EVALUATING THE VALIDITY OF MANUFACTURING 3D PRINTED LENSES;

USING COMMERCIAL SLA MATERIALS AND DIAMOND TURNING PROCESSES

By: Sandra Glynn

With support of University of Arizona and BAE Systems

INTRODUCTION

Topics to be Discussed

Personal Background

Acknowledgements

Dedications

Statement of Purpose

Personal Background

- **Education**
  - *M.S. Optical Sciences Candidate, College of Optical Sciences University of Arizona 2016-2020*
  - *B.S. Optical Engineering from University of Rochester Class of 2015*
- **Work Experience**
  - *BAE Systems (2019 – Present)*
  - *L3 SSG (2015 – 2019)*
  - *Rockwell Collins (6 Month CO-OP)*
  - *QED Optics (3 Month Internship)*
- **Hobbies**
  - *Amateur Photography*
  - *Adventuring*

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- I am very grateful to my adviser, Dr. Rongguang Liang. I would also like to acknowledge the members of my committee, Dr. Daewook Kim and Dr. Jose Sasian, who took their time to review this thesis and gave me valuable suggestions.

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

Dedications

- This thesis is dedicated to my late father James D. Westover and my husband John J. Glynn IV.

Statement of Purpose

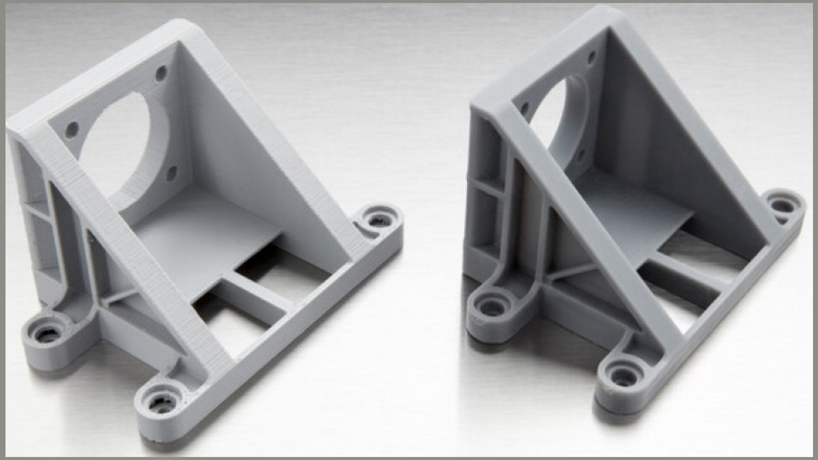
- Optics are traditionally made from subtractive machined substrates that are then ground, polished, and/or diamond turned for an optical surface. This study probes the validity of producing lens substrates by leveraging additive machining. Stereolithography (SLA) 3D printing was used to produce optical 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.

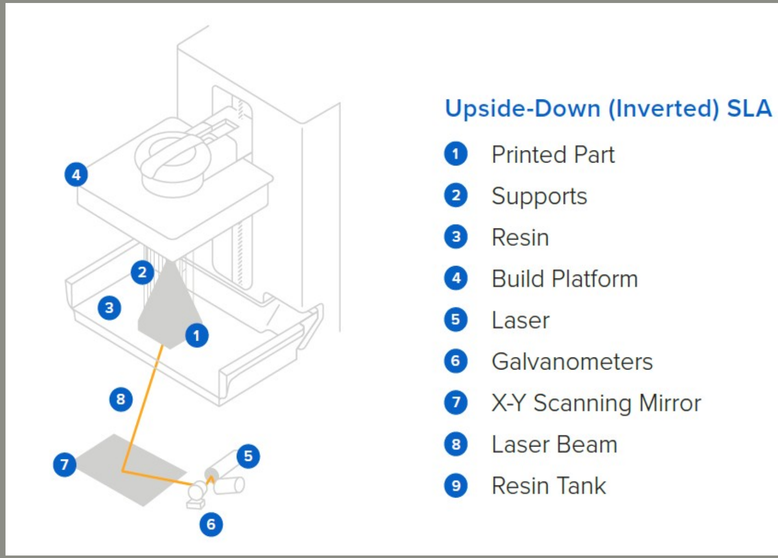
BACKGROUND

Topics to be Discussed

Stereolithography Style 3D printing
Related Studies

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.
- 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. Rather than extruding the material, SLA printers use a laser beam to cure a liquid resin into its desired shape.

Relevant White Papers

Direct to Print Study

- The study using the Luxexcel material uses direct to print methods. Luxexcel lens are the best reported lenses to date.
- These lenses are not post processed and are limited to the optometry industry.

Post Processed Study

- The study using the VeroCear material produces optical flats. Surface WFE and roughness were not tested. The study does give us diamond turning and transmission results.
- The study using the FormLabs Clear material produces plano-convex lenses that were post processed using a spin coat technique. These resulted in WFE better than the Luxexcel lenses but a much higher surface roughness result.

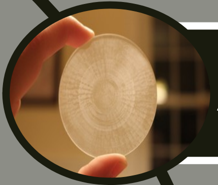
SLA Material	White Paper Name	Sample Diameter	Surface Roughness	Surface Figure
Luxexcel	“Quantitative evaluation of performance of three-dimensional printed lenses”	12.7 – 50mm	100-200Å	1.5 – 1.7 waves
VeroClear	“The research on surface characteristics of optical lens by 3D printing techniques and precise diamond turning”	50mm	--	--
FormLabs Clear	“Fabrication of optical components using a consumer-grade lithographic printer”	12.7mm	120-220Å	0.37 waves

EXPERIMENTAL METHODS

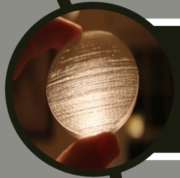
Topics to be Discussed

Substrate Materials & Production
Diamond Turning Processing
Material Properties Testing
Lens Quality Evaluation

Substrate Materials & Production



Acrylic- CNC machined Control



WaterClear Ultra- SLA Printed optical resin

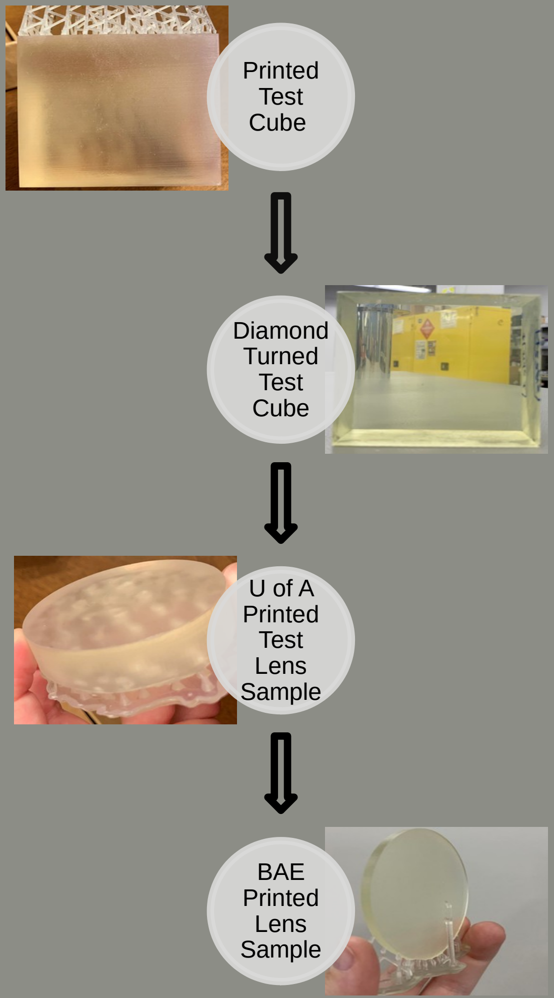
Accura ClearVue – SLA printed optical resin

VeroClear- SLA printed commercial printer

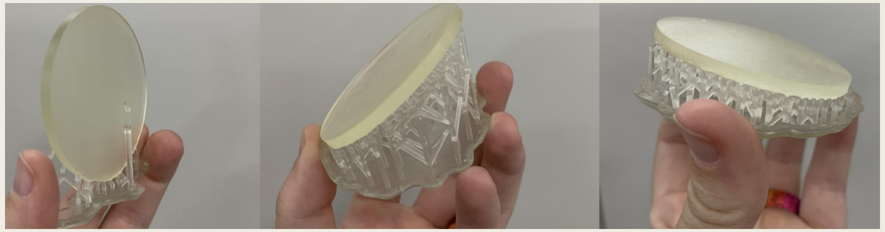
Formlabs- SLA printed commercial printer

- There are four main commercial materials that produce a “clear” print.
- A simple 58mm diameter plano-convex with a 100mm radius of curvature lens with a max thickness of 8mm was printed out of each material.
- Printed Substrates were printed by Xometry with a “Strip and Ship” finish which removed the support material*
- *The FormLabs prototypes were produced using the FormLabs printers at University of Arizona and BAE

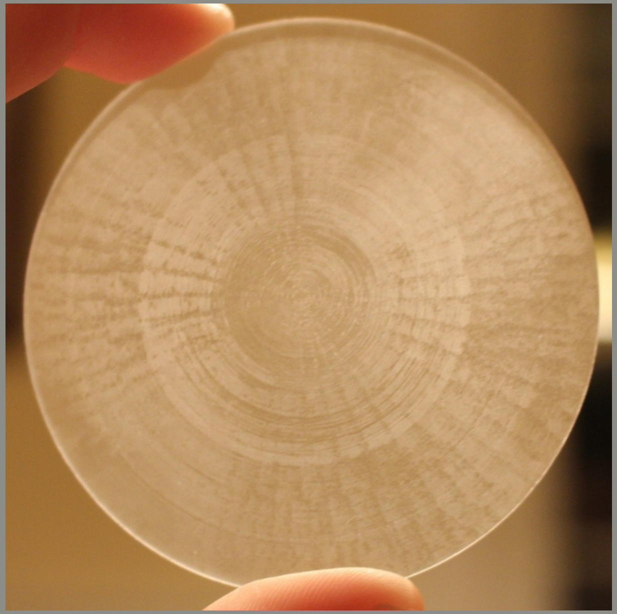
Substrate Baseline: FormLabs Clear



- A Test Cube was printed on a Formlabs printer out of Clear material with standard processes. The UV cure standards resulted in significant yellowing. Diamond Turning of the material went well but the yellowing persisted.
- A new plano-convex lens sample was printed of the same material but using a shorter UV cure time. This resulted in less yellowing but a more gummy and soft material. The shape and form of the print is also lacking due to these settings.
- Because of this, plano-convex lenses were printed by BAE Systems using standard settings in 3 different print configurations for diamond turning.



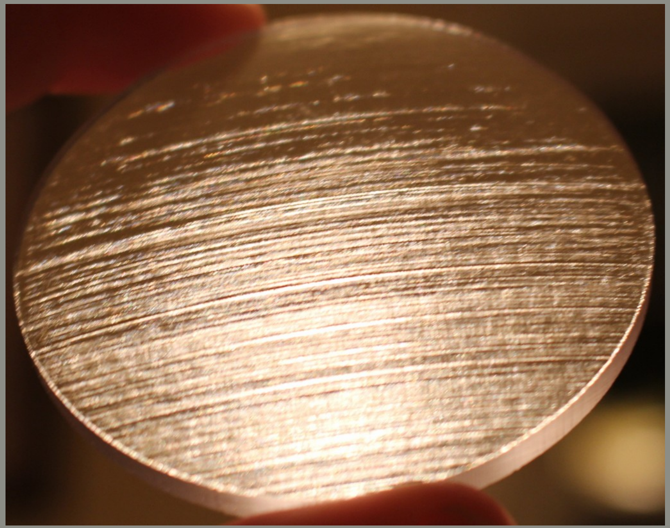
Substrate Baseline: Acrylic (Control)



- This substrate was CNC machined out of a .45 thick sheet acrylic that was held down on the vacuum table to machine it.
- Processing was done by Xometry out of OPTIX Acrylic by Plaskolite; using standard processes.
- This sample was produced for the purpose of a Control.

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

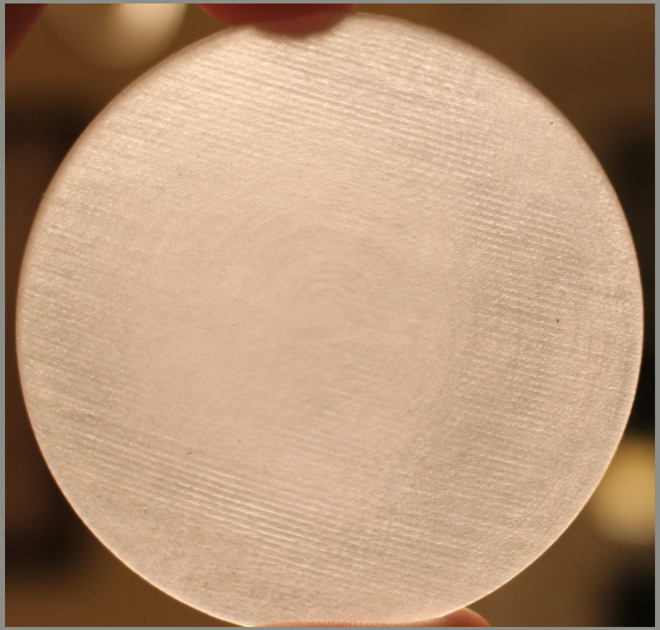
Substrate Baseline: WaterClear Ultra



- Printed by Xometry using standard resolution on a SLA 5000 printer

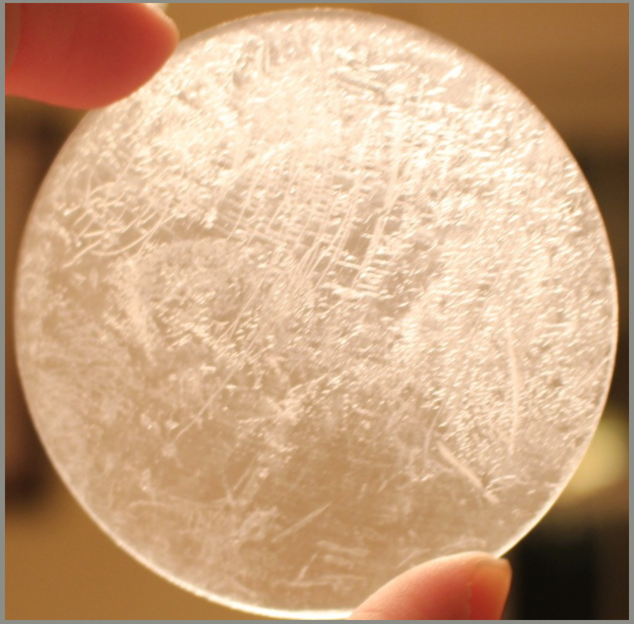
Liquid Properties		Optical Properties		
Appearance	Optically clear, colorless	E_C	10.0 mJ/cm²	[critical exposure]
Viscosity	~165 cps @ 30°C	D_P	6.5 mils	[slope of cure-depth vs. In (E) curve]
Density	~1.13 g/cm³ @ 25°C	E_{10}	47 mJ/cm²	[exposure that gives 0.254 mm (.010 inch) thickness]
		D542	1.52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

Substrate Baseline: VeroClear



- Printed by Xometry using standard resolution on a Connex 500 printer.
- "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." – ***Technical Data Sheet***

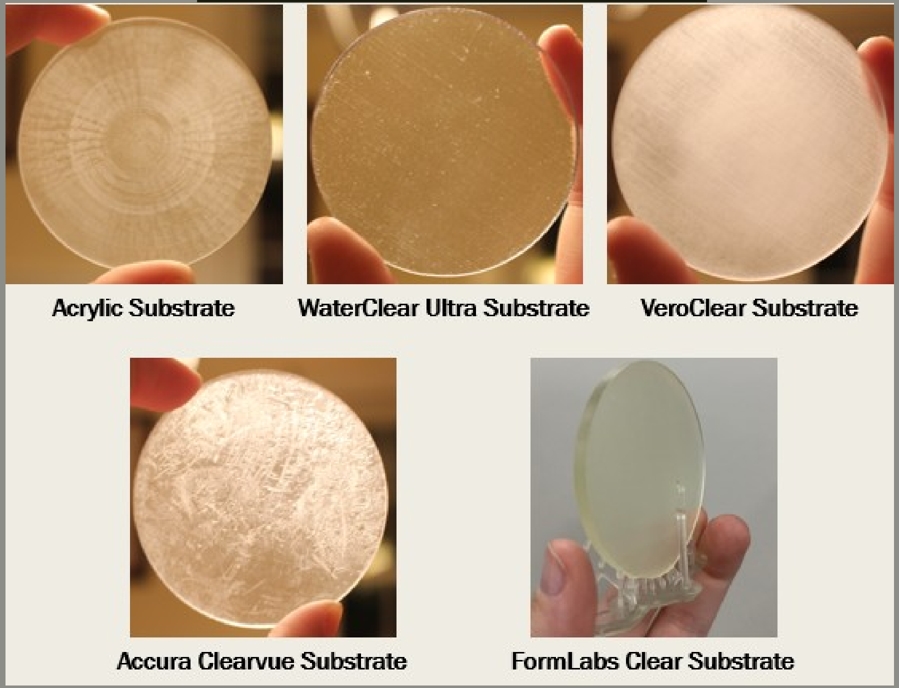
Substrate Baseline: Accura ClearVue



- Printed by Xometry using high resolution on a Projet 7000.
- Support material was placed on the Convex surface which left some residual material on the surface.

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

Summary of Printed Substrates



Acrylic Substrate | WaterClear Ultra Substrate | VeroClear Substrate

Accura Clearvue Substrate | FormLabs Clear Substrate

- The Printed and CNC machined subtracted from Xometry all came out well.
- The WaterClear Ultra substrate was visibly clearer then all of the other samples but had significant stepping.
- The Accura ClearVue substrate had some residual support material on the convex surface
- The FormLabs Clear 3 samples showed significant yellowing. The sample with the best results after diamond turning will move forward.

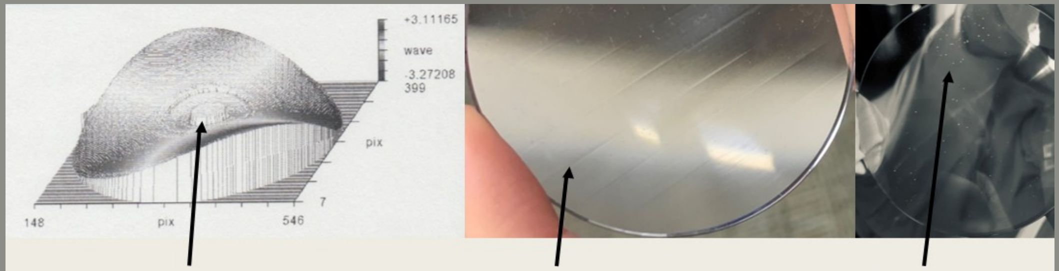
Diamond Turning Processing

- 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.
- All lens substrates in this study were diamond turned by BAE Systems in their diamond turning shop on a Nanoform 250 Ultra.
- For this study, the diamond turning processes transforms the unfinished printed or machined substrates into final form lenses.

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

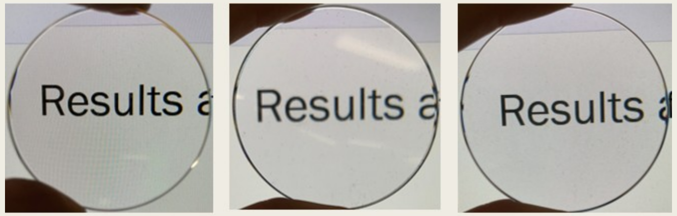
Summary of Diamond Turning Results

FormLabs Clear Lens Vertical Configuration | FormLabs Clear Lens CX Down Configuration | FormLabs Clear Lens Plano Down Configuration

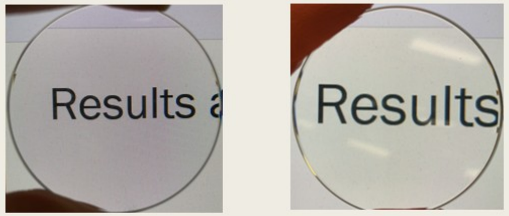


Central Artifact | Stepping Layer Lines | Air Bubbles

- All 3D printed and CNC machined substrates were able to be successfully diamond turned with no significant issues.
- Two of the three FormLabs lenses revealed air bubbles and artifacts in the print after turning. The Vertical configuration lens had no defects and was used for further testing.
- The WaterClear Ultra lens had a significant central artifact, visible stepping layer lines, and air bubbles. Further testing was done on this lens to evaluate the material.

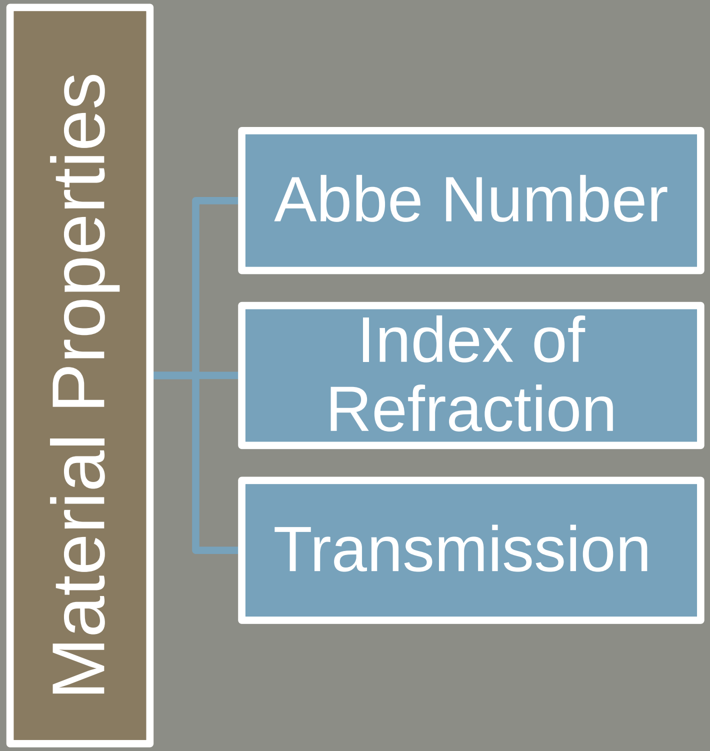


Acrylic Substrate | WaterClear Ultra Substrate | VeroClear Substrate



Accura Clearvue Substrate | FormLabs Clear Substrate

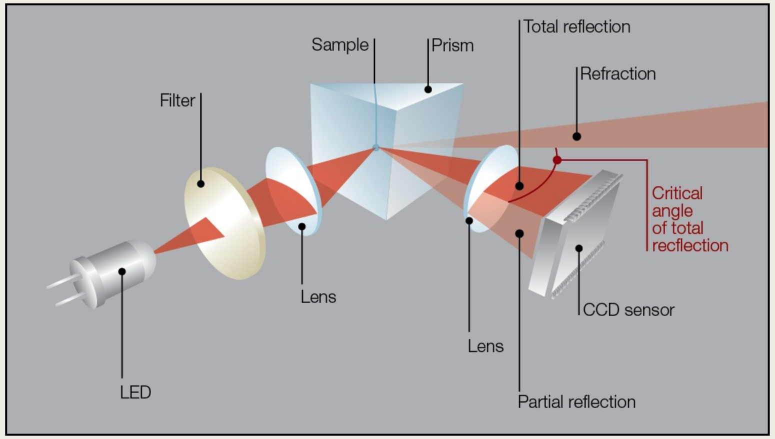
Material Properties



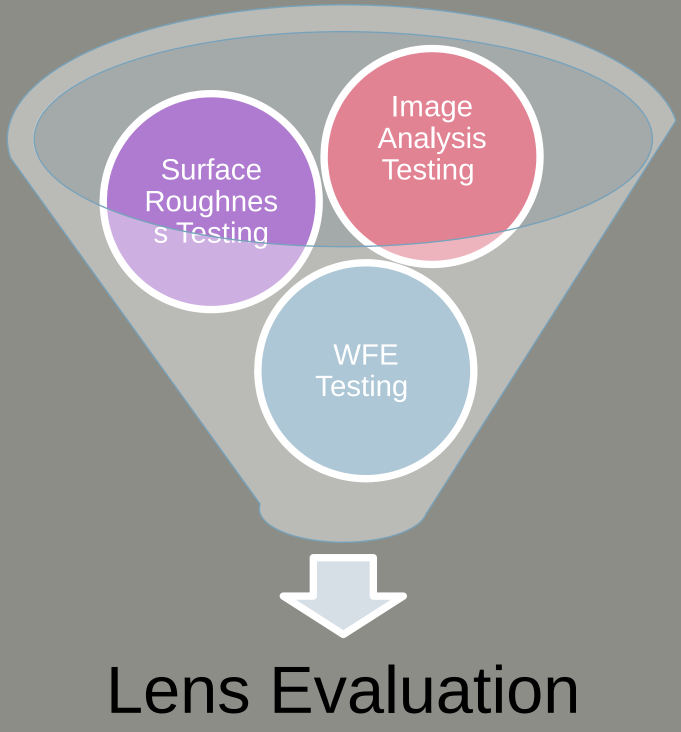
- Abbe Number
  - *Calculated using Index measured by the University of Arizona.*
- Index of Refraction
  - *Measured by the University of Arizona on an ATAGO's multi-wavelength Abbe refractometer DR-M2.*
  - *ATAGO DR-M2 reports a measurement accuracy of ±0.0002.*
- Transmission
  - *Transmission Values and curves were reported from the material data sheet and/or previous studies.*

Abbe Number Equation

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

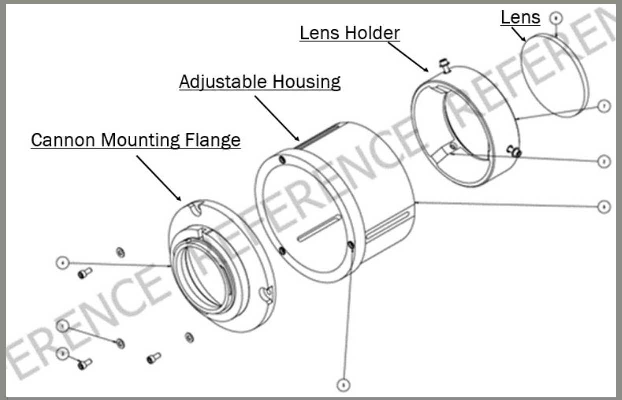


Lens Quality Evaluation



- WFE
  - *Testing was done on a 4” HeNe Zygo interferometer.*
  - *Power, Tip, & Tilt was subtracted from the RMS values in the MetroPro software.*
  - *4” transmission flat & f/1.5 transmission sphere was used respectively*
- Surface Roughness
  - *Testing was done 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 were used as the comparative metric for this study.*
- Image Analysis Testing
  - *Analysis was done using images from a Cannon Rebel T5i in which the lenses were mounted.*
  - *An Image J gray value histogram was then used to calculate the Michelson contrast.*

Image Analysis & Testing



- For this study the lenses were mounted onto a Cannon Rebel T5i with a Cannon EF mount. To achieve a course adjustment and lens mounting a 3D printed housing, mounting flange, and lens holder were printed on a FormLabs printer.
- The lens holder has a seat and inlets for potting the lens into the holder. Plastic shim-stock was used to center the lens in the holder before bonding. Three #4 screws allow the lens holder slide along the slots in the housing to coarsely adjust focus. These screws were also measured to assure the lens was not tilted when focusing the lens.
- Photos were taken of a high contrast set scene at best achievable focus using a tripod. 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 and a gray value histogram was produced. From that the Michelson Contrast was calculated.

Michelson Contrast Equation

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

MATERIAL PROPERTIES RESULTS

Topics to be Discussed

Transmission Responses

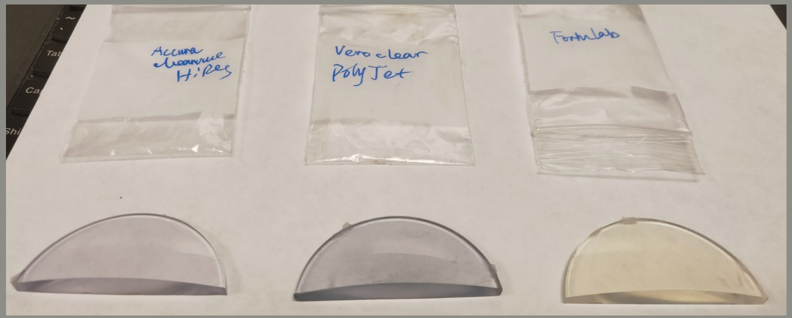
Index & Abbe Number Results

Transmission Responses

- Transmission Values for Acrylic, and Accura ClearVue were taken from their respective data sheets.
- Transmission Values for Vero Clear were taken from test data reported in “The research on surface characteristics of optical lens by 3D printing techniques and precise diamond turning”
- Transmission Values for WaterClear Ultra was taken from Digital Engineering article.
- Transmission Values for Formlabs were taken from test data reported in “Fabrication of optical components using a consumer-grade lithographic printer”
- Its import to note that the FormLabs Clear data in this graph is from a sample that didn’t have significant yellowing. The yellowing effect varies and will cause a degradation in the transmission for wavelengths nearing the blue and UV spectrums.

Index of Refraction & Abbe Number Results

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



- The Index of Refraction testing was done by the University of Arizona on an ATAGO's multi-wavelength Abbe refractometer DR-M2. The lenses had to be cut in half in order to be measured on the machine. The cut area was re-polished before testing. Accura ClearVue, VeroClear, and FormLabs lenses were tested.
- Because of the change in geometry this test was done last. The Acrylic material properties are known so the control lens was not tested. These values are listed from the datasheet.
- The WaterClear Ultra lens was also not tested. Print errors that will be discussed in the WFE and Image Testing sections inhibited the ability for this lens to be tested. Index from Datasheet is listed.
- 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.
- It is of interest that the Accura ClearVue reported value differs from the measured value by 0.008. This difference is far outside the measurement error of ±0.0002. While this difference is not a significant error a further study into the repeatability of the index and dispersion over multiple prints could be of interest.

LENS QUALITY TEST RESULTS

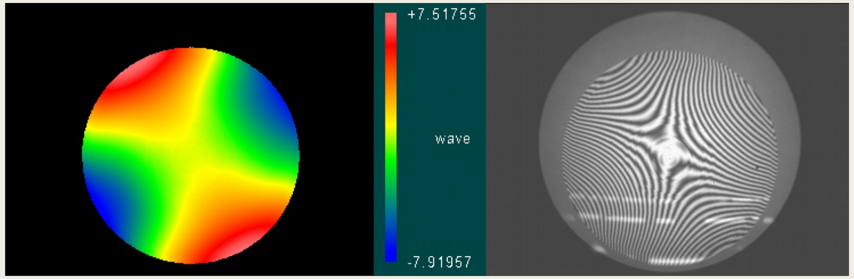
Topics to be Discussed

WFE Results
Surface Roughness Results
Image Analysis Results

WFE Results

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**

- 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.



WFE Results: Seidel Coefficients

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

- 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.
- These values give a sense of how much astigmatism is contributing to the overall WFE.

Aberration Coefficients in terms of Seidel sums

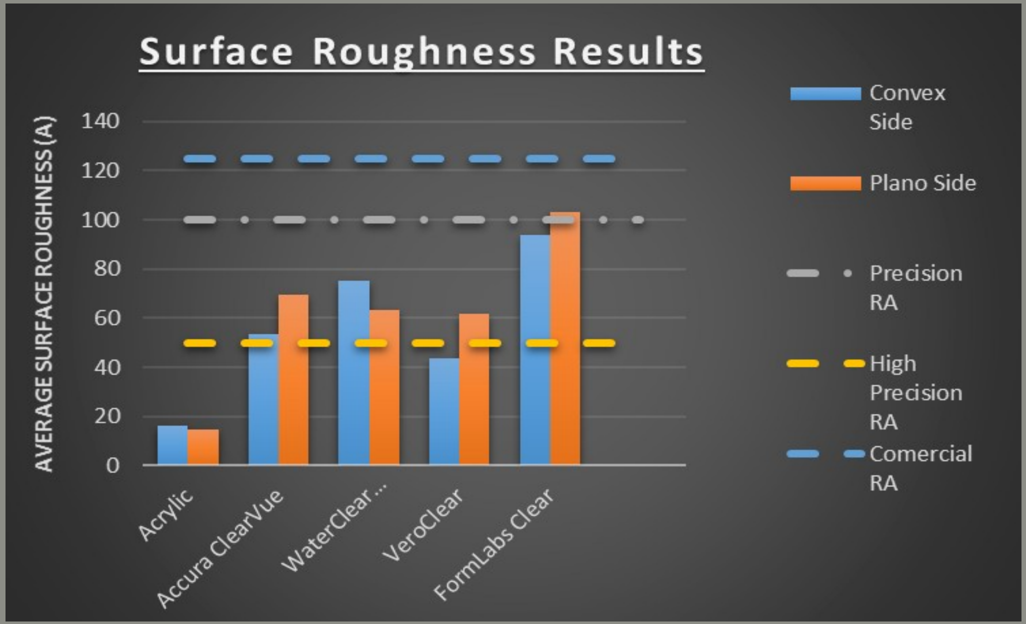
Coefficient	Seidel sum
$W_{040} = \frac{1}{8} S_I$	$S_I = -\sum_{i=1}^{j} \left(A^2 y \Delta \left(\frac{u}{n} \right) \right)_i$
$W_{131} = \frac{1}{2} S_{II}$	$S_{II} = -\sum_{i=1}^{j} \left(A \bar{A} y \Delta \left(\frac{u}{n} \right) \right)_i$
$W_{222} = \frac{1}{2} S_{III}$	$S_{III} = -\sum_{i=1}^{j} \left(\bar{A}^2 y \Delta \left(\frac{u}{n} \right) \right)_i$
$W_{220} = \frac{1}{4} (S_{IV} + S_{III})$	$S_{IV} = -\mathcal{K}^2 \sum_{i=1}^{j} P_i$
$W_{311} = \frac{1}{2} S_V$	$S_V = -\sum_{i=1}^{j} \left(\frac{\bar{A}}{A} \left[\mathcal{K}^2 P + \bar{A}^2 y \Delta \left(\frac{u}{n} \right) \right] \right)_i$
$W_{311} = \frac{1}{2} S_V$	$S_V = -\sum_{i=1}^{j} \left(\bar{A} \left[\bar{A}^2 \Delta \left(\frac{1}{n^2} \right) y - (\mathcal{K} + \bar{A} y) \bar{y} P \right] \right)_i$
$\delta_\lambda W_{020} = \frac{1}{2} C_L$	$C_L = \sum_{i=1}^{j} \left(A y \Delta \left(\frac{\delta n}{n} \right) \right)_i$
$\delta_\lambda W_{111} = C_T$	$C_T = \sum_{i=1}^{j} \left(\bar{A} y \Delta \left(\frac{\delta n}{n} \right) \right)_i$

WFE Results: Astigmatism Removed

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

- While it is unlikely that all astigmatism could be reduced, 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, these numbers are not absolute but give a representation of what could be achieved.
- To try and find the root cause optics experts at BAE systems were consulted. 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. For that purpose of this study, these lenses are sufficient in comparing the materials.

Surface Roughness Results



- The results for the 3D printed lenses are all roughly in family of each other.
- According to the standard diamond turning capabilities (as reported by Edmund Optics) the results fall either in the precision or high precision categories for all sample lenses.

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

Image Analysis Results

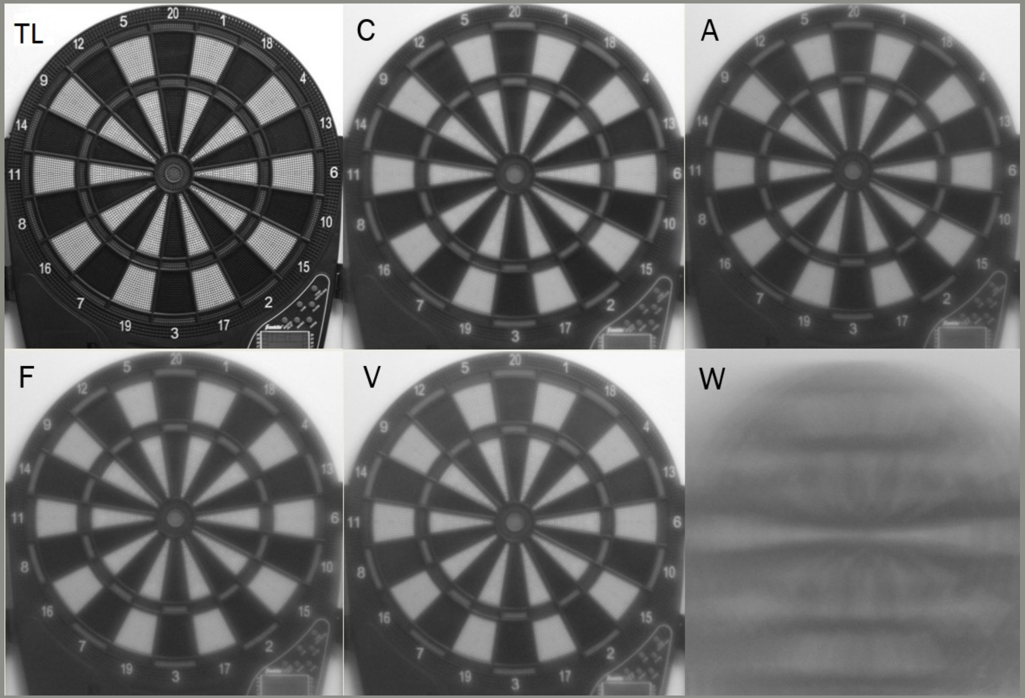
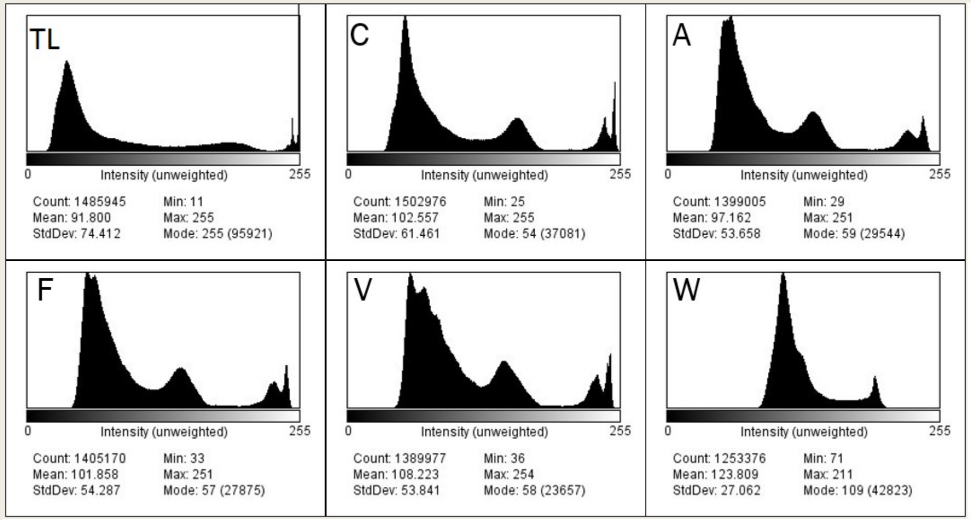


Figure Shows Image produced from each lens; Telephoto lens (TL), Control lens (C), Accura ClearVue (A), FormLabs Clear (F), VeroClear (V), and WaterClear Ultra (W).

- The WaterClear Ultra lens was unable to produce a viable image due to the print errors noted prior. Contrast calculated from Gray values was used to differentiate between the remaining lenses.
- The Telephoto Lens (TL) is a Cannon 200 focal length multi-element lens. This was used as an ideal comparison.



	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

STUDY CONCLUSIONS

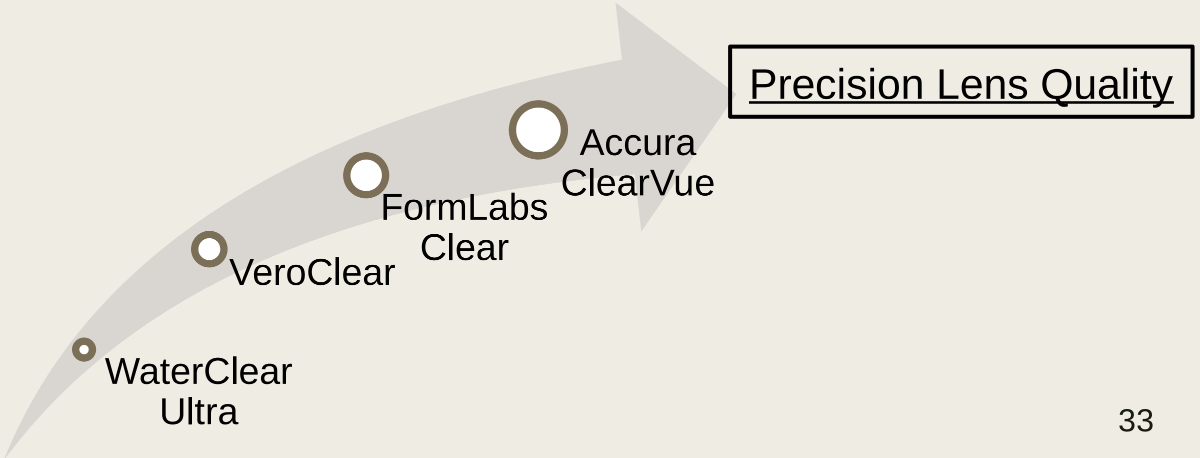
Topics to be Discussed

Summary of Lens Performance

Summary of Lens Performance

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*

- 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. The WaterClear Ultra material was unable to produce a viable lens.
- The Accura ClearVue lens stood out among the rest with a WFE and Surface Roughness better than that of the Luxexcel lenses reported in outside studies.



FURTHER STEPS

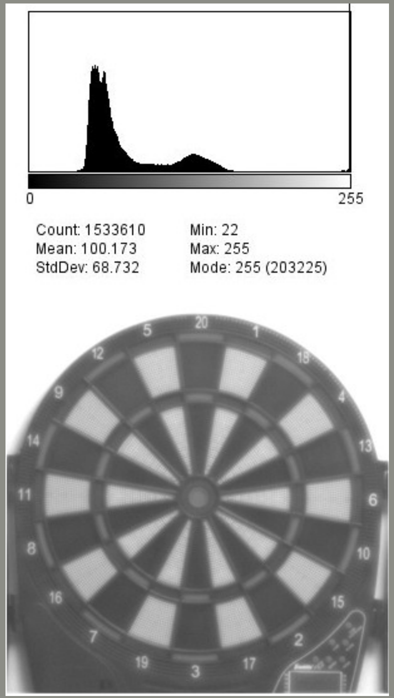
Topics to be Discussed

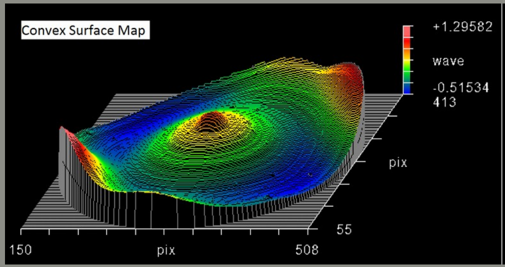
Additional Test Lens Evaluation

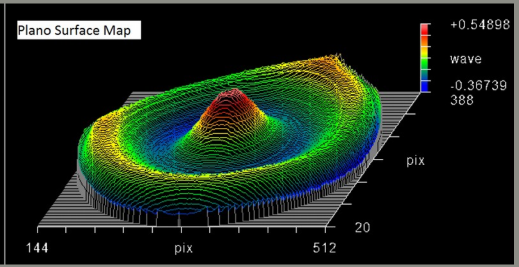
Potential Future Studies

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 with a lowered aspect ratio of 4.83:1 rather than the 7.25:1 of the original test lenses.
- The results of this limited testing 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. The results of this study shows that with the right parameters a usable and precise lens could be achieved from a 3D printed substrate in the near future.







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**

Potential Future Studies

- **Suggested Next Steps for This Area of Study Include:**
  - *Increase lens count for statistical results and better understanding repeatability of material properties among prints.*
  - *Attempt additional polishing steps post diamond turning.*
  - *Thermal testing of materials.*
  - *Testing of mechanical straining of the materials.*
  - *Attempt to print a replica lens of an BAE flight part mimicking it’s processing and testing.*
  - *Investigation into a new VeroUltra Clear material that was announced in Oct. 2019 for future release.*

REFERENCES

Topics to be Discussed

Clickable References

Clickable References

SLA Background

SLA Background Paper

Related Outside Studies

Direct to Print Study

Vero Clear Study

FormLabs Study

Material Properties Data

Acrylic Data Sheet

Accura ClearVue Data Sheet

VeroClear Data Sheet

WaterClear Ultra Data Sheet

WaterClear Ultra Transmission Data

WFE & Surface Roughness References

Seidel Aberration Coefficients

Diamond Turning Capabilities Reference

Experimental Methods References

Refractometer Specifications Reference

Refractometer Background Reference

Abbe Number Background Reference

Michelson Contrast Reference

Full Thesis Paper

Full Thesis Paper