.9	High thermal diffusivity
Polymethyl methacrylate (PMMA)	Acrylic, Plexiglass	IM, DT	1.492	57.2-57.8	Great overall
Polystyrene	Styron	IM, DT	1.590	30.8	Low water absorption
Styrene acrylnitrile	SAN	IM	1.567–1.571	37.8	Stability

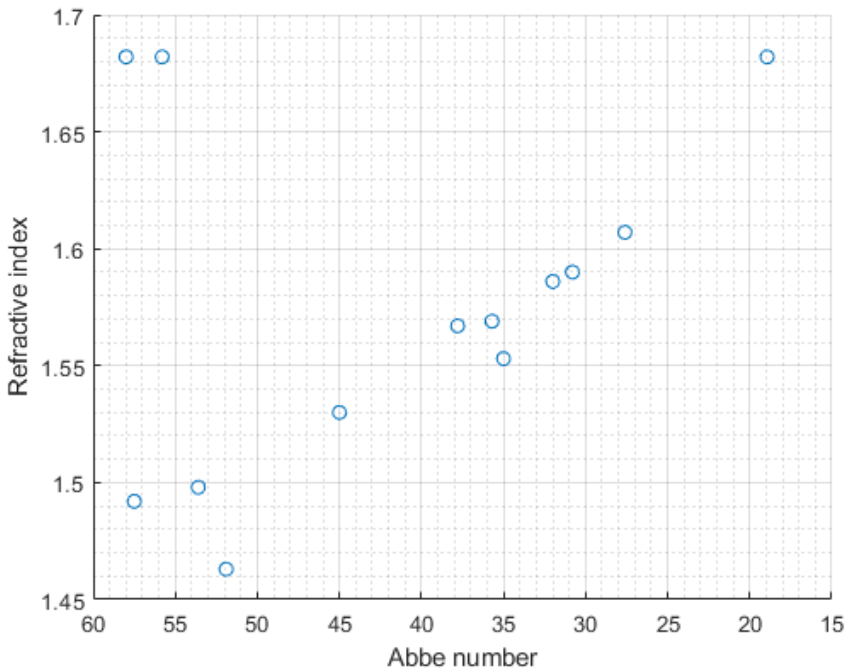

Figure 2.10: An Abbe diagram of the gathered optical plastics.

Chapter III

Equipment & manufacturing

The equipment used and manufacturing steps taken are presented in this chapter. The printer and its working principle is described with some insight in to the lens printing process, and the measurement setup and its theoretical framework briefly depicted.

3.1 PrintOptical® Technology by Luxexcel

As described in the end of section 2.3.1, the PrintOptical® Technology is a 3D-printing method suitable for manufacturing plastic optical components, possibly up to imaging quality. Created and patented by the Dutch-Belgian company Luxexcel, the technology was originally aimed towards printing custom opthalmic lenses and lighting solutions, and in 2013, the company was the first in the world to print complete opthalmic glasses for reading [58]. As was discussed in section 2.3.4, studies in the optical possibilities of the technology have been conducted by various research groups worldwide and, even though the technology is relatively new, promising results have already been shown.

The technology differs from regular additive manufacturing methods in the sense that instead of injecting molten material or submerging the model in a vat, it relies on jetting micrometer-scale droplets of liquid printing material with a custom industrial inkjet printer. Material is thereby deposited by utilizing piezoelectrically controlled print heads that jet acrylic photopolymer droplets (OptiClear) on a printing substrate. The tiny droplets merge on impact and are then cured under UV radiation, leaving little to no visible interfaces between layers and resulting in

layer heights of single micrometers. [7] Simultaneously, the technology succeeds in removing post-processing steps, such as grinding and polishing, from the manufacturing chain of plastic optical components. [56]

Creating high-quality surfaces (up to ISO quality level [59], RMS values of 10-30 nanometers [25, 49]) and having the possibility of printing complex freeform geometries [49], PrintOptical® Technology manages to simplify the process of manufacturing plastic lenses with traditional methods (as discussed in 2.3.2, 2.3.3) and streamline the workflow of opthalmic labs. The versatile technology can also be directly applied in manufacturing custom centimeter-scale optical elements, such as the aspheric lens of Senop Oy, making room for fast prototyping and iterating of plastic optics.

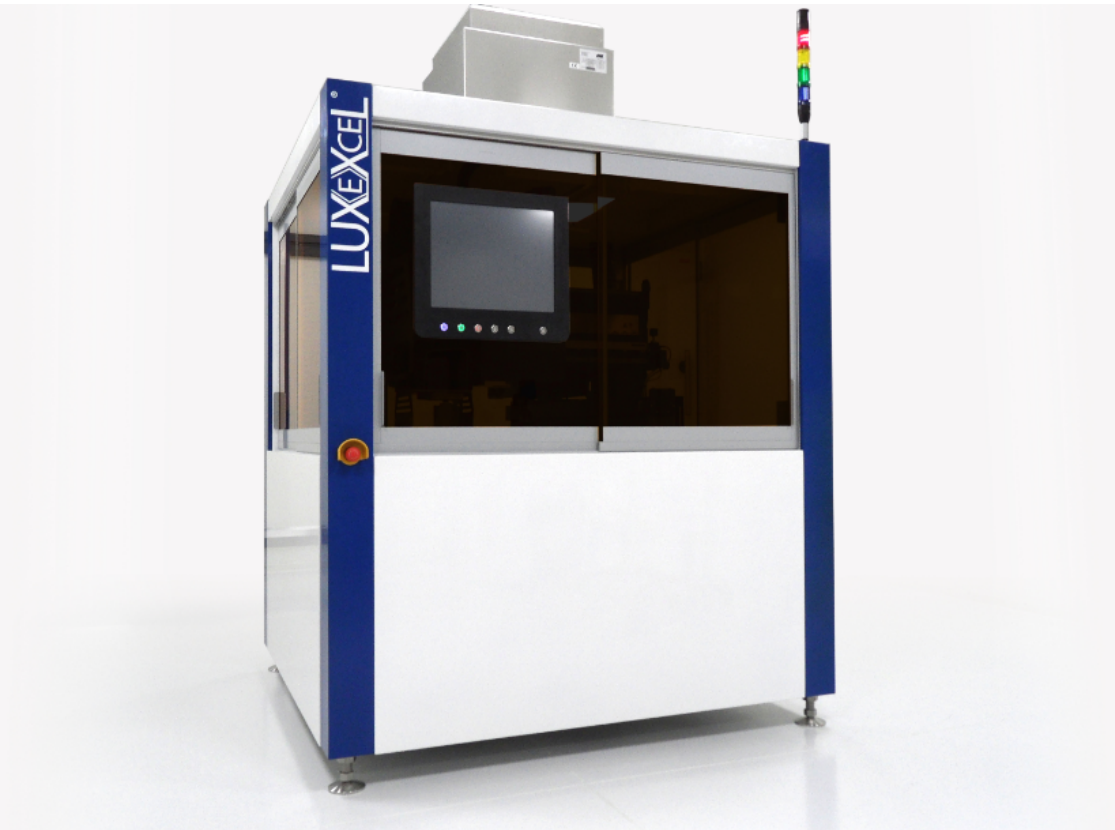

Figure 3.1: Luxexcel Printoptical® 3D-printer. [60]

3.1.1 Printing an aspheric plastic lens

The plastic optical component manufactured for this thesis is based on a design created by the personnel of Senop Oy in Zemax OpticStudio® (Zemax LLC) optical design software. The component is a centimeter-scale plano-convex aspheric lens depicted in figure 3.2. The material used in the design is OptiClear by Luxexcel, which was also utilized in the printing phase. The lenses were printed in pairs of two on "base plate" of a few millimeters for easier detaching from the printing substrate.

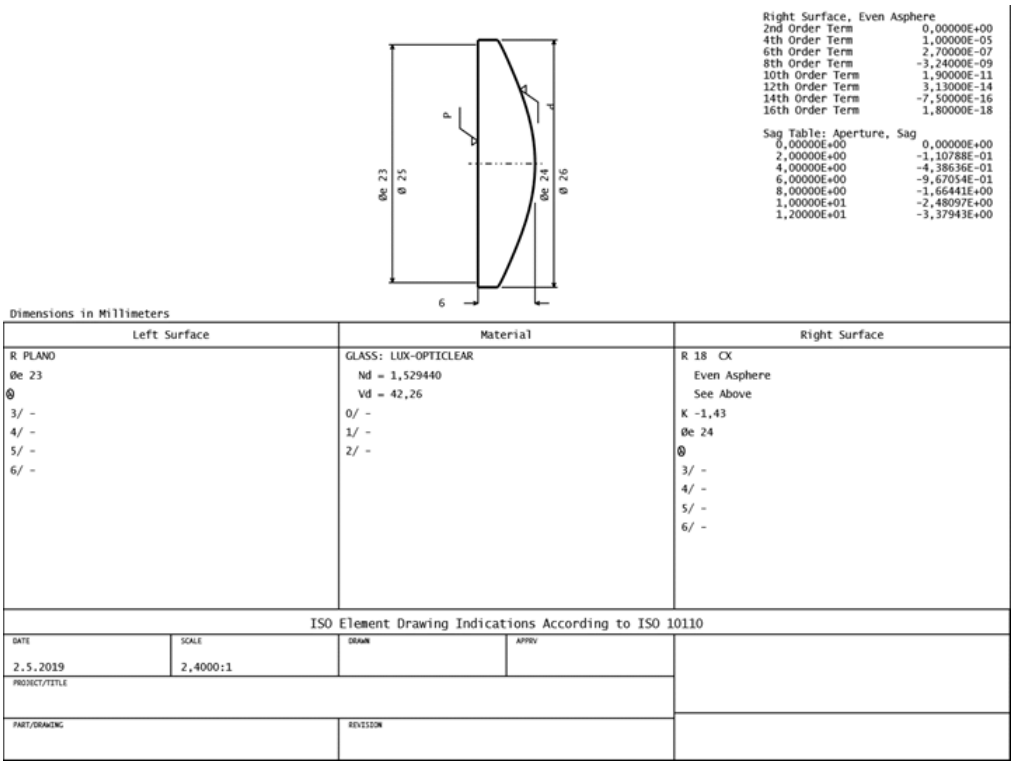

Figure 3.2: The plans of the aspheric lens designed by Senop Oy.

The printing itself is somewhat straight-forward a process: the Zemax file is turned to a printer-friendly file form with a few slicing and conversion softwares (NetFabb, IrfanView), and then transported to the printer via a USB-drive. After setting various parameters for the printing process, turning on all required system components (e.g. HEPA filter, chillers, power supply) and making sure there is resin in the tank, the printing substrate is prepared on the printing table and the process started with

a push of a button. The lenses are ready in some hours depending on various system parameters (e.g. layer height, curing time), after which the lenses are separated from the substrate plate and cut out with a laser cutter from the base plate, resulting in two separate but ideally identical lenses. Aftercuring in a UV-oven is a possibility for making sure the lenses are properly hardened.

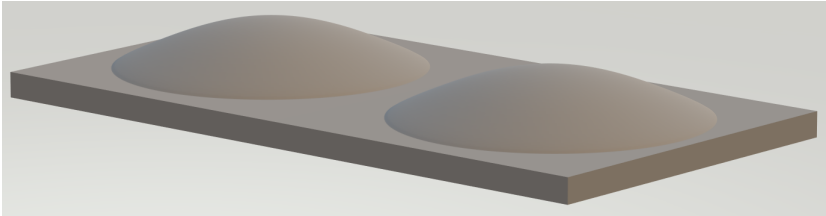

Figure 3.3: A 3D-model of two lenses on a base plate.

Many different batches of two lenses were printed with varying process parameters, finally leading to the four lenses from the last two batches that were deemed acceptable for measurements. The printing took place in a laboratory of the Physics and Mathematics Department of the University of Eastern Finland in Joensuu, Finland. The lenses were laser cut from the base plate, spent some time in a UV-oven, were storaged for approximately a month, and were then transported to Senop Oy & Millog Oy in Lievestuore for interferometric measurements.

Figure 3.4: An early test-print illustrating the printing quality.

3.2 MarOpto TWI 60 Tilted Wave Interferometer

The interferometric measurement system used in characterizing form deviation and surface roughness of the four printed lenses was the MarOpto TWI 60 by Mahr GmbH. The device is a tilted wave interferometer (TWI) that can accurately measure aspheric lenses in relatively little time: data acquisition takes only 30 seconds for the whole surface of the lens without any stitching required. Being able to measure aspheres that differ from a spherical form up to 10 degrees, MarOpto TWI 60 offers ease-of-use and quickness in interferometric metrology of more complex freeform surfaces. [61, 62]

Figure 3.5: MarOpto TWI 60. [63]

TWI as a name reflects the way illumination of the surface under test (SUT) is produced: a coherent laser source produces a wavefront which is split via a polarizing beam splitter, and the wavefronts are then directed to a micro lens array that, with the help of a pinhole array, creates spherical wavefronts, which are again split and then collimated to become a set of planar wavefronts with varying levels of tilting relative to each other. Again transforming from planar to spherical by an objective lens, the basic best-fitting spherical form of the SUT is compensated for each area. Reflections created by the SUT send wavefronts returning back to a beam splitter, and unwanted interferometric fringes are filtered by an aperture, leading to a interferometric patches on a camera sensor that can be evaluated after a single measurement cycle. [62]

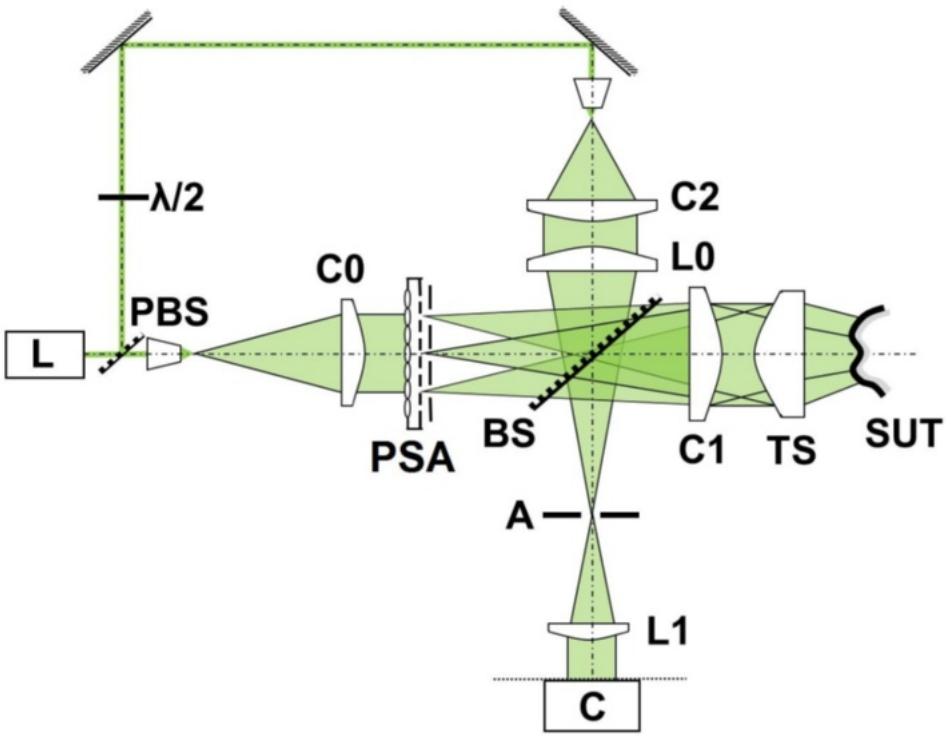

Figure 3.6: A schematic of the tilted wave interferometer. [64]

Chapter IV

Measurements & results

Four copies of the aspheric lens were printed, and determining how much they differ from the original design is achieved by utilizing the TWI system at Millog Oy. The measurements and received results are presented in this chapter.

4.1 TWI measurements

Measuring form deviation and surface roughness of a lens is a somewhat simple procedure with a TWI system, as it mostly only requires pre-setting parameters and inputting the formula describing the aspheric properties of the surface geometry of the lens to which the system compares the measured results. The only manual operation to perform is a pre-focusing of sorts: the device requires an optimal starting position to start the measurement, which in turn is completely automatic. When an acceptable starting point is found, in approximately 30 seconds the machine provides a measurement report, which includes a phase map, surface parameters, Zernike terms and Seidel aberrations. The measured data is also available in various different file forms for further analysis. The measurements in this study were conducted on all four lenses in the facilities of Millog Oy, and the results shown in the next section.

4.2 Form & surface results

The output image of the measurements is essentially a topographical comparison between the input asphere formula (the ”target”) and the measured values. The higher the peaks and lower the valleys are, the further the surface is from the initial

design. A colour scheme illustrates the results both in 2D and 3D - the ideal colour would be orange, whereas red areas are too high and blue areas too low when compared to the target geometry. The results of the form measurements are visually shown in figures 4.1 to 4.4, and numerically (PV for form deviation, RMS for surface roughness) in table 4.2.

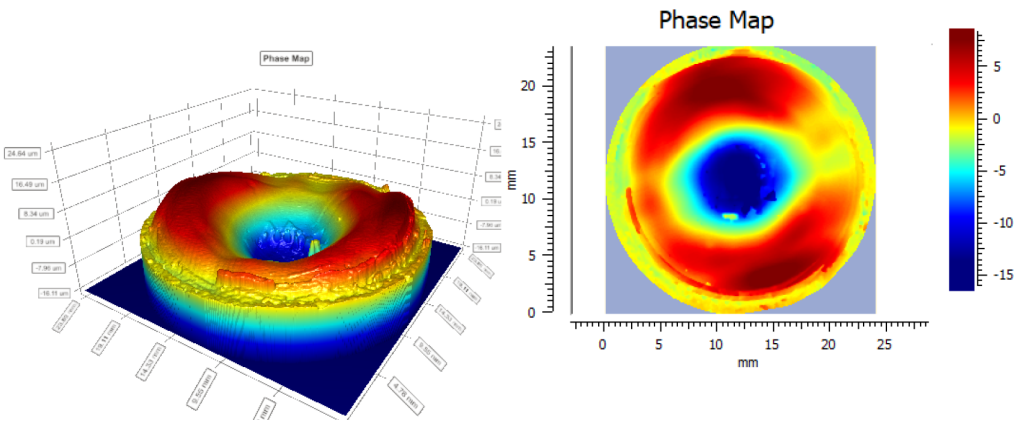

Figure 4.1: The result of the measurements of the first lens.

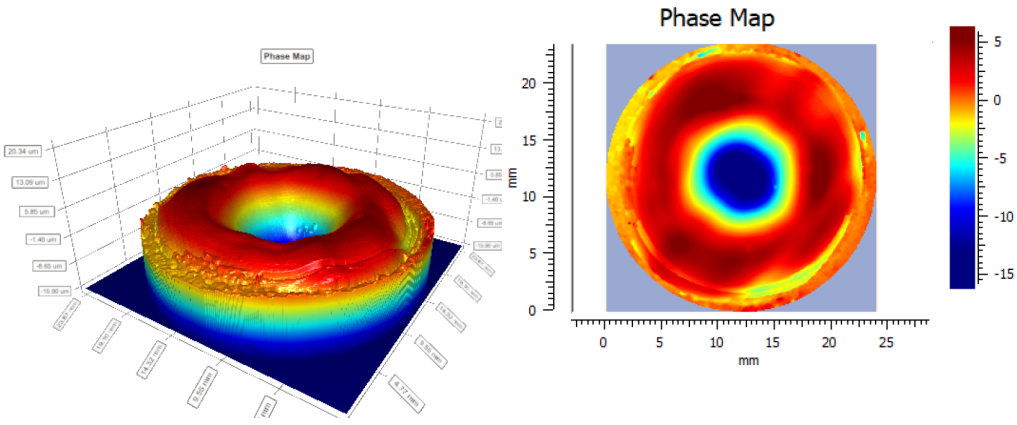

Figure 4.2: The result of the measurements of the second lens.

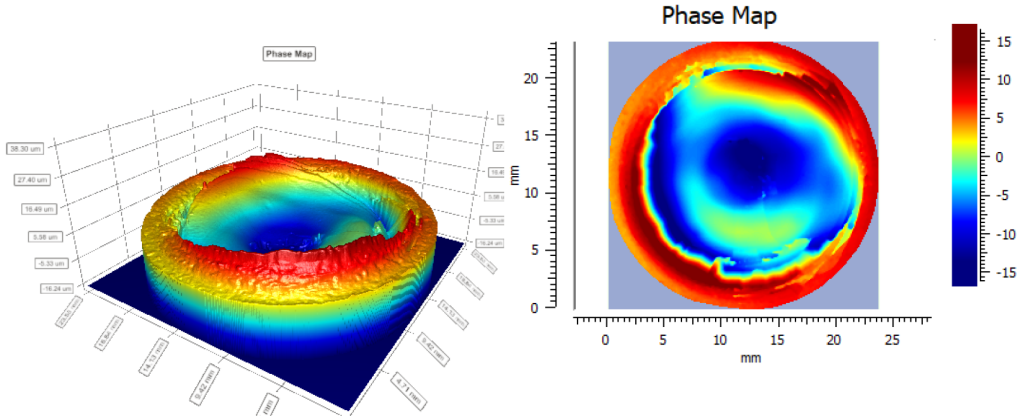

Figure 4.3: The result of the measurements of the third lens.

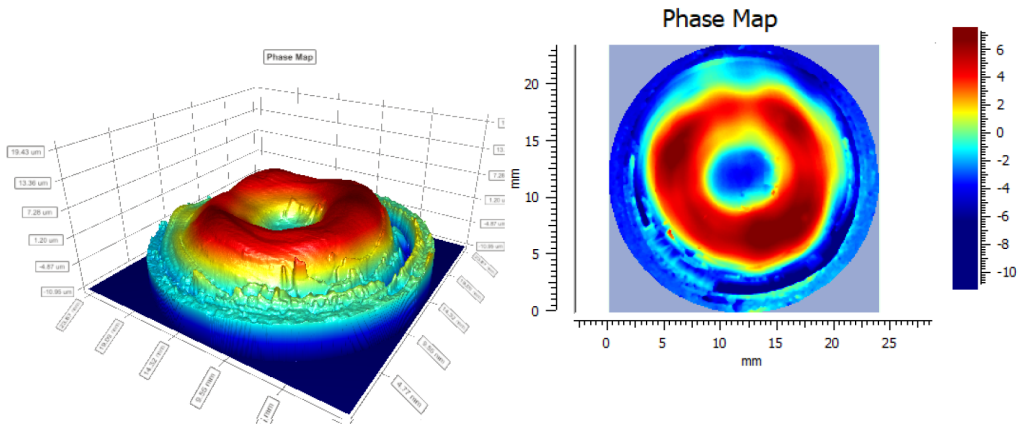

Figure 4.4: The result of the measurements of the fourth lens.

Table 4.1: Results of the measurements in numerical form.

Lens	PV [µm]	RMS [µm]
1	24.45	4.77
2	21.74	3.98
3	32.73	6.90
4	18.23	3.63

Chapter V

Discussion

This chapter deals with analyzing the results of the measurements by reviewing the images and explaining the tabulated results. The significance of the results is also discussed, and further improvements suggested.

5.1 Analyzing the measurement results

The topographical maps created by the TWI system show that most of the shapes resemble toroids more than flat surfaces, except that of lens 3, which appears more planar, indicating it is close to the target surface by form. However, its inner surface seems somewhat tilted and has discontinuous areas in the top section, which may have been caused by a measuring or fitting error by the metrology system, causing the result to be implausible altogether. Considering the other three samples that appear more similar to each other, their outer sections (the areas beyond a radius of approximately $r > 10$ mm) and edges seem very grainy and nonuniform, though mostly being in the target height, having orange to light green colours. However, they appear somewhat discontinuous from the middle areas (5 mm$< r < 10$ mm), which in turn appear smoother on the surface but are, in general, too high (red tones). Finally, the central areas ($r < 5$ mm) are somewhat smooth but too low (blue tones) compared to the target asphere, causing a hole of sorts in the middle parts. Some high individual peaks appear in the middle area of the first lens, which are possibly caused by dust or other debris.

Overall, all the results fall between similar magnitudes of form deviation and surface roughness, though the fourth lens appears the best by the phase map uniformity

and the numerical results, and the third lens, if the results are blindly trusted, certainly the worst. Lenses 1 and 2 are quite similar in all senses, but it cannot be confidently determined whether they came from the same batch or not. However, judging only by the surface geometries of the phase maps, lenses 1 and 2 appear to have larger measurable areas (up to $r < 10$ mm), whereas lens 4 seems to have suffered more from an analyzing error of the outer areas. In any case, though being clearly transmissive and close enough to the target asphere for measurements, the PV and RMS parameters having values in multiple (tens of) micrometers together with the toroidal phase maps indicate that the lenses are not sufficient for imaging quality when the whole aspheric areas are considered.

This is, however, not the complete truth. The odd-looking images and somewhat poor numerical results can possibly be explained by several matters that may have affected the final outcomes of the measurements. First of all, the graininess on the outlines of the lenses can have been caused by measurement errors made by the metrology system, meaning that the device may not have been able to analyze the areas furthest from the centre properly. This may have happened due to striae or other optical artifacts hindering the measurements: a preview image of a plastic and a glass reference lens taken during the manual finding of starting position differed significantly, the former having considerably more striae visible than the latter. Also, the graininess appeared only in the edges for all the measured samples, further strenghtening the possibility of an error in the interpretation and analysis of measurements. What is more, a partial reason for the graininess might originate from the fact that the lenses were cut from the base plates with a laser cutting system, which may have spread micrometer-scale molten plastic on the edges.

A second possible explanation for the results is that the lenses were not quite kept in cleanroom-level environments during the whole chain of printing, transporting and measuring, fundamentally exposing them to e.g. dust and humidity, albeit they were manufactured in an optical laboratory and measured in an industrial-level optics manufacturing and measuring complex, and kept in a plastic box inside a cleanroom-quality cloth during transportation. The third matter actually concerns the transportation box itself: the pressure from the box ceiling might have pushed down on the central area of the lenses, causing them to dent, partly explaining the

sagging central parts, though the sag can have been caused by the printing process itself. Finally, at some points, some of the lenses had to be touched with protective gloves, possibly exposing them to contaminants. All these reasons could have increased the total errors of both form and roughness of all the manufactured lenses, resulting in their sub-imaging level optical quality.

5.2 Emphasis on the significance of the results

In spite of the results suggesting only mediocre quality when considering real-world optical components, which require nanometer-scale RMS and single micrometer-scale form deviation values, there are many aspects to appreciate in the whole scenario. It needs to be noted that 3D-printing optically clear macroscale aspheric lenses with micrometer-scale form deviation and surface roughness is no easy feat, and achieving these results without any iterative processes (that have earlier lead to at least locally low deviation and roughness values [65]) or post-processing of any kind (excluding aftercuring) in a few batches in merely hours is an achievement in itself. Moreover, the way the data is processed and fitted by the measurement system remains unknown, and if e.g. only certain areas could be studied locally, the results could turn out to be magnitudes lower than when compared to those of the whole area, which could be applied in other products, e.g. a lens that has its incident light limited by an aperture.

In addition to a more robust and iterative printing process (print, measure, understand, compensate, repeat) and more extensive analysis of the data, the results could be improved by taking greater care of the cleanliness of the lenses, ensuring a shorter time between the printing and final measurements, and by utilizing new compensation methods by testing different lens geometries and finding out how the technique could be improved. Having both the printer and the measurement system physically closer to each other could tremendously speed up the development of the method. Ultimately, the most important aspect for the future of 3D-printing optical components and improving the whole process chain is including more researchers and companies in the field, and even though being able to rival moulding and turning methods is still far from reality, the novel technology appears promising for the future of plastic optics.

Chapter VI

Conclusions

This manufacturing-themed thesis has given a literature-based overview of modern plastic optics, studied commercially available transparent polymers and conducted a comparison of the various fabrication methods of plastic optical components. Most importantly, the concluded research has concentrated on additive manufacturing of Senop Oy's aspheric lenses in the form of 3D-printing with the novel Printoptical® Technology. The measuremens taken with a tilted-wave interferometer have shown that the technology can already produce micrometer-scale surface accuracies across the whole area of the component without any post-processing or iterative cycles, suggesting that printing centimeter-scale lenses might become a notable option for the early-stage prototyping needs of optical manufacturers in the near future.

Moreover, having introduced the basic theories governing modern optics, such as the propagation of light and the dispersive qualities of common optical components, a general investigation of transparent polymer materials has shown both their forth- and shortcomings when compared to optical glass materials: even though plastic components can generally not rival their glass counterparts when considering stability or optical qualities, they have a competitive edge in certain situations due to their low weights and costs, efficient mass-production capabilities as well as broader optomechanical possibilities. Considering production, additive manufacturing, injection moulding and diamond turning have been presented as the essential manufacturing methods of plastic optical components, and their process chains, optical suitabilities and requirements been reviewed. A quality-cost-availability comparison of the methods has also been conducted and various plastic materials have had their

optical properties catalogued, presenting suggestions and guidance for companies possibly interested in experimenting with plastic optics. Notably, even though a newcomer on the field, 3D-printing could be particularly advantageous to manufacturers working in the early phases of creating new products, as its relative easiness and cheapness can reduce risks of aggressive product development, hence enabling experimenting with otherwise unthinkable solutions.

All in all, the field of plastic optics is constantly developing, as research is being conducted on discovering new methods and materials for producing high-quality traditional components, and companies aim for innovative solutions in hopes of cutting expenses related to the more traditional production of glass optics. Parties currently working with glass and interested in plastics should, however, pay great attention to the differences between the materials, their limits and production-related requirements all the way from how the components and optical systems are designed. Even if clear for a glass component, various issues regarding the usage of a plastic replacement will come up, and questions, such as what is the purpose of the product in the complete system, what are its optical and mechanical tolerances, where the system will be used and how many components are required, require answers for determining the best possible solutions. It is therefore suggested that every the step in the chain of realizing plastic optical components should include the party ultimately responsible for the manufacturing phase, as the answer with plastics is always ”it depends”.

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