EVALUATING THE VALIDITY OF MANUFACTURING 3D PRINTED LENSES; USING COMMERCIAL SLA MATERIALS AND DIAMOND TURNING PROCESSES

By

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Finally, I'd like to thank my parents, friends, and husband for their continued support.

DEDICATION

This thesis is dedicated to the man who taught me that the speed of light was 186,000 m/s when I was 5 years old, my late father James D. Westover.

This thesis is also dedicated to my husband John J. Glynn IV. This study would not have been possible without his support, Starbucks runs, and stupid jokes.

Contents

List of Tables

List of Figures

List of Equations

ABSTRACT

Optics are traditionally made from subtractive machined substrates that are then ground, polished, and/or diamond turned for an optical surface. This study probes the validity of producing lens substrates by leveraging additive manufacturing. Stereolithography (SLA) 3D printing was used to produce optical substrates which were then diamond turned into a final lens. Four commercial grade materials were investigated to determine what, if any, material could produce a viable precision lens. The materials used in this study include; Somos WaterClear Ultra, Accura ClearVue, FormLabs Clear, and VeroClear. The Somos WaterClear Ultra and 3D systems Accura ClearVue even list optical properties including Index of Refraction. Whereas, Stratasys material VeroClear and FormLabs Clear do not list such data but advertise that the material is “optically clear”.

Material properties were recorded for all four materials in the form of transmission responses, Abbe Number, and Index of Refraction. Lens quality evaluating tests were also performed for all four material lenses. These include surface wavefront error, surface roughness, and image quality testing. An Acrylic control lens was produced using CNC machining and tested alongside the four 3D printed lenses. On average the 3D printed lenses performed in family with the Acrylic control. Overall, this study shows a promising future for further development into producing 3D printed lenses.

1 INTRODUCTION

Optics are traditionally made from subtractive machined substrates that are then ground, polished, and/or diamond turned for an optical surface. Typically, substrates for reflective optics are produced out of a metal or crystalline material. While, traditional substrates for refractive optics are produced from optical glass or crystalline material. As the optics industry has advanced, polymers like Acrylic have been included as usable materials for producing refractive optics. Standard optical manufacturing techniques can result in high precision optics however, off-axis and complex geometries can be difficult to produce. Standard optics manufacturing can also be expensive and extremely time consuming, making rapid prototyping difficult. As freeform surfaces become more prominent in optical designs the industry is looking for alternative ways to produce high precision optical surfaces.

Significant scientific and technological interest exists in additive manufacturing like 3D printing technologies. New print forms and materials are coming out for commercial grade printers on a regular basis. The optics community has started to leverage 3D printing, typically for optomechanical purposes. Studies have begun to look into 3D printing as a means to produce optical substrates. The majority of these substrates are utilized as reflective optics printed in metal using laser sintering. BAE Systems and others have had success post processing these mirror substrates and producing final precision optics. Few studies have looked into using additive manufacturing for producing refractive optics. Some companies have had success producing direct to print lenses using 3D printers with ink-jet technology. These lenses are produced with a resin like material that attempts to simulate Acrylics. The idea of the “direct to print” lenses is that the lenses coming off of the 3D printers are in final form and do not undergo post processing. Luxexcel is a leader in producing these types of 3D printed lenses. However, Luxexcel’s materials and printers fall outside of the commercial additive manufacturing realm; as their machines are priced, sized, and exclusive to mass production of lenses for the prescription eyewear community. There are some other groups that are working on similar direct to print lenses, however they are mostly in the early stages of development. It has yet to be seen if direct to print lenses can be produced for high precision applications without post processing for best quality.

This thesis study probes at the validity of producing a precision quality optic using substrates that were printed using commercial rapid additive manufacturing. Within the realm of commercial rapid additive manufacturing there are four main materials that boast themselves to be “transparent”. These are the Somos WaterClear Ultra, Accura ClearVue, FormLabs Clear, and VeroClear. The Somos WaterClear Ultra and 3D systems Accura ClearVue even list optical properties including Index of Refraction. Whereas, Stratasys material VeroClear and FormLabs Clear do not list such data but advertise that the material is “optically clear”. These materials are a resin like stereolithography (SLA) materials for use with SLA 3D printers. A lens substrate sample was produced out of each of the four SLA materials listed. These prints produce a lens substrate with some support material. Once the support material is stripped it mimics a CNC machined plastic substrate. An Acrylic lens substrate was CNC machined as a standard optical substrate for the purpose of a control. All five substrate samples were produced from the same .STP file of a simple 58mm diameter plano-convex lens. This form was chosen for its simplicity in order to more easily evaluate the lens materials. For this study the substrates were post processed by way of diamond turning. This is a standard optical process for producing high precision lenses. No further processing was done on the lens samples. This control was post processed and tested alongside the four SLA 3D printed substrates. Wavefront Error (WFE), Surface Roughness, Index of Refraction, Abbe Number and Image testing was done for evaluation of all lenses.

2 BACKGROUND

2.1 Stereolithography Style 3D Printing

There are a variety of different 3D printing techniques, the most common being Fused Deposition Modeling (FDM) which extrudes a filament layer by layer to build up the print. This a fine technique for producing many mechanical parts but is very limited in terms of creating refractive optical substrates. The FDM prints are limited in their ability to be machined. If machined too aggressively the layers of the FDM print will delaminate causing a critical failure. For these reasons and others when looking at manufacturing 3D printed lenses, stereolithography (SLA) printers give us the best chance of success. SLA printers belong to a family of additive machining techniques known as vat photopolymerization.[1] These systems use a completely different philosophy then the more well-known FDM machines. SLA uses a liquid resin material which results in a higher resolution solid print. Figure 2.1.1 shows a comparison of a FDM print and an identical SLA print. Rather than extruding the material, SLA printers use a laser beam to cure the resin into its desired shape. This process is done in a stepped layering processes, where the build platform is raised in order for the next layer to be cured. There are some variations between different SLA printers, however the basics remain relatively the same. Figure 2.1.2 shows a schematic of the basic mechanics of a SLA 3D printer.

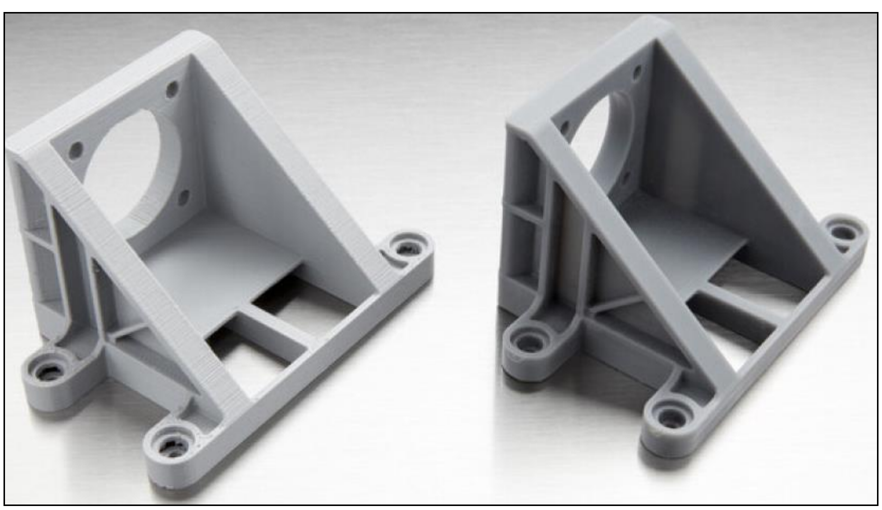

Figure 2.1.1: Shows a comparison print between FDM (left) and SLA (right) printers. [1]

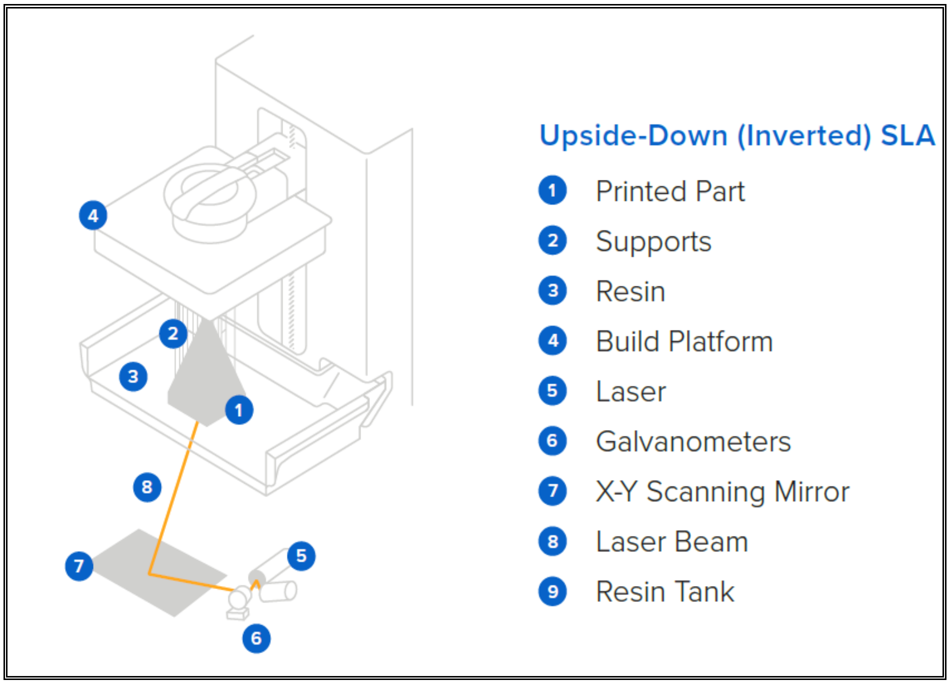

Figure 2.1.2: shows a schematic of the basic mechanics of a SLA 3D printer. [1]

SLA 3D printing is not new, in fact it has been around since the early 1970's. 3D systems, the big name in SLA printers, have been producing SLA printers and materials since 1986. However, those printers were largely cost prohibitive and required skilled technicians to run and maintain. In recent years companies like FormLabs and Objet have pushed the SLA and other vat photopolymerization type printers into the consumer and rapid prototyping community. Larger companies like 3D systems and Stratasys have followed suit and manufactured SLA printers that are more robust and reasonably priced. With this, a surge in SLA materials have come onto the market to cater to the engineering community with optical and thermodynamic properties. While FormLabs and Objet printers are targeted towards the desktop community, 3D systems and Stratasys printers are more geared towards engineering departments with lab space. Both forms are pretty self-efficient when printing from .STL files. This is still a vast improvement from the warehouse size printers that sometimes required significant man hours. With these improvements in 3D printers many new rapid prototyping companies like Protolabs and Xometery have popped up onto the scene. These companies offer machining and 3D printing from .Step and .STL files at an economic price. This has given consumers and prototyping community access to one off parts with high resolution at low cost. This also allows consumers to test out different materials and printers before committing to purchasing a printer. Without these advancements in SLA printers and rapid prototyping companies this thesis study would have been limited in scale.

2.2 Related Studies on 3D Printed Refractive Optics

One of the most recent facets of rapid prototyping that has immerged with the new wave of SLA printers and materials is 3D printing lenses. Many new companies and research groups are looking into vat photopolymerization printers, in order to do direct to print lenses. The main direct to print solution on the market now is Luxexcel's printers and Opticlear material. These printers act similar to an inkjet printer, slowly laying the resin layer on top of the print. The Luxexcel and materials are larger warehouse size printers that are licensed solely to the optometry community. This makes it out of reach of other optics disciplines and also leaves to question how precise the Luxexcel direct prints are. Eye glasses lenses are not high precision surfaces and typically have pretty achievable specifications. Even still, Luxexcel lens are the first 3D printed refractive optics of note to be produced and used. Therefore, Luxexcel's direct to print lenses can be used as a bench mark for where we stand on making usable 3D printed lenses.

A study was done as part of a National Institute of Health grant entitled "Quantitative evaluation of performance of three-dimensional printed lenses". This study focused on the Luxexcel printer and Opticlear material, comparing the lens performance to that of Edmund Optics glass lenses of similar shape. As is the philosophy with direct to print lenses no post processing of the surfaces were done once the lenses were cured. Surface roughness and Wavefront Error testing was done on the 3D printed parts. The results were decent for a 3D printed part but preformed below that of a standard lens. The surface roughness of the parts varied between 100-200Å on their samples ranging from 12.7 – 50mm in diameter.[2] It is standard even on commercial level lenses to have a surface roughness of less than 100 Å, often less than 50 Å depending on the diameter of the lens.[3] The Wavefront error RMS results ranged from 1.5 – 1.7 waves at 632nm.[2] This again is promising for an additive manufactured lens but is far from the high precision quarter or eighth wave values often required. With Luxexcel materials and direct to print methods largely out of reach for most of the optics community; the questions holds if there is a valid 3D printing material or method that can produce lens on the level or better than Luxexcel's direct to print lenses.

It is clear that SLA printers and materials are our best shot at producing a usable 3D printed lens. In that sphere there are four main commercial materials that produce a "clear" print. These are the Somos WaterClear Ultra, Accura ClearVue, FormLabs Clear, and VeroClear. There are a limited number of white papers on the topic of producing lenses out of these materials. However out of the four materials there are a few studies that utilized the two commercial grade materials which are the FormLabs Clear and the VeroClear. These studies give us a glimpse at the capabilities of these "optically clear" materials that have limited reported material properties from their vendors.

The study done using the VeroClear material is entitled "The research on surface characteristics of optical lens by 3D printing techniques and precise diamond turning". This study was done using optical flats as the test subject. Because the test pieces were optical flats instead of powered lens the surface error was tested using a CMM rather than an interferometer. For that reason this study's surface error results have little comparison to standard lenses or the direct to print lens results. However, this study does show that the VeroClear material is capable of being diamond turned to produce a transparent optical flat. Figure 2.2.1 below shows the final VeroClear optical flat produced from this study after being diamond turned.

Figure 2.2.1: Shows VeroClear optical flat produced in a separate study. [4]

An applicable study using FormLabs Clear material is entitled "“Fabrication of optical components using a consumer-grade lithographic printer”. In this study plano-convex lenses were printed using the FormLabs Clear material and then post processed using the same resin. A spin coating technique was used in order to give the lenses a precise surface. This technique is more akin to direct printing than post process machining or polishing. They had successful results using 1600 RPM for a 9second duration.[5] Using this method two lenses of 12.7mm diameter were produced with a focal length of 15mm and 25mm respectively. With these final lenses they were able to achieve surface roughness results between 120-220Å. These results are akin to the Luxexcel lens results but still beyond industry standards. The Wavefront error RMS results for the lenses faired very well with average results of 0.37 waves. This result is far better than the direct to print values and may be the best surface error results for a 3D printed lens to date. The FormLabs spin coating technique has promising WFE results however, it also has several limitations. The spin coat method has limitations of geometry and size of the optic. This may be a good method for small simply optics.

The Luxexcel and FormLabs Clear lens studies show promise for usable 3D printed lenses. However, in both cases the surface roughness and WFE results were beyond that of most industry standards. The lenses made were also on the smaller side. For this thesis study all four main commercial “clear” SLA materials will be used alongside conventional diamond turning processes. This is done to ensure that any positive results from this study can be applied to more complex geometries and parts such as freeform surfaces. Producing complex geometries is one of the main advantages of additive manufacturing over subtractive manufacturing. Therefore, it is import these types of profiles are kept in mind when validating new methods for producing 3D printed optical substrates. In addition to using traditional post processing techniques the lens profile in this study will be a 58mm diameter lens with a 100mm radius of curvature. This was chosen for its ability to fit on a standard DSLR camera format. While there are many applications for smaller diameter lenses, the larger diameter allows us to evaluate the ability to produce a standard imaging lens. This is also one of the largest documented 3D printed lenses.

3 EXPERIMENTAL METHODS

3.1 Substrate Materials and Production

For this study five plano-convex lenses with a radius of curvature of 100mm, 58 mm diameter, and an 8mm central thickness were produced. Four of the lens substrates were produced using SLA additive printers each of a different 3D printing material. The four 3D printing materials are Accura ClearVue, FormLabs Clear, VeroClear, and WaterClear Ultra. These are all commercial grade materials that were printed on commercially available printers. Xometry (a rapid prototyping company) was used for printing all but the FormLabs substrate. For all Xometry substrates, the "Strip and Ship" finish was applied, which simply removes the support material before shipping. The fifth lens is an Acrylic substrate that was produced using typical subtractive CNC machining methods.

Accura ClearVue is an SLA additive material that is supplied by 3D Systems. The Accura ClearVue lens substrate sample for this study was produced by Xometry using a Projet 7000 printer. High resolution was used for printing this sample. The technical data sheet for this material reports optical properties, these are seen below in Table 3.1.1.

OPTICAL PROPERTIES		
MEASUREMENT	CONDITION	VALUE
Haze @ 0.495 mm (0.195 in)	ASTM D1003-13	4.3 %
Luminous Transmittance @ 0.495 mm (0.195 in)	ASTM D1003-13	87.2 %
Diffuse Transmittance @ 0.495 mm (0.195 in)	ASTM D1003-13	3.8 %
Index of Refraction	ASTM D542-14	1.508
L*		95.45
a*		-0.54
b*		1.36

Table 3.1.1: Shows the Technical optical data from the Accura ClearVue data sheet. [6]

WaterClear Ultra 10122 is an SLA additive material that is supplied by Somos. The WaterClear Ultra 10122 lens substrate sample for this study was produced by Xometry using an SLA 5000 printer. Standard resolution was used for printing this sample. The technical data sheet for this material reports optical properties, these are seen below in Table 3.1.2.

Liquid Properties		**Optical Properties**		
Appearance	Optically clear, colorless	E_C	10.0 mJ/cm²	[critical exposure]
Viscosity	~165 cps @ 30°C	D_P	6.5 mils	[slope of cure-depth vs. In (E) curve]
Density	~1.13 g/cm³ @ 25°C	E_{10}	47 mJ/cm²	[exposure that gives 0.254 mm (.010 inch) thickness]
		D542	1.52	Index of Refraction (cured)

Table 3.1.2: Shows the Technical optical data from the WaterClear Ultra 10122 data sheet. [7]

VeroClear is an SLA additive material that is supplied by Stratasys. The VeroClear lens substrate sample for this study was produced by Xometry using a Connex 500 printer. Standard resolution was used for printing this sample. There are no optical properties reported for this material in the technical data sheet. The technical data sheet does however state that "VeroClear simulates PMMA (polymethyl methacrylate), commonly known as acrylic, and enables the visualization of internal components and features ideal for form and fit testing of see-through parts such as eyewear, light covers and medical devices".[8] While few optical properties are readily available for this material a study entitled "The research on surface characteristics of optical lens by 3D printing techniques and precise diamond turning" was found in the SPIE proceedings. In this study the transmission of the material was measured on diamond turned flat samples that were printed in different configurations out of the VeroClear material. These results are shown in Figure 3.1.1 below.

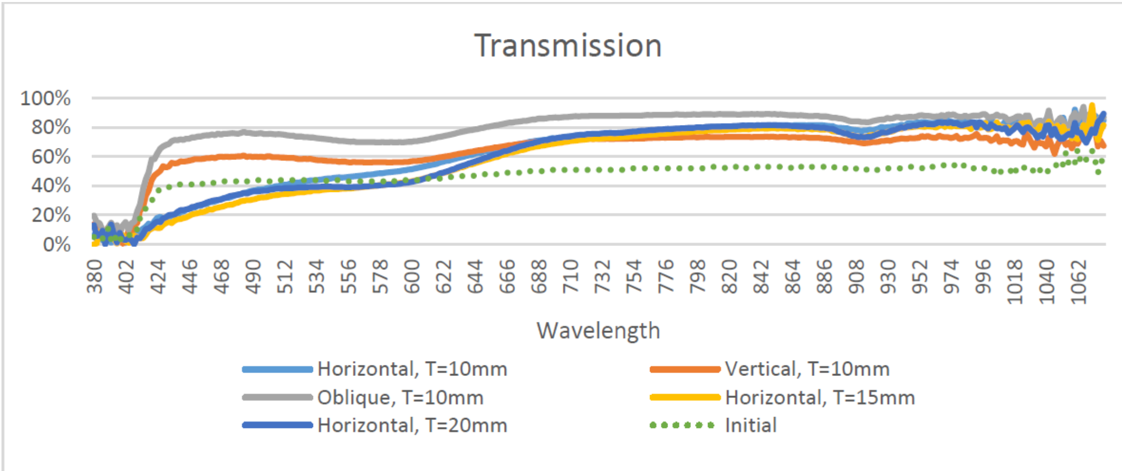

Figure 3.1.1: Shows transmission results for VeroClear produced in a previous study. [4]

FormLabs Clear is an SLA additive material that is supplied by FormLabs themselves. The material is marketed to be optically clear, without much more detail or data to back up the claim. While few optical properties are readily available for this material a study entitled “Fabrication of optical components using a consumer-grade lithographic printer” was found in Optics Express publication. In this study the transmission of the material was measured on a flat sample block. This sample was finished after printing by coating the top surface with clear resin and spinning the sample at 1600 RPM for 10 seconds.[5] These results are shown in comparison to Acrylic and PMMA in Figure 3.1.2 below.

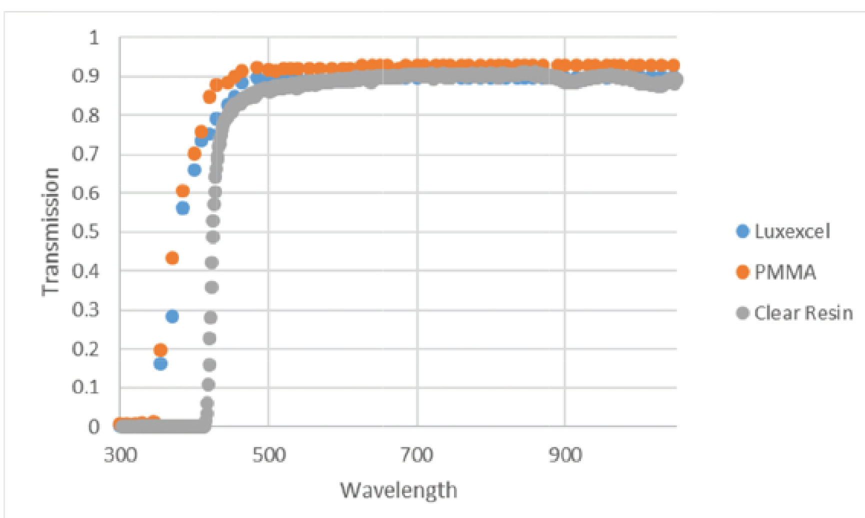

Figure 3.1.2: Shows transmission results for FormLabs Clear produced in a previous study. [5]

Although the transmission results reported look promising, the FormLabs Clear resign is subject to significant yellowing of the material. This yellowing hinders certain applications in the visible spectrum. Figure 3.1.3 shows the results of printing and diamond turning a block sample of the FormLabs Clear material.

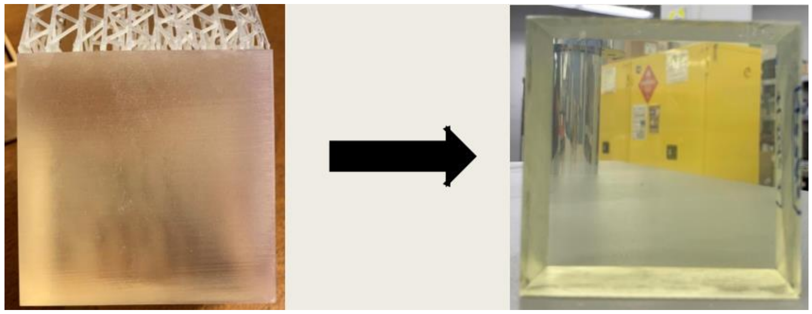

Figure 3.1.3: Shows the progression of the FormLabs Clear block from left to right.

By reaching out to contacts at the University of Arizona and FormLabs themselves it was determined that the yellowing condition was due to the UV curing of the print. Attempts were made to produce successful prints with a reduced UV curing time by the University of Arizona’s lab. These samples are seen in Figure 3.1.4, and resulted in a less rigid substrate with significant derogation in form. The prints featured a significant wedge factor as well. In addition to these errors the yellowing was only mildly improved.

Figure 3.1.4: Shows FormLabs prints that were printed with less UV cure time.

Given these results it was decided to produce the lens sample with the standard FormLabs recommended settings. Three samples were printed per the sample .STL file as the other four lenses substrates. These samples were printed by BAE Systems in three different support configurations as seen in Figure 3.1.5. All three FormLabs Clear samples were diamond turned and measured for WFE. The FormLabs Clear lens sample with the best results was then chosen to move forward with the rest of the testing for this study.

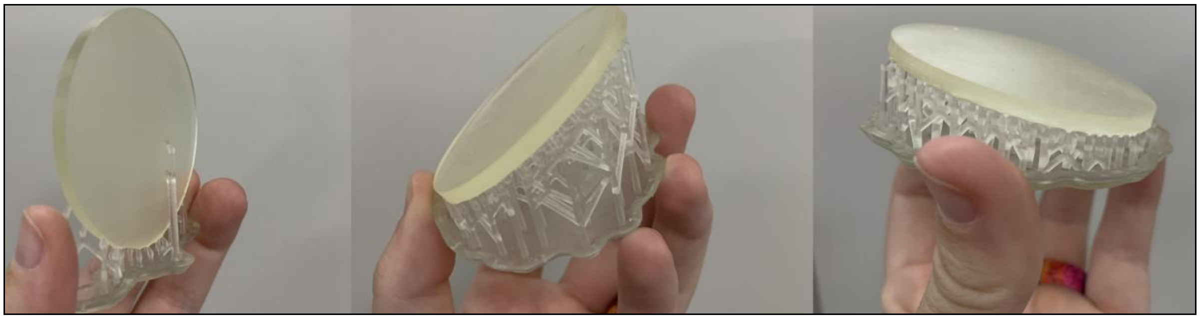
Figure 3.1.5: Shows the three different FormLabs print configurations (Vertical, Convex down, and flat down).

Acrylic is a standard material for use in plastic optics manufacturing. It can produce substrates by molding or CNC machining. For this study an Acrylic substrate was CNC machined out of a 0.45 thick sheet acrylic that was held down on a vacuum table to be machine. The sample was machined by Xometry out of OPTIX Acrylic by Plaskolite. The technical data sheet for this material reports optical properties, these are seen below in Table 3.1.3.

Physical	***Test Method***	***Units***	***OPTIX Value***
Specific Gravity	ASTM D-792	-	1.19
Optical Refractive Index	ASTM D-542	-	1.49
Light Transmission - Total	ASTM D-1003	%	92
Light Transmission - Haze	ASTM D-1003	%	2

Table 3.1.3: Shows the Technical optical data from Plaskolite Acrylic data sheet. [9]

3.2 Diamond Turning Processing

Diamond Turning is a subtractive CNC machining technique for producing high precision optical surfaces; by use of a diamond tip against a metal, crystalline material, or plastic substrate. This process is common in the world of high precision optics manufacturing. Diamond turning is an iterative process with multiple surface form checks to ensure best possible finish. Standard diamond turning capabilities are listed in Table 3.2.1 as reported by Edmund optics. [3]

Diamond Turning Capabilities			
	Commercial	**Precision**	**High Precision**
Reflective Wavefront Error (P-V @ 632nm)	λ	λ/2	λ/8
Transmitted Wavefront Error (P-V @ 632nm)	λ	λ/2	λ/4
Surface Quality	80-50	60-40	40-20
Surface Roughness			
Diameter: ¼” – 1”	50 Å	30 Å	<30 Å
Diameter: 1” -2”	125 Å	100 Å	50 Å

Table 3.2.1: Shows the standard diamond turning capabilities as reported by Edmund Optics. [3]

All lens substrates in this study were diamond turned by BAE Systems in their diamond turning shop on a Nanoform 250 Ultra seen in Figure 3.2.1. BAE Systems’ diamond turning shop is very experienced, especially with plastic substrates. No set specifications were given to the diamond turning shop other than to use best practices to ensure the best possible lens quality.

Figure 3.2.1: Shows a representation of the Nanoform Diamond Turning machine. [10]

For this study, the diamond turning processing transforms the unfinished printed or machined substrates into final form lenses. Figure 3.2.2 shows the five lens substrates before diamond turning. In comparison, Figure 3.2.3 shows the finished lenses after the final diamond turning iteration for best form as compared to a 100mm radius of curvature plano-convex lens.

Figure 3.2.2: Shows the unprocessed lens substrates before Diamond Turning.

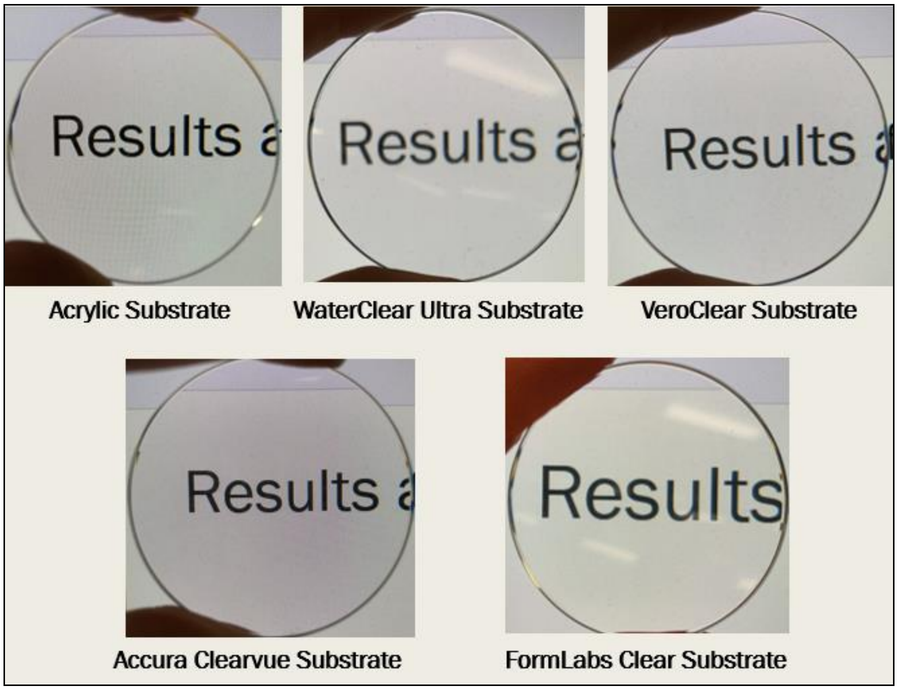

Figure 3.2.3: Shows final lens forms after Diamond Turning.

3.3 Index of Refraction and Abbe Number Testing

Index of refraction is the value of how fast light travels through a medium and effects how the angle of which the light bends. The index of refraction is calculated by dividing the speed of light in a vacuum by the phase velocity of light in the medium.[11] This can be best tested with a refractometer. For this study the index of refraction was tested by the University of Arizona on an ATAGO's multi-wavelength Abbe refractometer DR-M2. The ATAGO's multi-wavelength Abbe refractometer DR-M2 reports a measurement accuracy of ±0.0002.[12]

Abbe Number is a measurement of how the index of refraction of a material varies with wavelength, this is better known as dispersion. Abbe Number can be calculated using the index of refraction for the C, D, and F spectral lines (656.3 nm, 589.3 nm, and 486.1 nm respectively).[13] For this study the Abbe Number was calculated using Equation 3.3.1 and index results measured by the University of Arizona on an ATAGO's multi-wavelength Abbe refractometer DR-M2.

Equation 3.3.1: Abbe Number Equation [x]

$$v_d = \frac{n_d - 1}{n_f - n_c}$$

Figure 3.3.1 shows a general schematic of a refractometer. The refractometer places the sample in contact with the refractometer's prism. A range of incident angles are tested to find the critical angle of total reflection for the sample material as measured using the CCD sensor.[11] This is done to calculate the index of refraction. Filters are used to measure the index at C, D, and F spectral lines in order to calculate the Abbe number of the material.

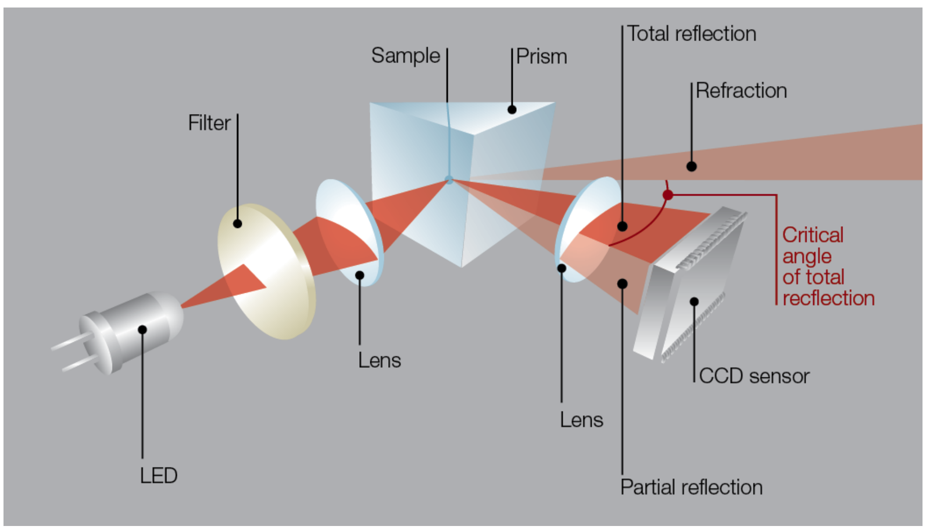

Figure 3.3.1: Shows a general schematic of a refractometer.[11]

3.4 WFE and Surface Roughness Testing

WFE (wavefront error) testing was done using a 633nm Zygo interferometer with a similar configuration to that seen in Figure 3.4.1 below. The lens sample was placed in a three-prong spring mount and aligned to the interferometer. To account for any mounting errors power, tip, and tilt was subtracted from the RMS values in the Metropro software. For the plano side a 4" transmission flat was used for testing. While a 4" f/1.5 transmission sphere was used to test the 100mm convex surface. This testing reports the surface form deviation to that of an ideal optical wave front of a perfect surface.

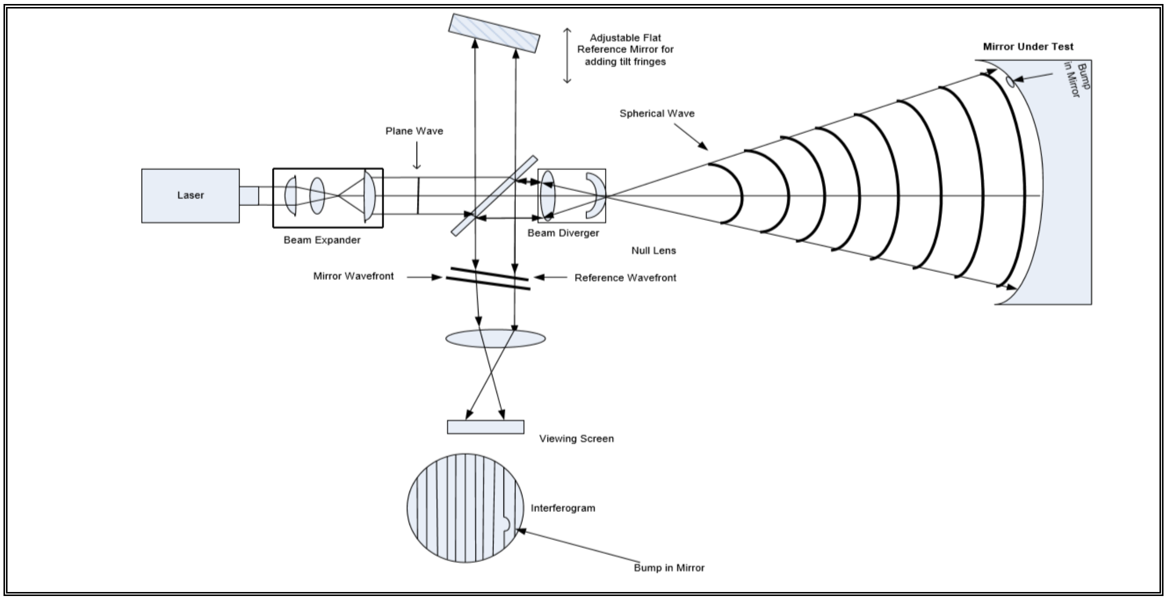

Figure 3.4.1: Shows a general schematic of an interferometer.

Surface Roughness is tested using a 3D optical profilometer system, ZeGage by Zygo. This system uses white light interferometry to evaluate the surface quality at the Angstrom level with high precision. Average roughness (Ra) over a region of interest measured on both the convex and plano side of the lens samples was used as the comparative metric for this study. Figure 3.4.2 shows an Acrylic lens sample measurement as an example.

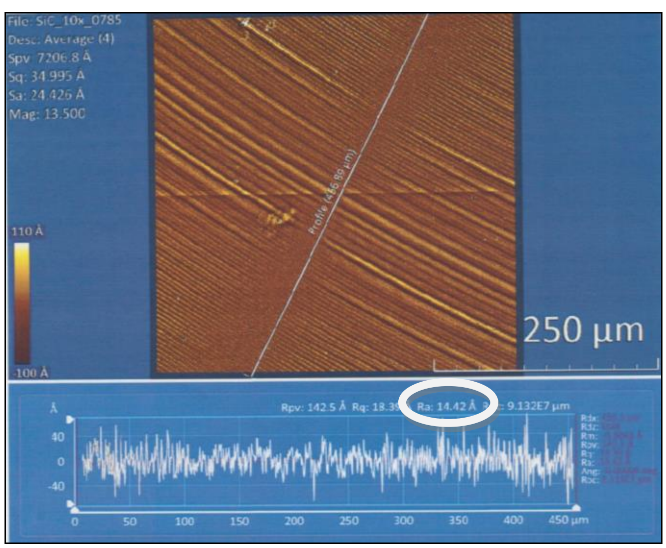

Figure 3.4.2: Shows the software interface and output for Surface Roughness measurements.

3.5 Image Analysis and Testing

The lens substrates were designed with dimensions for utilization on a standard Cannon DSLR. For this study the lenses were mounted onto a Cannon Rebel T5i with a Cannon EF mount. The singlets have a fairly long focal length so to get the accurate tube length a macro extension tube set was purchased. This set accounts for the majority of the length needed and was mounted to the camera base. To achieve a course adjustment and lens mounting a 3D printed housing, mounting flange, and lens holder were printed on a FormLabs printer. Figure 3.5.1 shows the schematic of the 3D printed pieces used for attaching the lenses to the DSLR camera.

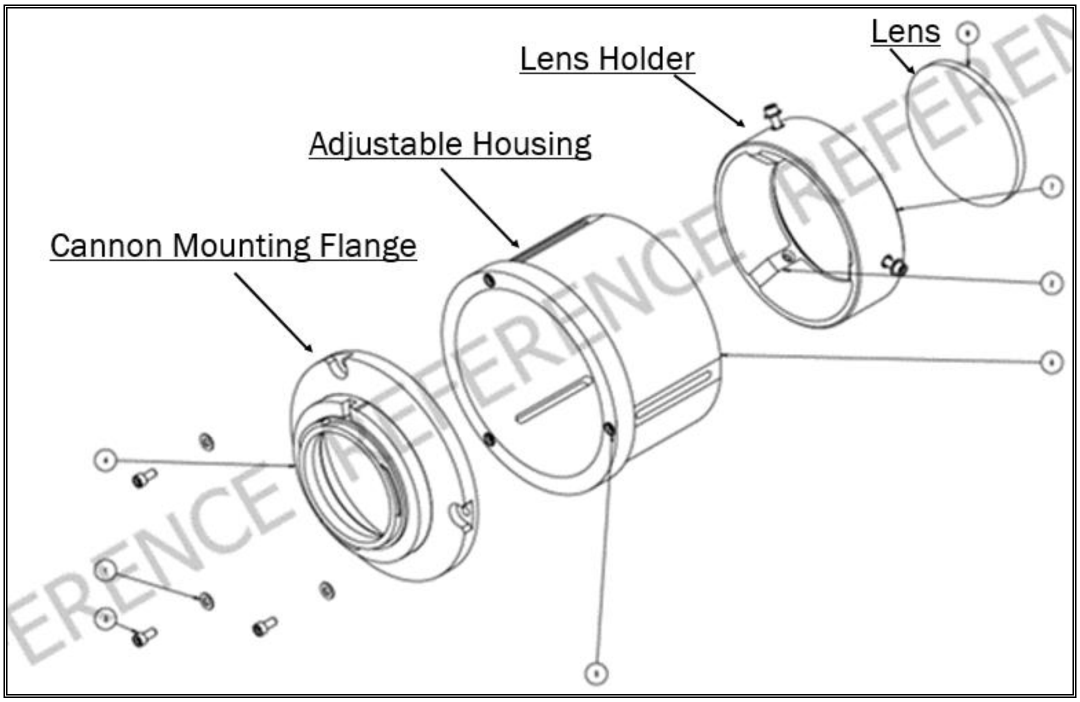

Figure 3.5.1: Shows schematic of 3D printed lens housing and holder.

The lens holder has a seat and inlets for potting the lens into the holder. In this case 5 minute epoxy was used to glue the lenses into their holders. Plastic shim-stock was used to center the lens in the holder before bonding. Three #4 screws allow the lens holder to slide along the slots in the housing, which coarsely adjusts focus. These screws were also measured to assure the lens was not tilted when focusing. The 3D printed mounting flange was then mounted to the macro extension tubes to achieve the appropriate length. Given that the flange is thin and likely to break with repeated use the flange was printed as a separate part that attaches to the housing with #4 screws. Figure 3.5.2 shows the lens mounted onto the DSLR camera using the 3D printed pieces and extension tubes.

Figure 3.5.2: Shows 3D printed lens mounted to DSLR camera.

With the lenses mounted onto the DSLR camera, photos were taken of a set scene that had high contrast. These images were taken at best achievable focus using a tripod. This process was repeated for each of the five lenses. This testing was done in order to see how functional the lenses were at producing imagery over the lens aperture. Once the photos were taken, they were then uploaded into Image J in order to generate a gray value histogram. From the gray value histogram values the contrast of the image was calculated using the Equation 3.5.1 below. Equation 3.5.1 defines the Michelson contrast of the image where I_{max} is the highest luminance, and I_{min} is the lowest luminance value.[14]

Equation 3.5.1: Michelson Contrast Equation [14]

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

4 Material Properties

4.1 Transmission Responses

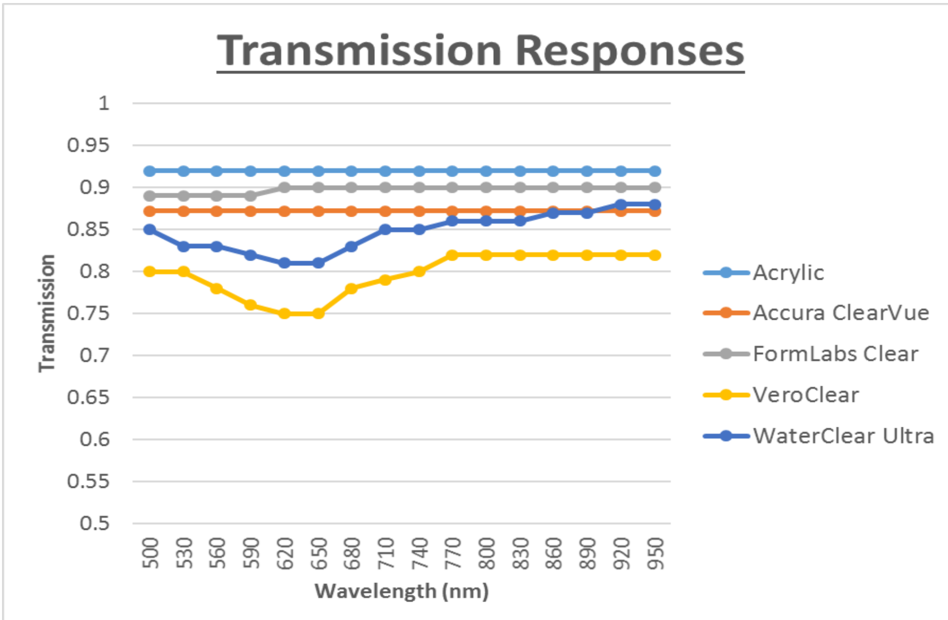

Figure 4.1.1: Shows the Transmission responses for all lens types shown in this study from 500-950nm.[4,5,6,9,15]

Transmission values in Figure 4.1.1 were graphed using reported transmission data from previous studies (for VeroClear, FormLabs Clear, and WaterClear Ultra) and reported data in the materials technical data sheet (for Acrylic and Accura ClearVue). Many plastics have very poor transmission for wavelengths below 500nm, this was the case for all five of the materials in this study. For this reason the responses were plotted from 500-950nm in order to clearly view the results for the usable wavelengths. As seen in Figure 4.1.1 the transmission responses for the five materials are all in family with one another. The VeroClear and WaterClear Ultra material shows some variance with VeroClear having a slightly worse transmission than the other materials. It is import to note however, that the FormLabs Clear data in this graph is for results that didn't have significant yellowing. The yellowing of the FormLabs Clear material varies from print to print and will cause a degradation in the transmission for wavelengths nearing the blue and UV spectrums. This will limit the potential uses cases for the FormLabs Clear lens.

4.2 Index of Refraction & Abbe Number

The Index of Refraction testing was done by the University of Arizona on an ATAGO's multi-wavelength Abbe refractometer DR-M2. Due to the size of the machine and the diameter of the parts (58mm), the parts could not be measured without modifications. Therefore, in order for the Index to be measured the lenses were cut in half and then polished along the cut area. The resulting lenses can be seen in Figure 4.2.1 below. This testing was done last to account for the needed change in geometry. The Acrylic control lens was not tested as, there is significant data available on the index and dispersion properties of this material. The reported Abbe number and Index of Refraction for Acrylic from the given datasheet is listed in Table 4.2.1 below for ease of comparison. The WaterClear Ultra lens was not tested due to print errors that caused significant diffraction. These errors are explained in the following sections 5.1 WFE Results and 5.3 Image Analysis Results.

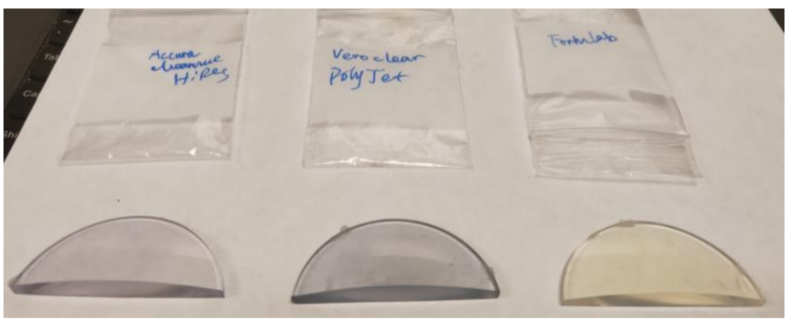

Figure 4.2.1: Shows the Accura ClearVue, VeroClear, and FormLabs lenses cut for Index testing.

Table 4.2.1 below shows the measured average Index of the D spectrum for Accura ClearVue, VeroClear, and FormLabs Clear as well as the Abbe Number calculated using Equation 3.3.1 and average test data. While the WaterClear Ultra lens could not be tested the expected Index value is listed from the technical data sheet. The Accura ClearVue and Acrylic expected Index is also listed from their respective data sheets.

Substrate Samples	Abbe Number	Measured Index of Refraction (nd)	Expected Index (nd)	Delta from Expected (nd)
Acrylic Control	55.3	-	1.49	-
Accura ClearVue	53.19	1.516	1.508	0.008
WaterClear Ultra	-	-	1.52	-
VeroClear	46.95	1.531	N/A	N/A
FormLabs Clear	50.55	1.519	N/A	N/A

Table 4.2.1: Shows the Abbe Number and Index of Refraction test results for applicable lenses. [6,7]

The results of Index and Abbe Number testing for the three SLA materials are all in family with one another. Accura ClearVue has the closest dispersion (53.19) and Index of Refraction (1.516) to that of the reported Acrylic values of 55.3 and 1.49 respectively.[6] For all four of the SLA materials the reported or measured Index is higher than that of Acrylic, but is akin to other known plastic optical materials. It is of interest that the Accura ClearVue reported value differs from the measured value by 0.008. Depending on the application this may not be of great importance but could be an issue for certain use cases. This difference is far outside the measurement error of ±0.0002, but not so large to be a major concern.[12] Unfortunately, Accura ClearVue is the only material that we can see this comparison. Before a material can regularly be used in the optics industry the variation of key properties from batch to batch must be known. Therefore, a further study into the repeatability of the Index and dispersion over multiple prints for each of the viable SLA lens materials could be of interest.

5 Lens Quality Evaluation Testing

5.1 WFE Results

All final lens samples were tested for WFE after being diamond turned. This includes the three FormLabs Clear samples that were printed in different configurations. The FormLabs Clear lens with the best wavefront error was that printed in the Vertical Configuration. This lens will move forward as the represented lens for the FormLabs Clear material. The other two FormLabs lenses will not be used in further testing. Table 5.1.1 below shows the reported surface roughness error for all samples that were tested. Figure 5.1.1 shows all three FormLabs lenses after diamond turning.

Substrate Samples	Convex Surface RMS	Plano Surface RMS
Acrylic Control	3.303 waves	1.931 waves
Accura ClearVue	1.712 waves	0.730 waves
WaterClear Ultra	1.408 waves	2.006 waves
VeroClear	2.492 waves	3.088 waves
FormLabs Clear **Vertical Configuration**	2.659 waves	1.289 waves
FormLabs Clear **Convex Side Down Configuration**	2.954 waves	1.189 waves
FormLabs Clear **Plano Side Down Configuration**	4.520 waves	1.510 waves

Table 5.1.1: Shows the surface RMS WFE results for all lenses with Tip, Tilt, and Power removed.

As seen in Figure 5.1.1 the FormLabs Clear lens printed in the convex side down configuration had a significant artifact in the lens as well as air bubbles. The FormLabs Clear lens printed in the plano side down configuration also had some air bubbles and a small black artifact inside the print. The FormLabs Clear lens printed in the vertical configuration is of higher quality than the other two configurations. No inherent artifacts or air bubbles were found in the FormLabs Clear lens printed in the vertical configuration.

Figure 5.1.1: Shows final FormLabs Clear lenses printed in different configurations.

While the WaterClear Ultra lens WFE results were in family with the rest of the lenses in this study, there is a significant central artifact that can be seen in the interferogram. At first this is assumed to be due to mid-spatial frequency errors from the diamond turning. Under further review it was determined that this error seems to be an artifact left over from the print. During this inspection the 3D printed stepping layer lines were visible as well as some internal air bubbles. This inspection was done with standard room lighting with no significant magnification. The WaterClear Ultra lens is the only remaining lens in this study that has significant stepping and air bubbles visible. These errors are seen in Figure 5.1.2 below. This material was also softer and “gummy” as compared to the other materials when diamond turning. The lens will be further tested for full evaluation of this material. However, these errors would have to be rectified before a lens of this material could be utilized for a precision lens. With the small sample size it is unclear if these are a material or application issue.

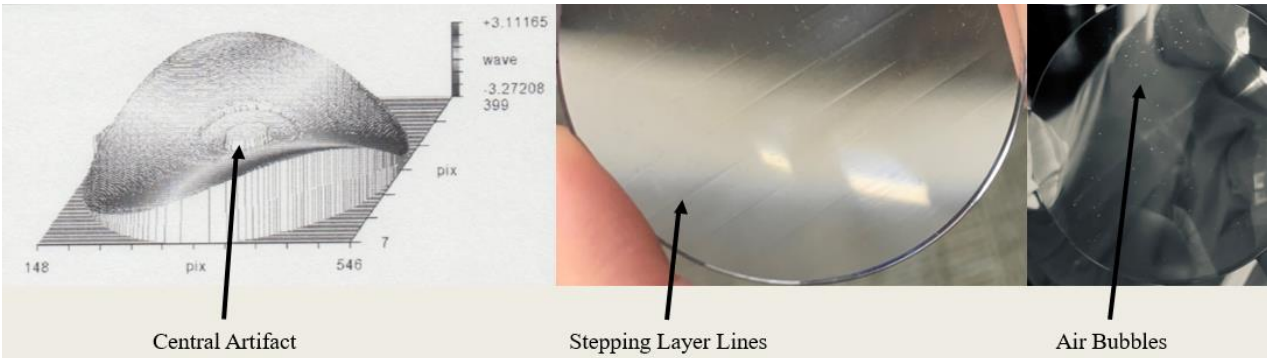

Figure 5.1.2: Shows defects in WaterClear Ultra lens.

The WFE results show all final 3D printed lenses to have generally better results than the Acrylic control sample. Its promising that the 3D lenses are in family with the Acrylic control. However, it is expected to be able to achieve far better WFE for an Acrylic lens than 3 waves RMS. In fact according to the Zemax ideal lens for Acrylic material the RMS WFE should be around 0.195 waves. Although there are errors in manufacturing, it is expected for the lens to be much closer to the modeled value than the 3 waves result. Diving into the WFE results it shows that the Astigmatism value for all tested lenses was the dominating contributor to the error. While astigmatism is a common issue in manufacturing of optics the amount of astigmatism is beyond standard manufacturing errors. The interference plot of the Acrylic lens' convex surface is shown in Figure 5.1.3. The Seidel coefficient for astigmatism of each lens sample is shown in Table 5.1.2. These coefficients were reported from the Metropro software using the recorded WFE data for each sample. To iterate how much astigmatism is contributing to the overall WFE, astigmatism was subtracted from the WFE and reported in Table 5.1.4. This gives us an idealized sense for the WFE that could be achieved if the astigmatism was able to be resolved.

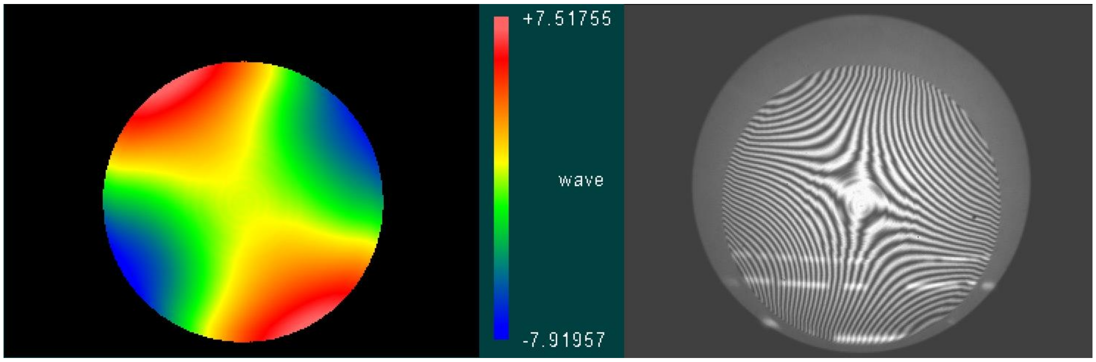

Figure 5.1.3: Shows WFE plot for Acrylic lens featuring large amount of astigmatism.

Substrate Samples	Convex Surface Astig. Seidel Coefficient	Plano Surface RMS Astig. Seidel Coefficient
Acrylic Control	16.121	9.756
Accura ClearVue	9.116	3.627
WaterClear Ultra	7.523	8.314
VeroClear	15.241	17.506
FormLabs Clear **Vertical Configuration**	12.996	6.148

Table 5.1.2: Shows the Astigmatism Seidel coefficients for all lens RMS WFE results.

The Seidel coefficient is the contribution to the Wavefront equation for the respected aberration. These coefficients are derived using the related Seidel sum. Seidel sums are calculated using first-order ray data that is derived from Wavefront measurements. Table 5.1.3 below shows examples of the relationship between aberration coefficients and Seidel sums. Coefficient W_{040} represents spherical aberration, while W_{131} and W_{222} represent Coma and Astigmatism respectively.[16]

Aberration Coefficients in terms of Seidel sums	
Coefficient	Seidel sum
$W_{040} = \frac{1}{8} S_I$	$S_I = -\sum_{i=1}^{j} \left(A^2 y \Delta\left(\frac{u}{n}\right)\right)_i$
$W_{131} = \frac{1}{2} S_{II}$	$S_{II} = -\sum_{i=1}^{j} \left(A\bar{A} y \Delta\left(\frac{u}{n}\right)\right)_i$
$W_{222} = \frac{1}{2} S_{III}$	$S_{III} = -\sum_{i=1}^{j} \left(\bar{A}^2 y \Delta\left(\frac{u}{n}\right)\right)_i$

Table 5.1.3: Shows the equations for Seidel coefficients for Coma, Astigmatism, and Spherical. [16]

While it is unlikely that all astigmatism could be reduced, Table 5.1.4 shows that if we could find the root of the astigmatism we could possibly achieve precise half wave lenses. Some amount of astigmatism is inherent to the design. Therefore, the numbers in Table 5.1.4 are not absolute but give a representation of what could be achieved.

Substrate Samples	**Convex Surface RMS**	**Plano Surface RMS**
Acrylic Control	0.310 waves	0.285 waves
Accura ClearVue	0.555 waves	0.488 waves
WaterClear Ultra	0.408 waves	0.627 waves
VeroClear	0.383 waves	1.046 waves
FormLabs Clear **Vertical Configuration**	0.378 waves	0.331 waves

Table 5.1.4: Shows the surface RMS WFE results with Tip, Tilt, Power, and Astigmatism removed.

To try and find the root of this error diamond turning experts and plastic optics experts at BAE systems were consulted. The plano-convex 100mm radius of curvature, 58mm diameter with an 8mm central thickness lens form is pretty standard and simplistic. However, it was discussed that the 7.25:1 aspect ratio may have been too high for an Acrylic lens being diamond turned. It is a common issue with diamond turning that the vacuum chuck, which holds the lens sample, can produce astigmatic errors. If the aspect ratio is too high in a material that is not very stiff a springing effect can occur when the sample is taken off the vacuum chuck. This can result in astigmatism that is very difficult, if not impossible, to chase out of the part. Given that the results are all in family, for the purpose of this study the original WFE results will be used for comparison. The charter of this study is to produce initial lens results to determine the potential for quality 3D printed lenses. For that purpose, these lenses are sufficient in comparing the materials, and will continue to be tested as the subject of this thesis. However, a further study with lenses of a lower aspect ratio would be of interest in the future to confirm this theory. Specifically, the FormLabs Clear and Accura ClearVue lens materials showed great promise for such a study as seen from results in Table 5.1.4.

5.2 Surface Roughness Results

Table 5.2.1 below shows the results of the surface roughness testing on both the convex and plano side of all five lens samples. Unlike the WFE results the surface roughness results are significantly superior for that of the Acrylic control sample. The results for the 3D printed lenses however all are roughly in family of each other.

Substrate Samples	**Convex Surface Ra**	**Plano Surface Ra**
Acrylic Control	15.96 Å	14.42 Å
Accura ClearVue	53.38 Å	69.24 Å
WaterClear Ultra	75.33 Å	63.09 Å
VeroClear	43.86 Å	61.60 Å
FormLabs Clear **Vertical Configuration**	93.73 Å	102.9 Å

Table 5.2.1: Shows the Surface Roughness results for each lens measured on both sides.

All lenses perform well for a lens of a diameter greater than 2”. According to the standard diamond turning capabilities as reported by Edmund Optics shown in Table 3.2.1, the surface roughness results fall either in the precision or high precision categories for all sample lenses. Figure 5.2.1 below graphically shows how the lens results compare to the standards.

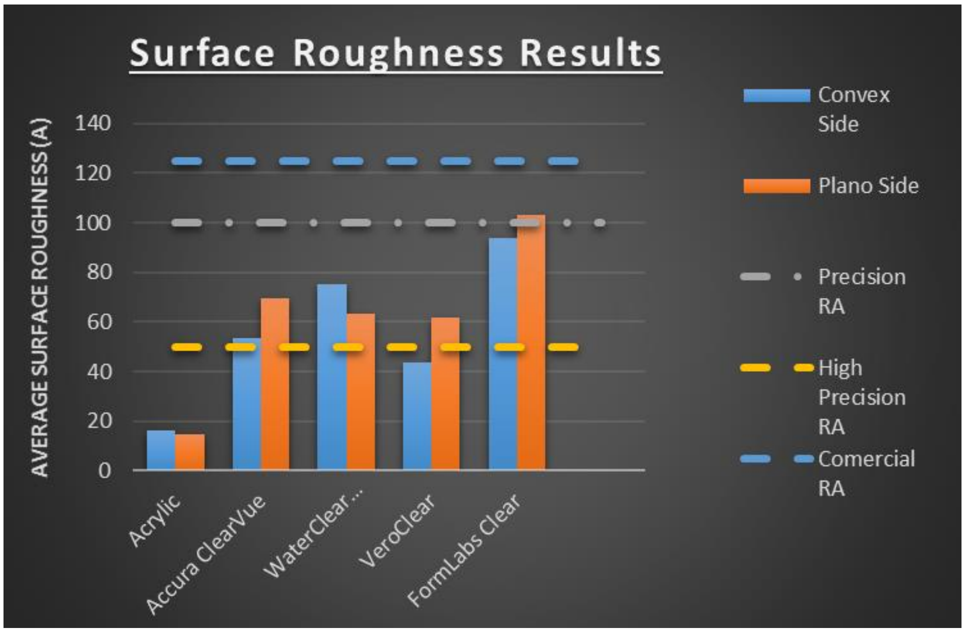

Figure 5.2.1: Shows Surface Roughness results graphed against Industry standards from Edmund Optics [3]

5.3 Image Analysis Results

In order to assess the practicality of a 3D printed lens, the imaging abilities of the plano-convex 100mm radius of curvature, 58mm diameter and 8mm central thickness lenses were evaluated. For this test the lenses under test were glued into cells and mounted into the adjustable lens mount as seen in aforementioned Figure 3.5.1. The system was then mounted onto a Cannon SLR with a digital sensor, this can be seen in Figure 3.5.2 as shown in the Experimental Methods section of this study. For this test we simply wanted to show the imaging ability of the lenses by implementing a typical use case. A controlled scene with high contrast and many small resolvable details was chosen. A standard regulation dart board with black and white sections and detailed numbered sections was chosen as the target and illuminated with a white light source.

The camera system was mounted onto a tripod and set at a standard distance from the target. This was the same for all test lenses. The individual lens and holder was then positioned for best possible focus. The images were compared for best focus and contrast. Figure 5.3.1 below shows the resulting images. This test was done for all 3D printed lenses (Accura ClearVue, FormLabs Clear (vertical config.), VeroClear, and WaterClear Ultra) as well as the Acrylic control lens. In addition to these test lenses an industry standard glass lens was also used for comparison. The lens used is a 200mm focal length telephoto Cannon lens. This is a multi-element glass lens system with automatic focusing system and well corrected stray light solutions. The telephoto lens gives us an image that is very close to ideal and beyond that of even a glass singlet with a 100mm radius of curvature. The telephoto lens' image is designated as TL in Figure 5.3.1 below. The images below were not edited in anyway except to adjust for some brightness caused by stray light in the singlet lens images. This was done uniformly for all tested lenses.

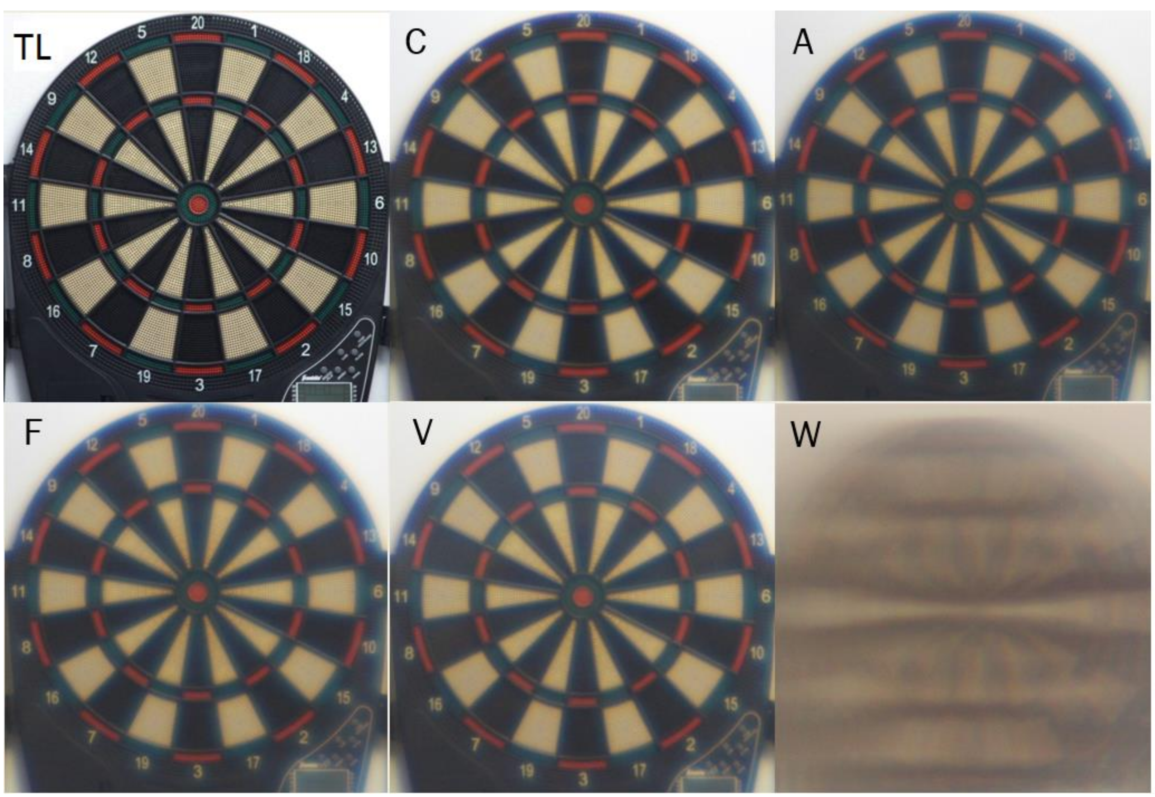

Figure 5.3.1: Shows colored images produced from each of the lenses; Telephoto lens (TL), Control lens (C), Accura ClearVue (A), FormLabs Clear (F), VeroClear (V), and WaterClear Ultra (W).

At first glance we can see that the Acrylic control lens preformed the best out of the singlet lenses. The WaterClear Ultra lens was unable to produce a viable image due to the print errors noted in Figure 5.1.2 of section 5.1 WFE Results. The other three 3D printed singlets performed similarly to each other. To quantify these image results the Michelson contrast of each image was calculated. To do this the images were converted to black and white images as seen in Figure 5.3.2 below and inputted into Image J program. The Image J program was then used to produce gray value histograms as shown in Figure 5.3.3 below.

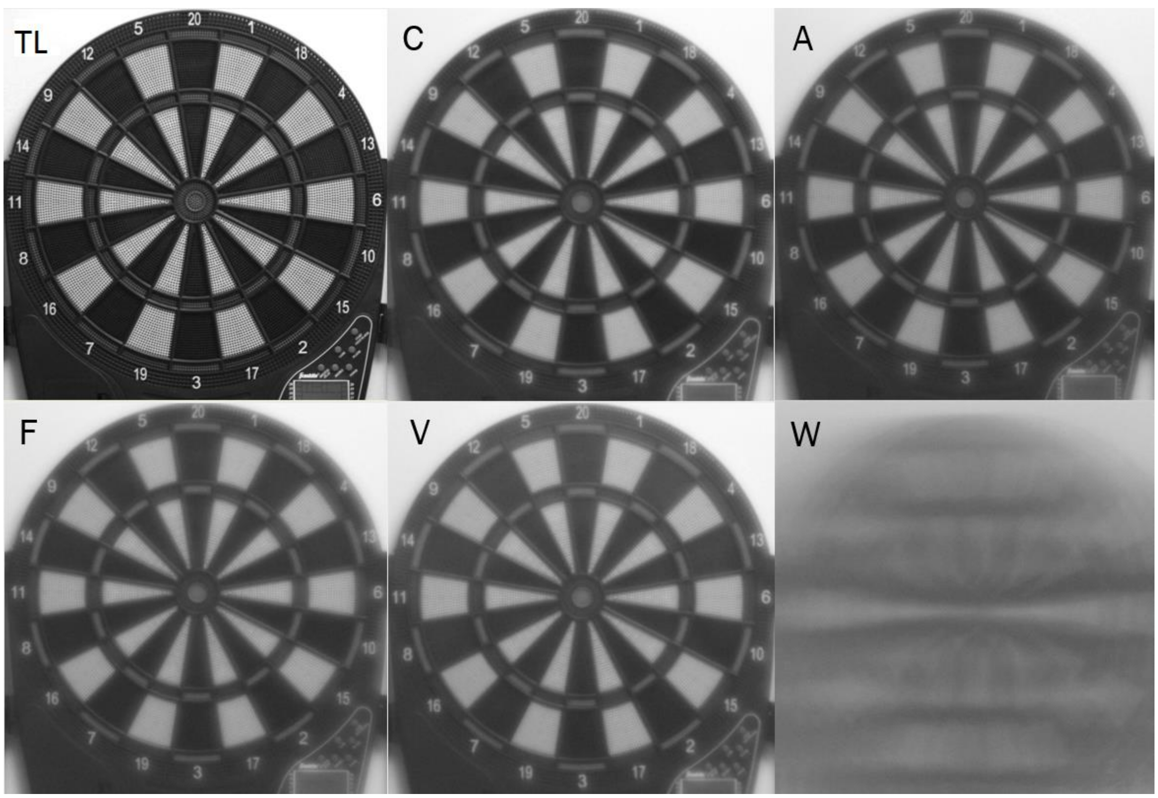

Figure 5.3.2: Shows black and white images produced from each of the lenses; Telephoto lens (TL), Control lens (C), Accura ClearVue (A), FormLabs Clear (F), VeroClear (V), and WaterClear Ultra (W).

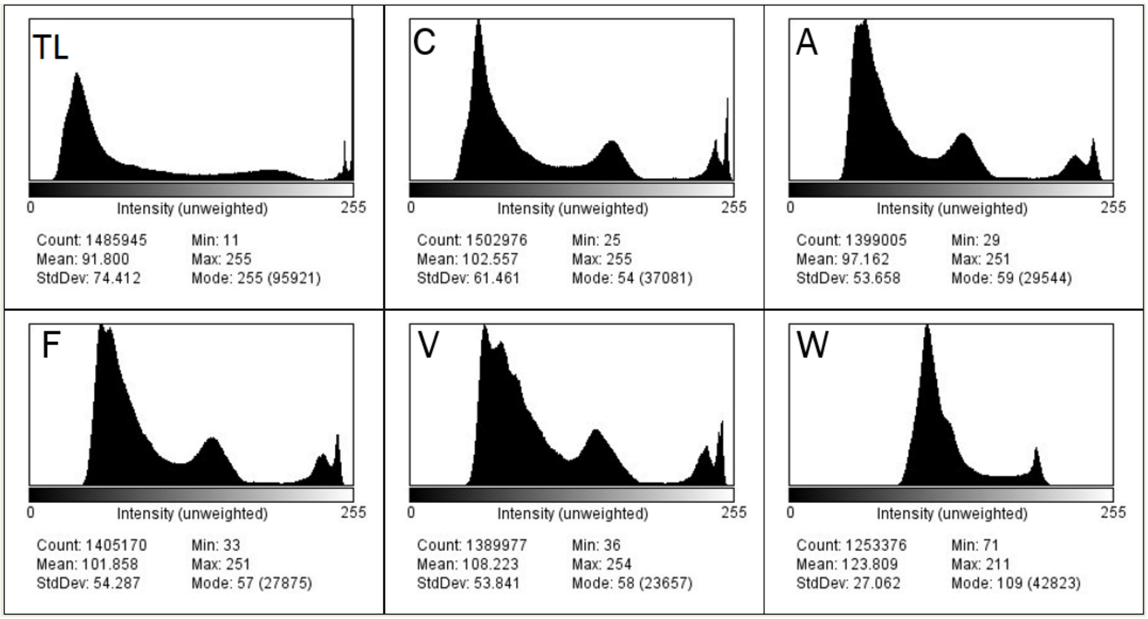

Figure 5.3.3: Shows Gray Values produced in Image J for each; Telephoto lens (TL), Control lens (C), Accura ClearVue (A), FormLabs Clear (F), VeroClear (V), and WaterClear Ultra (W).

The gray value histogram values seen in Figure 5.3.3 were then used along with Equation 3.5.1 in section 3.5 Experimental Methods. These calculated values are shown in Table 5.3.1 below.

	Telephoto Lens	**Acrylic Control**	**Accura ClearVue**	**FormLabs Clear**	**VeroClear**	**WaterClear Ultra**
Calculated Contrast	0.9245	0.8214	0.7929	0.7739	0.7639	0.5433

Table 5.3.1: Shows the calculated Michelson contrast for each lens' image.

The calculated Michelson contrast values in Table 5.3.1 confirm that the Accura ClearVue lens performed best out of the 3D printed singlets with the FormLabs and VeroClear singlets performing very similarly to one another. While the images are still fairly blurry compared to the ideal image, it is promising that the Accura ClearVue, FormLabs Clear, and VeroClear singlets were able to resolve the small numbers and details of the target.

6 STUDY CONCLUSIONS

6.1 Summary of Lens Performance

In Table 6.1.1 below shows all of the results of the lens quality evaluation testing. The top line of the chart shows the results for the Acrylic control lens as a comparison. The bold and underlined text highlights the best results out of the 3D printed lenses for that given test. The italicized and underlined text highlights the worst results out of the 3D printed lenses for that given test.

Sample Type	WFE	Surface Roughness	Image Contrast
Acrylic Control	Cx: 3.303 waves Plano: 1.931 waves	Cx: 15.96 A Plano: 14.42 A	0.8214
Accura ClearVue	Cx: **1.712** waves Plano: **0.730** waves	Cx: 53.38 A Plano: 69.24 A	**0.7929**
FormLabs Clear	Cx: 2.659 waves Plano: 1.289 waves	*Cx: 93.73 A* *Plano: 102.9 A*	0.7739
VeroClear	*Cx: 2.492 waves* *Plano: 3.088 waves*	Cx: **43.86** A Plano: **61.60** A	0.7639
WaterClear Ultra	Cx: 1.408 waves Plano: 2.006 waves	Cx: 75.33 A Plano: 63.09 A	*0.5433*

Table 6.1.1: Shows summary of lens evaluation test results for all lenses.

The results in Table 6.1.1 show that in general the 3D printed lenses performed in family to that of the Acrylic control. As stated earlier in section 5.1 WFE Results, these results including the Acrylic Control were worse than expected. It is likely this is due to the 7.25:1 aspect ratio. However, overall the test results for the 3D printed singlets are promising.

While the WaterClear Ultra lens had decent WFE and surface roughness results, the layering of the WaterClear Ultra lens shown in Figure 5.1.2 proved to be a fatal flaw. The stepping in this substrate print results in an ununiformed lens that is unable to form a viable image due to diffraction form the layering. This imaging result can be seen in Figure 5.3.2 part W. The inability to form a usable image overshadows any hope of this material producing a quality lens despite WFE and surface roughness values. It is possible that overtime the print quality could improve. However, with the test results and the complaint that the material was "gummy" when diamond turning, in the view of this study the WaterClear Ultra material does not produce a viable lens.

The FormLabs Clear lens performed fairly well, especially given the trials early on with this material. While the final test lens (of vertical configuration) still had some yellowing effects it was decided to continue the evaluation; for use cases that would not be effected. With that caveat aside the wavefront error and image contrast results were in family and performed fairly well. This is additionally promising given that FormLabs Clear is a material printed with a desktop commercial printer. However, the surface roughness of the lens was higher than the other lenses by about 30 – 40 Angstroms. The lens roughness falls just outside of the range considered "precision" by the Edmund optics diamond turning standards seen in Figure 5.2.1. This roughness result is in family with that from independent studies using the FormLabs material. The outside study is referenced in section 2.2 Related Studies on 3D Printed Refractive Optics, and reported a surface roughness of 120 – 220 angstroms. This outside study reported a WFE results of 0.37 waves which is far better than the 2.6 or 1.3 waves reported here.[5] However, as previously discussed if the additional astigmatism is removed the FormLabs material could possible achieve similar sub 1 wave results. For the purposes of this study the FormLabs Clear material is considered able to produce a viable lens for cases where yellowing and higher surface roughness is acceptable.

The VeroClear lens performed in the middle of the pack for most of the testing. The WFE is the worst for that of the 3D printed lenses. However, if we assume that the increased astigmatism is due to vacuum springing during diamond turning (as discussed in section 5.1 WFE Results) than that could be rectified in future cases. In fact looking back at Table 5.1.2 the VeroClear material seems to be affected the most by the additional astigmatism. The VeroClear lens has one of the best wavefront errors when the aberration is subtracted as shown in Table 5.1.4. With the WFE aside, the surface roughness and image contrast results are among the best of the 3D printed lenses. The surface roughness of the VeroClear lens is considered to be of highest precision and standard precision as defined by the Edmund optics diamond turning standards seen in Figure 5.2.1. The image contrast results for the VeroClear lens are below that of the Accura ClearVue and Acrylic Control lenses but are in family and very similar to that of the FormLabs Clear lens. The VeroClear lens produced a decent image that was able to resolve details in the image. The lens image may be of lower quality than the standard image, but it is promising. This is again especially interesting given that the VeroClear lens is printed on a desktop commercial printer. For the purposes of this study the VeroClear lens material is considered able to produce a viable lens. If the added astigmatism could be reduced the VeroClear material has the potential to produce an even higher quality lens than reported in this study.

The Accura ClearVue lens performed arguably the best of all the 3D printed lenses. The WFE of the lens has the best results with the convex side having a WFE of less than 2 waves and the Plano side having a WFE of less than 1 wave. These WFE results are on par or better than the WFE results of the Luxexcel lenses discussed in the study referenced in 2.2 Related Studies on 3D Printed Refractive Optics. In the outside Luxexcel study the WFE results were about 1.5 – 1.7 waves as compared to the 1.7 and 0.7 waves of the Accura ClearVue lens. With the results in Tables 5.1.2 and 5.1.4 it is implied that if the astigmatism can be reduced the WFE of this lens type could reach levels below half wave. This would place the lens into the "precision" as defined by Edmund optics diamond turning standards seen in Table 3.2.1. The surface roughness for this lens is also of "precision" grade and close to that of "high precision" as defined by Edmund optics diamond turning standards seen in Figure 5.2.1. These surface roughness results are far better than the 100 – 200 angstrom of the Luxexcel lens shown in the outside study.[2] The image contrast is also the greatest for that of the 3D printed lenses and closest to the values for the Acrylic control and Telephoto lens results. For the purposes of this study the Accura ClearVue material is considered able to produce a viable lens and the best of the 3D printed materials studied here. This material as shown here appears to be the best option of all 3D printed materials discussed in this study including the direct to print Luxexcel material.

In review, out of the four 3D printed materials, three of the lenses performed fairly well. These materials are still not to the level of high precision optics but could develop into useful alternatives for commercial or even precision needs. For further development the Accura ClearVue material shows the most promise and best performance. The VeroClear and FormLabs Clear materials also could develop into useful materials depending on the specific use case.

7 FURTHER STEPS

7.1 Additional Test Lens Evaluation

With the main charter of this study complete, some additional investigation was performed. Since the Accura ClearVue material seemed to perform the best overall, an additional lens of this material was produced. This lens however, was thicker than the original lenses. The general profile of 100mm radius of curvature and 58mm diameter was still used but, the center thickness was increased from 8mm to 12mm. This results in a lowered aspect ratio of 4.83:1 rather than the 7.25:1 of the original test lenses. Figure 6.2.1 below shows this thicker Accura ClearVue lens mounted in a lens holder.

Figure 7.1.1: Shows the Accura ClearVue thicker lens.

The lowered aspect ratio resulted in a better WFE than the original Accura ClearVue lens. The convex side had a measured WFE of 0.323 waves RMS with tip, tilt, and power removed. This is significantly better than the 1.712 waves of the original test lens. As for the plano side the WFE for the thicker lens was measured to be 0.221 waves RMS tip, tilt, and power removed. Again this is significantly better than that of the thinner test lens which was 0.730 waves RMS. Figure 6.2.2 below shows the surface plot for both the convex and plano sides.

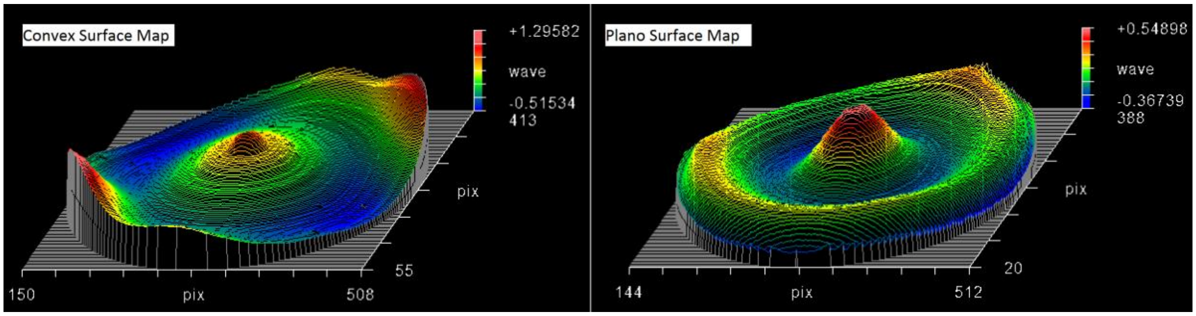

Figure 7.1.2: Shows surface plots for the Convex and Plano sides of the Accura ClearVue thick lens.

In addition to wavefront error testing the thicker Accura ClearVue lens was also tested for Image quality. This is done in the same manor described in section 3.5 Image Analysis and Testing and as shown in section 5.3 Image Analysis Results. Figure 6.2.3 below shows the black and white image produced by the lens as well as the gray value histogram produced using Image J.

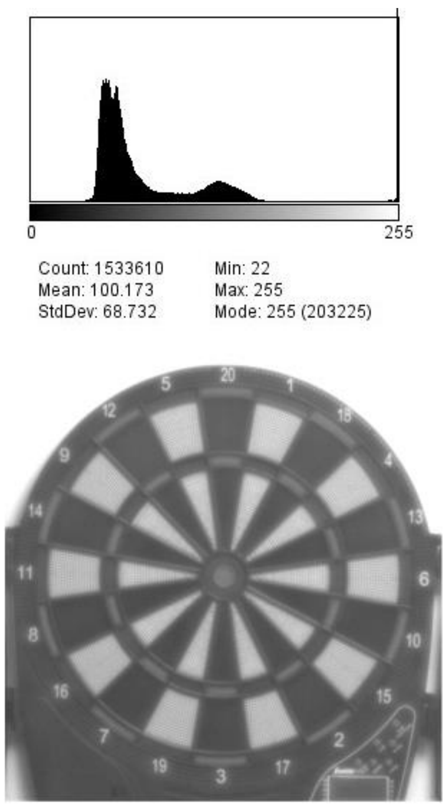

Figure 7.1.3: Shows Image and histogram from Accura ClearVue Thick Lens

The gray value histogram values seen in Figure 6.2.3 were then used along with Equation 3.5.1 in section 3.5 Experimental Methods to calculate the Michelson contrast. This value was calculated to be 0.8412, which is the best out of all the originally tested lenses including the control. Table 7.1.1 below shows a quick summary of the lens performance results for this thicker lens.

Sample Type	WFE	Surface Roughness	Image Contrast
Accura ClearVue **Low Aspect Ratio Lens**	Cx: 0.323 waves Plano: 0.221 waves	N/A	0.8412

Table 7.1.1: Shows summary of lens evaluation test results for Accura ClearVue thick lens.

The results of this limited testing for the thicker Accura ClearVue lens shows that the lower aspect ratio drastically decreased the astigmatism and WFE values. By resolving the astigmatism issue the Accura ClearVue material was able to produce a lens of higher quality that could be a viable lens for the right use case. It's recommended that further study into additional post processing be done to attempt an even higher quality lens. In addition a materials properties repeatability study is recommended to quantify the variance of index and dispersion values from print to print. The results of this study show that with the right parameters a usable and precise lens could be achieved from a 3D printed substrate in the near future.

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