Freeform Optics Fabrication

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APOMA Meeting
Photonics West San Francisco

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Optics & Materials Science & Technology
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LLNL-PRES-859408
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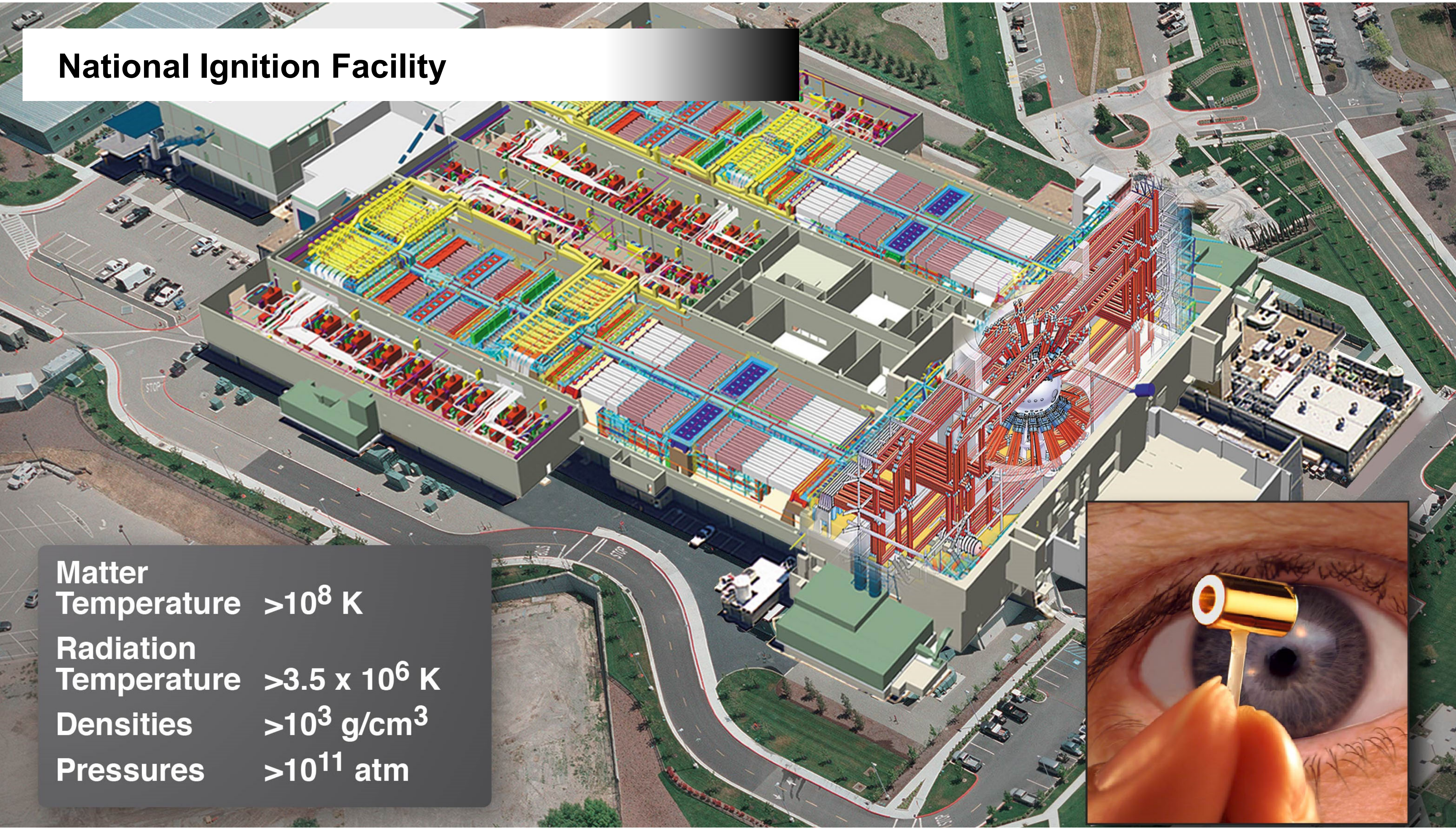
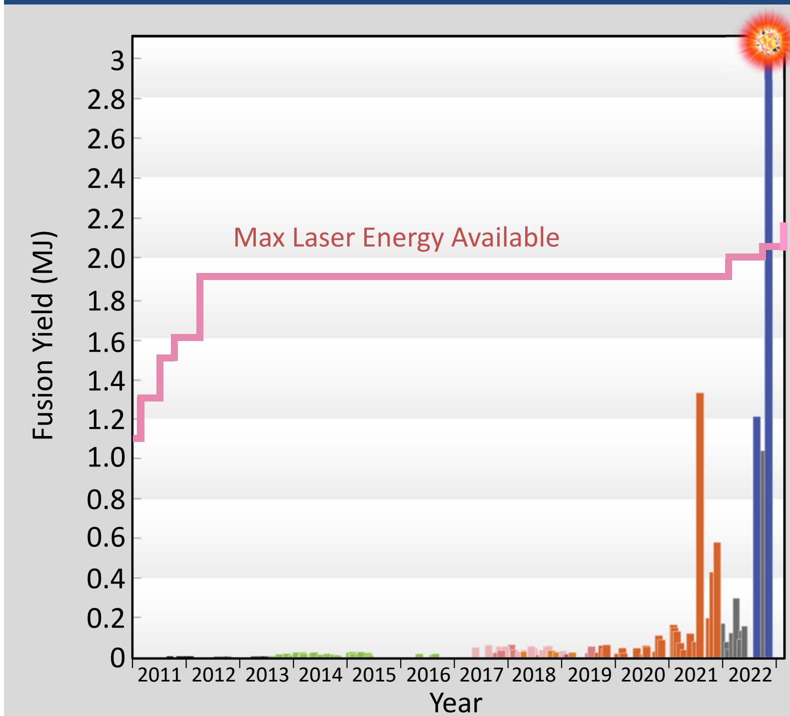

National Ignition Facility
Matter Temperature $>10^8$ K
Radiation Temperature $>3.5 \times 10^6$ K
Densities $>10^3$ g/cm^3
Pressures $>10^{11}$ atm

On December 5, 2022, NIF achieved ignition, with 3.15 MJ of fusion output for 2.05 MJ laser delivered

NIF Fusion Yield

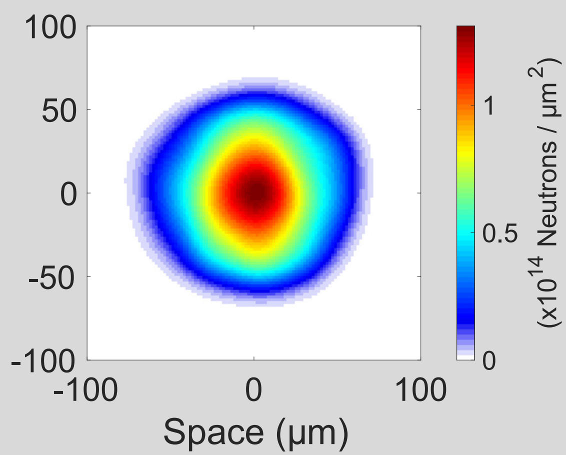


Output from 12/5/2022 Experiment

>30,000 trillion watts (30 PW),

~3.15 MJ with G_{target} ~ 1.5

10^{18} neutrons over ~100 ps



Fusion plasma ~100 μm

Temperature ~130,000,000 K

*National Academy of Sciences 1997 definition for ignition, target gain >1

[1]H. Abu-Shawareb et al., PRL, 129, 075001 (2022)
[2]A. L. Kritcher et al., PRE, 106, 025201 (2022)
[3]A. B. Zylstra et al., PRE, 106, 025202 (2022)
A. B. Zylstra et al., Nature 601, 542–548 (2022)

Charting the First Year of Ignition

First Ignition
December 5, 2022

Second Ignition
July 30, 2023

Third Ignition
October 8, 2023

Fourth Ignition
October 30, 2023

Inside the Nuclear Fusion Facility That Changed the World

By Alejandro de la Garza

The freeform fabrication facility at LLNL

Satisloh CNC grinder/polisher

Sub-aperture grinding and polishing (figure & smoothing)

QED Stitching Interferometer

Freeform surface figure measurement

QED MRF Precision Polisher

High precision final polishing

Digimar CMM

New

Optic Thickness Measurement

Taylor Hobson Profilometer

New

Ground freeform metrology

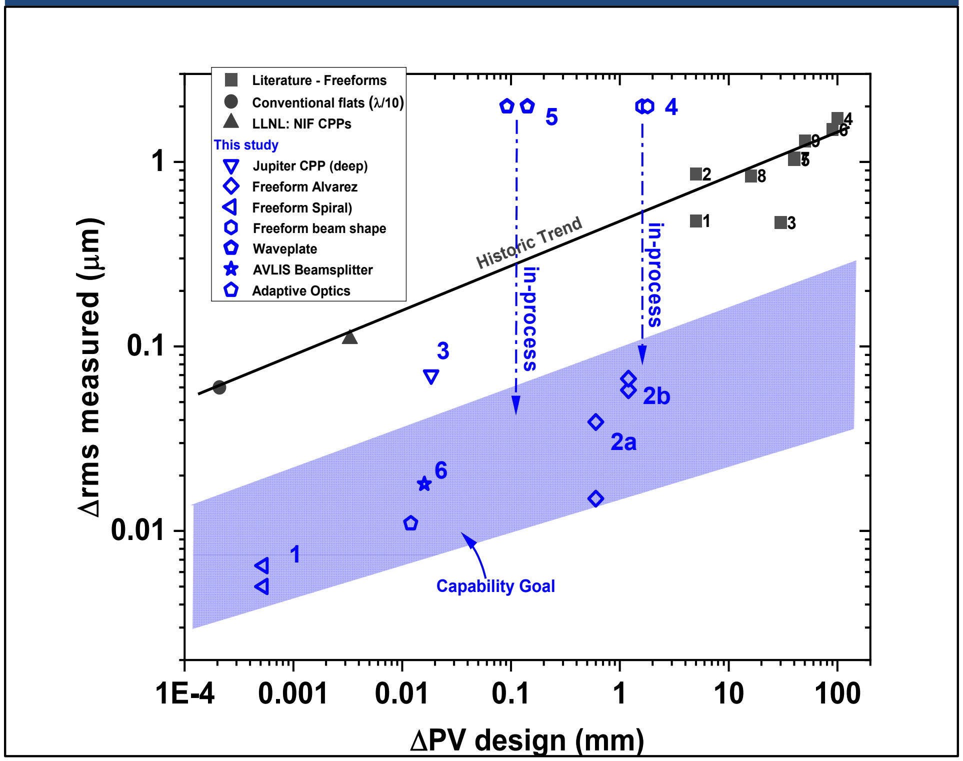
Optipro UFF300 polisher

New

Rapid freeform initial polishing

Our goal is to fabricate mm to cm scale PV freeform designs with ~10x reduction in typical deviation from target shape

Optical specification parameter space



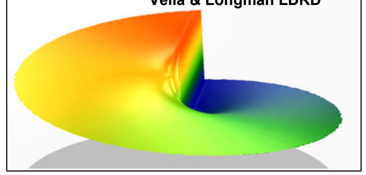
PV: Design Peak-to-valley of full optic

Δrms: Measured rms deviation from target surface figure

1. Spiral Optics

Δrms=5.0 nm

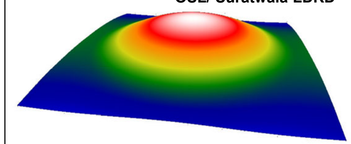
PV= 119 μm; 0.5 μm
Max slope=1.6 μm/mm
Quartz/Fused Silica (100-150 mm)
Vella & Longman LDRD



4. Beam Shapers

Δrms= In process

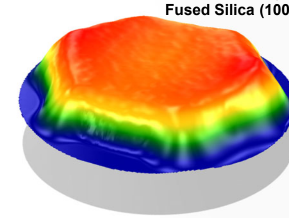
PV= 1500 μm
Max slope=37 μm/mm
Fused Silica (100 mm)
OSL/ Suratwala LDRD



7. Adaptive optic test

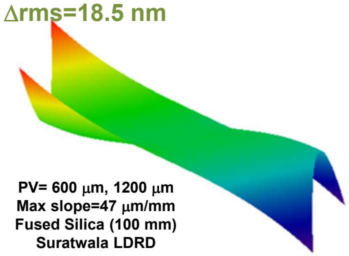
Δrms=11 nm

PV=12 μm
Max slope= XX μm/mm
Fused Silica (100 mm)



2. Alvarez Lens

Δrms=18.5 nm

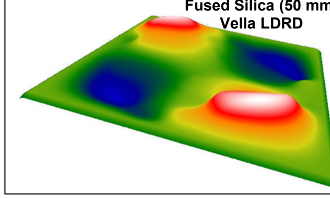


PV= 600 μm, 1200 μm
Max slope=47 μm/mm
Fused Silica (100 mm)
Suratwala LDRD

5. Waveplates

Δrms= In process

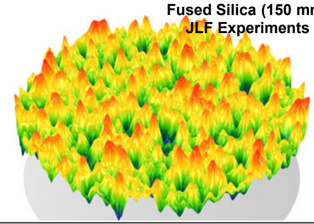
PV= 141 μm
Max slope=26 μm/mm
Fused Silica (50 mm)
Vella LDRD



3. JLF 2 mm CPPs

Δrms=70 nm

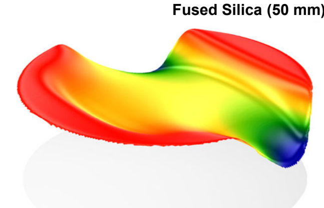
PV=18 μm
Max slope= 2.7 μm/mm
Fused Silica (150 mm)
JLF Experiments



6. Beamshaper

Δrms=18 nm

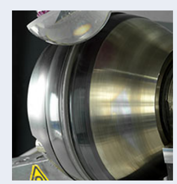
PV=16 μm
Max slope= XX μm/mm
Fused Silica (50 mm)



Ref: G. Matthews, SPIE 10448 2017; D. Walker, SPIE 5869 2005; Blalock, SPIE 9575 2015; Kong, IEEE 33(4) 2010; J. Menapace (Jupiter CPP)

General process route for making a freeform optic

+ Strategy to improve workpiece quality and/or reduce process time

	1. Coarse Grind	2. Fine Grind	3. Bulk Etch	4. Grayout	5. Smoothing I	6. Figure Correction I	7. Smoothing II	8. Figure correction II
Type	Grinding	Grinding	Chemical	Polishing	Polishing	Polishing	Polishing	Polishing
Purpose	Shape within 2-3 um	Shape within 1-1.5 um	Reduce polishing amount	Rapidly remove Gray	Remove grinding ripples (mid-spatial)	Figure to within ~300 nm PV	Remove polishing ripples (mid-spatial errors)	Surface figure to within <50 nm rms
LLNL Machine	Satisloh	Satisloh	Static bulk etch station	OptiPro Belt Polishing	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Q-flex MRF + ASI-Q Metrology + white light interferometry
Example	Cup or Wheel, Diamond 50 um 	Cup or Wheel, Diamond 15 um 	Buffered Oxide Etch	CEO Belt 	Multi-layer Pad/foam, CeO_2 	Hemi Pad/foam, CeO_2 	Multi-layer Pad/foam, CeO_2 	MRF ribbon, CeO_2 
	Required	Required			Required	Required		Required

1) Improved Figure Correction
Increase TIF determinism & repeatability

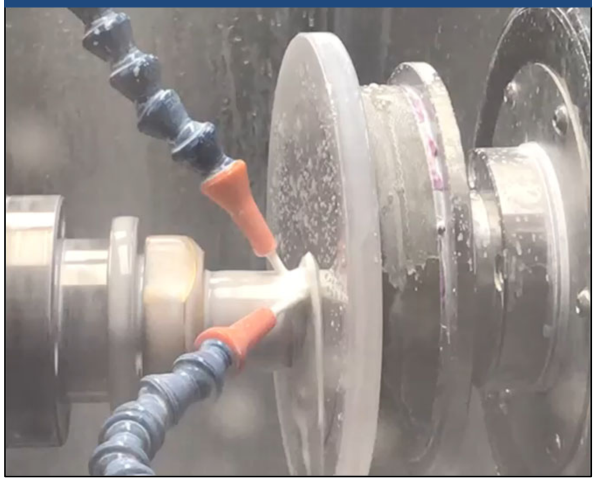
2) Minimize mid-spatial generation
Reduce ripple magnitude

3) Improve Smoothing
Increase ripple convergence & minimized figure degradation

TIF= tool influence function

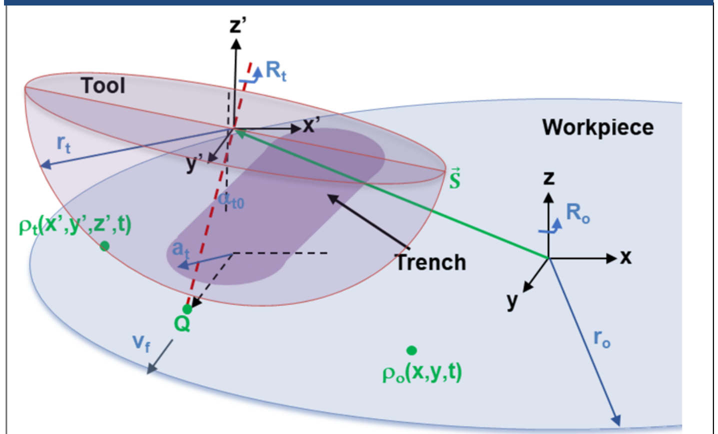
A systematic set of series of TIF spots, trenches & patches were created to understand both TIF shape & polishing induced feed & pitch ripples

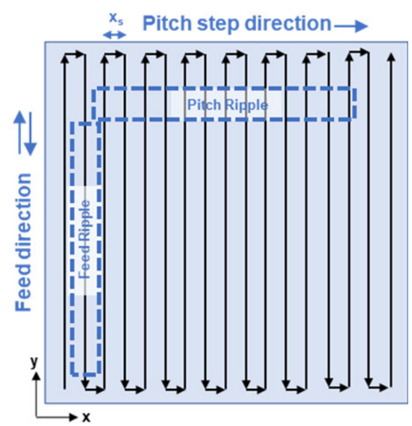
Polishing with hemispherical pad-foam polishing tool



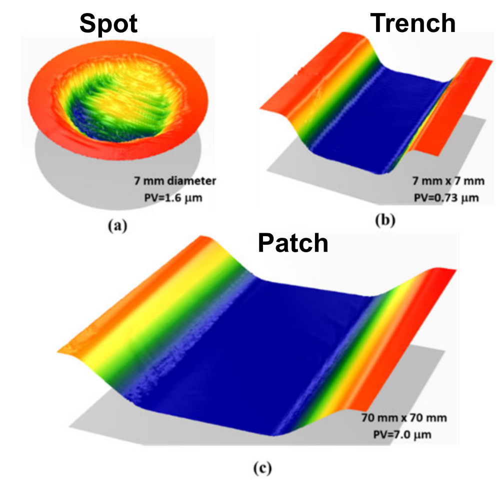
Key process variables
- Kinematics (rotation rate, tilt, stroke, feed velocity, pitch step, etc)
- Tool properties (radius, pad, foam backing, age, etc.)
- Displacement & dwell time
- Workpiece curvature

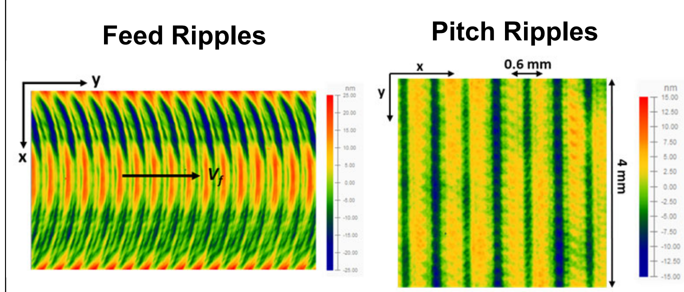
Kinematics & Experimental parameters





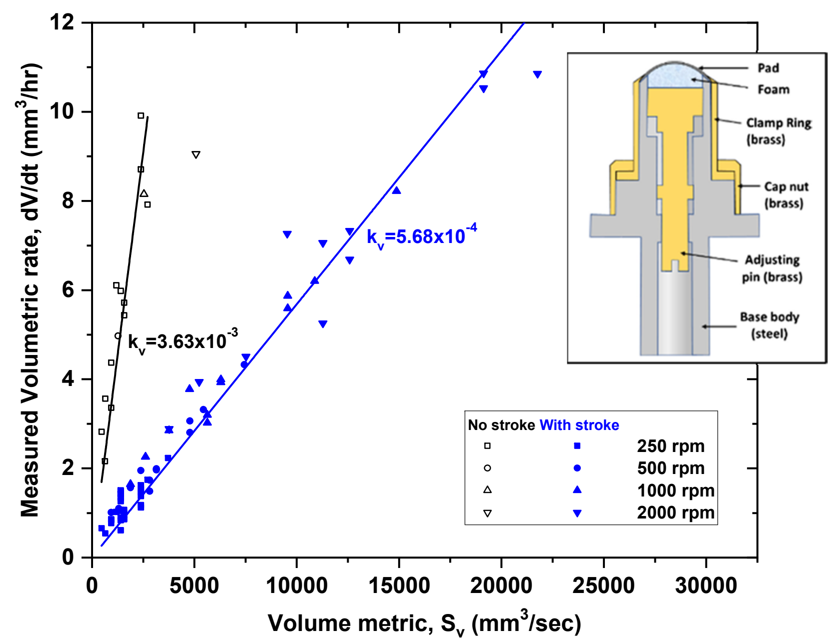
Ripple created within spots, trenches & patches





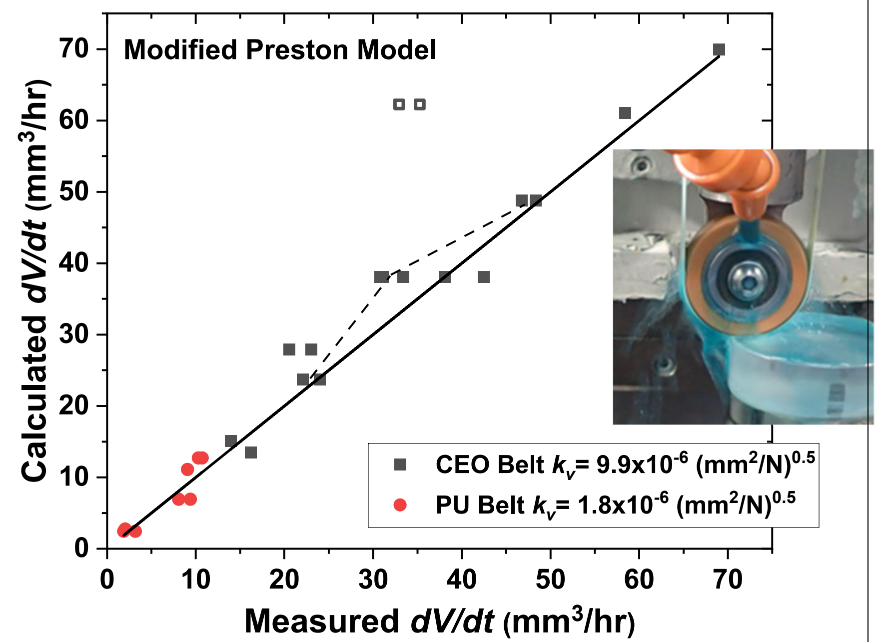
Sub-aperture tool volumetric polishing rate can be predicted with processing parameters

Hemispherical Pad Foam



$$\frac{dV}{dt} = k_v \pi a_t^2 V_{ave}$$

Linear Belt on Wheel



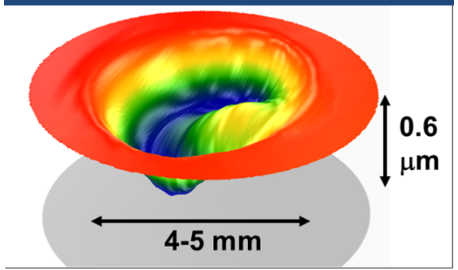
$$\frac{dV}{dt} = k_v V_r P$$

k_v= Volumetric Preston constant
a_t= contact area
V_r or V_{ave}= relative or average velocity
P= applied load

T. Suratwala, *Applied Optics* 60:1 (2021) 201-211
T. Suratwala, Applied Optics (2022)

We have identified & quantified numerous physical mechanisms that govern the shape of the TIF spot

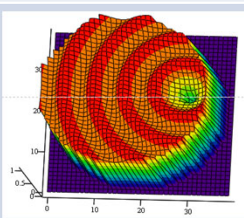
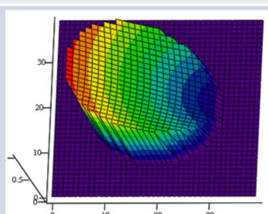
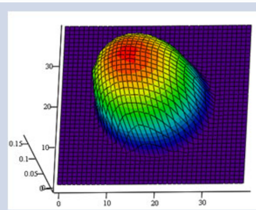
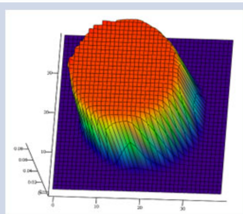
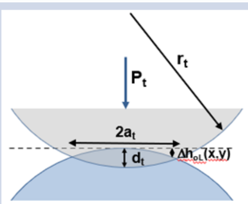
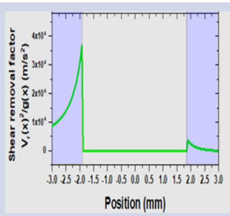
Example TIF spot



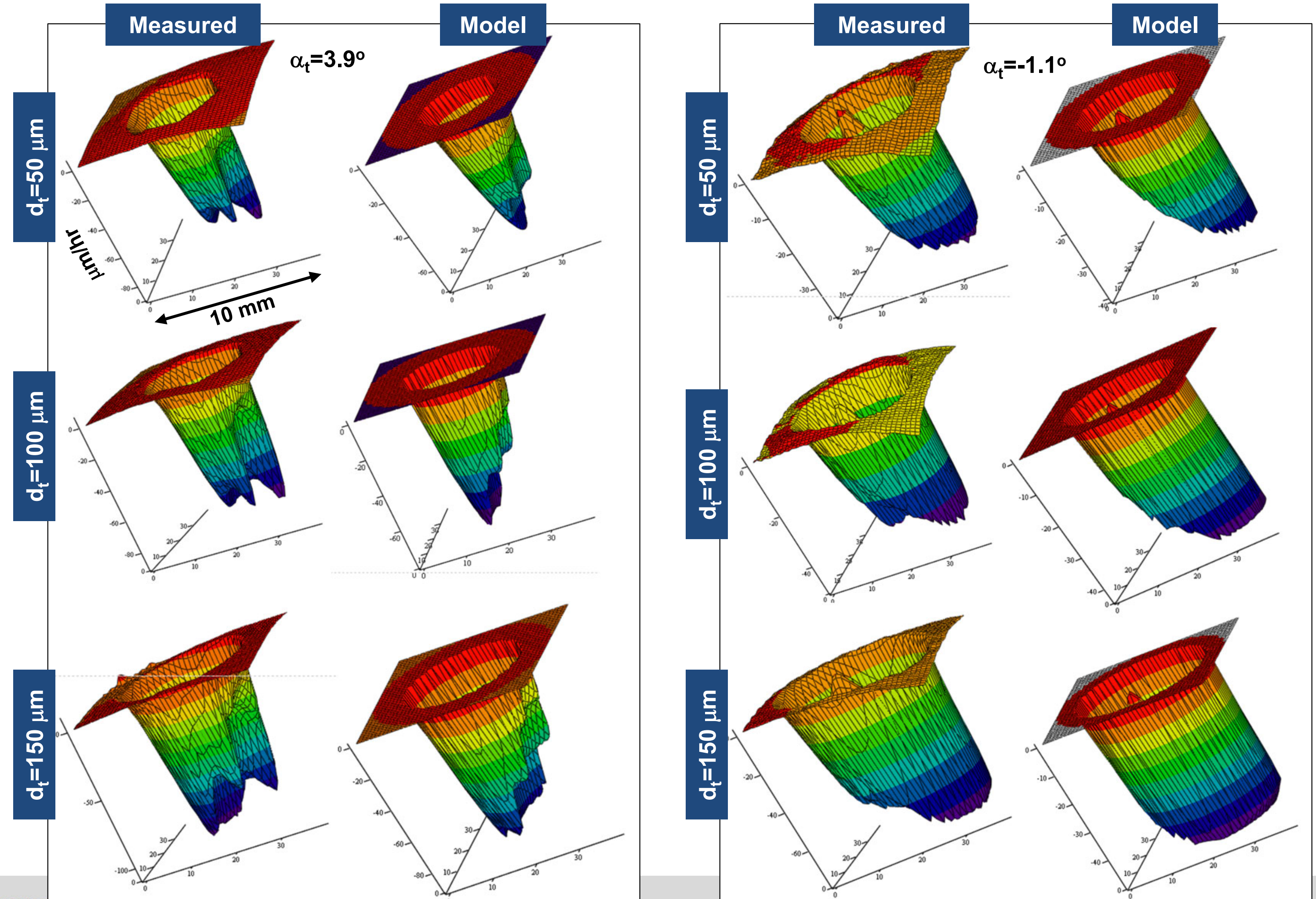
Removal rate

$$\frac{dh}{dt}(x,y,z,t) = k_p \mu V_r \sigma + k_{ps} V_r^{*} \tau$$

Normal load removal — Shear load removal

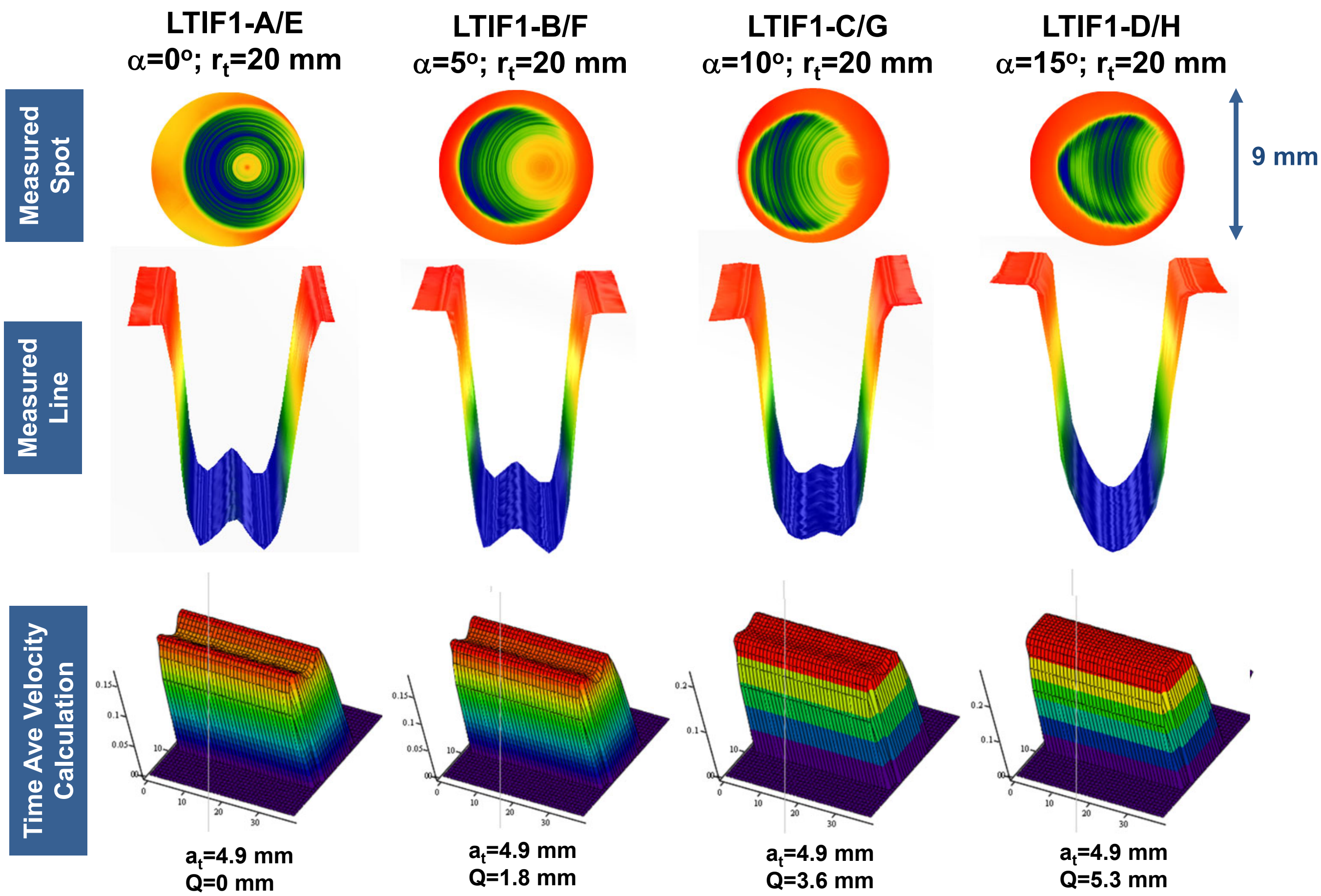
	Spatially dependent (μ)	Time ave velocity (V_r)	Elastic pressure (σ_e)	Hydrodynamic pressure (σ_h)	Workpiece-Lap Mismatch ($\sigma_{o\text{-}l}$)	Shear removal ($V_r\tau$)
Mechanism	Pad slurry islands & porosity distribution alter pad contact	Relative velocity proportional to # of particles removing material	Pressure determined by elastic mechanics	Pressure determined by Hydrodynamic forces	Pressure altered by mismatch (due to workpiece curvature)	Removal occurs where there is high particle velocity in fluid & little normal load
Model	1) Exponential increase in µ with radial distance from rotation axis 2) Sinusoidal radial fluctuations	3D kinematics model for tool & workpiece	COMSOL FEA elastic mechanics (& Hertzian contact mechanics)	COMSOL FEA elastic mechanics & hydrodynamics	Elastic sphere-sphere ESS contact model	Shear removal model Occurs on one edge of TIF spot
Simulation						

Removal rate model largely captures TIF shape over a wide variety of rotation rates (R_t), displacements (d_t) & angles (α_t)



Applied Optics 60 (1) 201-214 (2021)

TIF spots and corresponding trenches are correlated whose shape is dominated by the relative velocity distribution

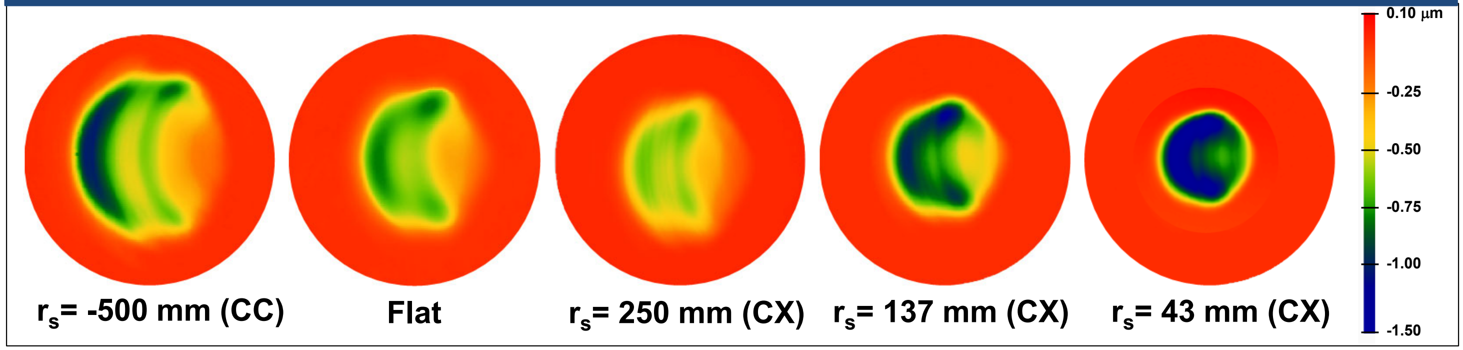


- **Trench cross section shape transitions from inward bump, to flat, to parabolic shape with increase in tilt angle**
- **Relative velocity distribution largely matches trench cross section shape**

Tilt parallel to linear stroke direction
Series A LTIF1: 20 mm radius tool (250 rpm; LP66 pad; 0.8 mm; green foam; 600 um displacement; no tilt stroke; 10 sec for spot; 127 mm/min for trenches; 12 passes)
*6 oscillations (12 passes) in 600 sec; each pass is 106 mm, V=12*106mm/600sec=127 mm/min

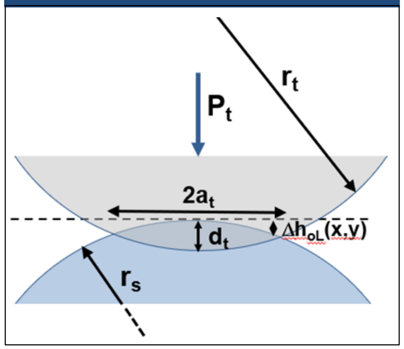
As workpiece transitions from flat to convex, spot gets smaller & deeper; As workpiece transitions from flat to concave, spot gets bigger & deeper

Measured TIF spots as a function of WP curvature

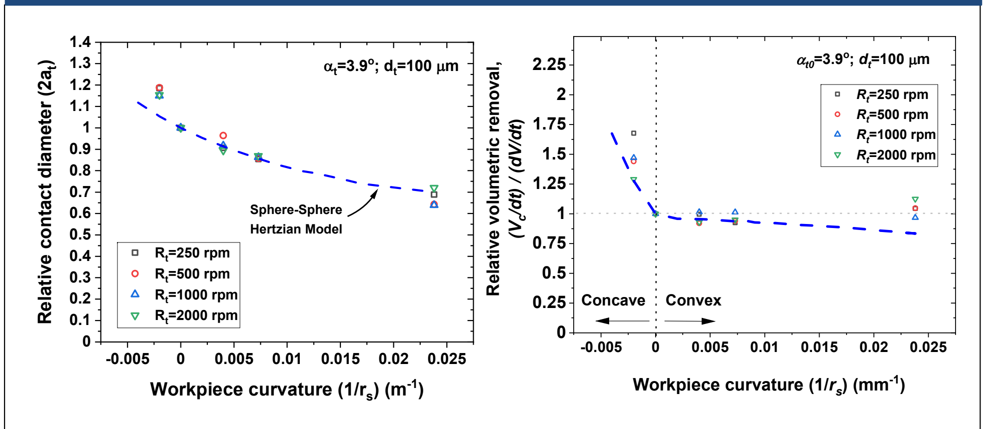


α_t=3.9°; R_t=500 rpm; d_t=100 µm; t=15 s

Sphere-sphere contact model



Model vs experiment



General process route for making a freeform glass optic

+ Strategy to improve workpiece quality and/or reduce process time

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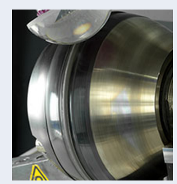
Purpose	Shape within 2-3 um	Shape within 1-1.5 um	Reduce polishing amount	Rapidly remove Gray	Remove grinding ripples (mid-spatial)	Figure to within ~300 nm PV	Remove polishing ripples (mid-spatial errors)	Surface figure to within <50 nm rms
LLNL Machine	Satisloh	Satisloh	Static bulk etch station	OptiPro Belt Polishing	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Q-flex MRF + ASI-Q Metrology + white light interferometry
Example	Cup or Wheel, Diamond 50 um 	Cup or Wheel, Diamond 15 um 	Buffered Oxide Etch	CEO Belt 	Multi-layer Pad/foam, CeO_2 	Hemi Pad/foam, CeO_2 	Multi-layer Pad/foam, CeO_2 	MRF ribbon, CeO_2 
	Required	Required			Required	Required		Required

1) Improved Figure Correction
Increase TIF determinism & repeatability

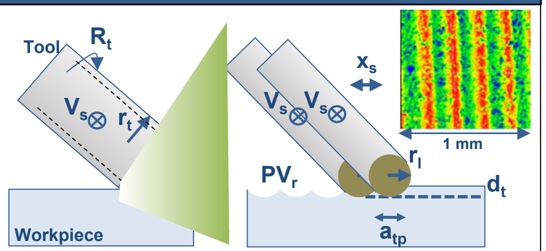
2) Minimize mid-spatial generation
Reduce ripple magnitude

3) Improve Smoothing
Increase ripple convergence & minimized figure degradation

Summary of pitch & feed ripple rule sets during grinding & polishing

Pitch Ripple

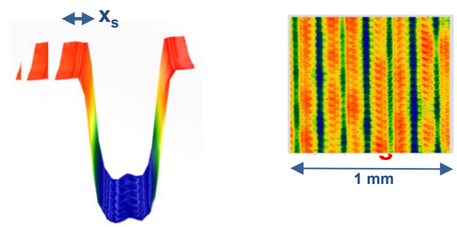
Cup Grinding



Contact zone in step view direction $a_{tp} = \sqrt{r_l^2 - (r_l - d_t)^2}$

Pitch ripple height $PV_p = r_l - \sqrt{r_l^2 - min\left(a_{tp}^2, \left(\frac{x_s}{2}\right)^2\right)}$

Hemispherical tool Polishing



TIF trench $\frac{dh(x)}{dt} = Ae^{-\left(\frac{x^2}{2a_t^2}\right)^P}$

Height profile $h(x) = -\sum_n \frac{dh(x + nx_s)}{dt} t_{dwell}$

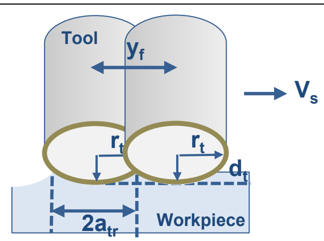
Pitch ripple height $\delta_p = h_{max} - h_{min}$

Ripple source:
Overlap of trench shape

Spacing:
Controlled by step distance x_s

Minimize strategy:
- Decrease x_s
- Increase r_l *(Grinding)*
- Flat bottom trench shape (Polishing)

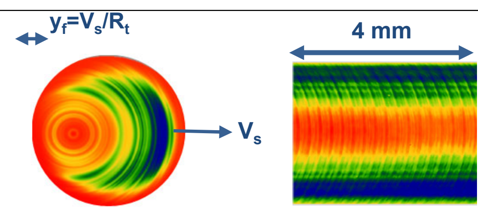
Raster Ripple



Contact zone in feed view direction $a_{tr} = \sqrt{r_t^2 \left(1 - \frac{(r_t\cos(\alpha_{to}) - d_t)^2}{(r_t\cos(\alpha_{to}))^2}\right)}$

Pitch ripple height & Feed/rotation $PV_r = a_{tr} - \sqrt{a_{tr}^2 - \left(\frac{y_f}{2}\right)^2}$ $y_f = \frac{V_s}{R_t}$

defined by <u>Geometry</u>



Contact zone in feed view direction $a_{tr} = \sqrt{r_t^2 - (r_t - d_t)^2}$

Average Velocity $V_{max} = (a_t + Q)R_t\cos(\alpha_{t0})$

Raster ripple height (∝ to amount removed) $\delta_f \propto r_f = V_{max}{}^{0.5}\frac{V_f}{R_t}$

defined by <u>Preston Model</u>

Ripple source:
Removal non-uniformities or asperities on tool

Spacing:
Controlled by feed/rotation x_f

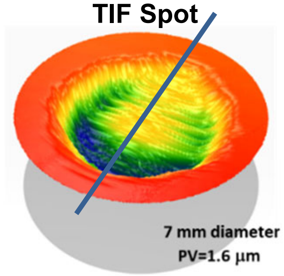
Minimize strategy:
- Reduce/remove tool non-uniformities (f_{pad})
- keep r_f<0.7 $mm^{1.5}/s^{0.5}$

Polishing feed ripples simulated from TIF spots suggest they are caused by pad non-uniformities on the scale length of the feed per rotation

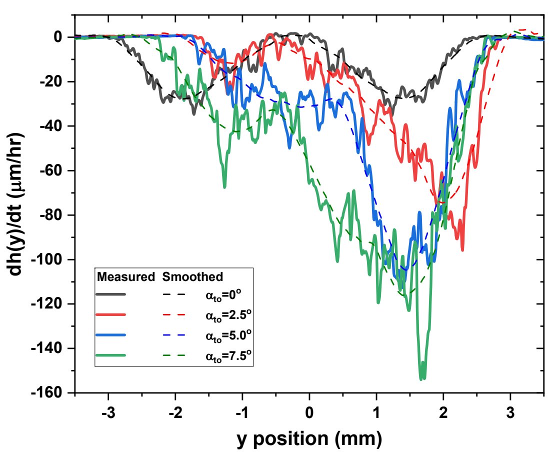
Hypothesis: ripples caused by pad porosity distribution

GR polishing pad

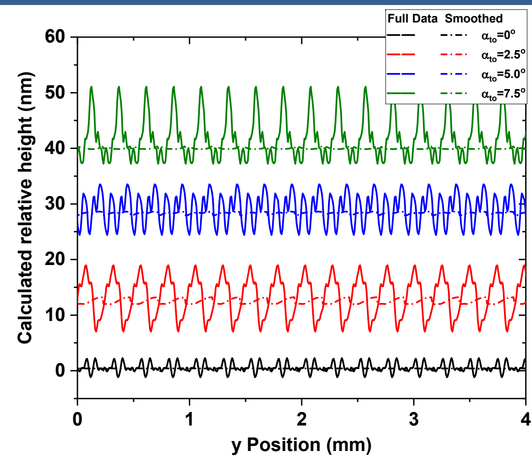
TIF Spot



Measured TIF spot lineouts



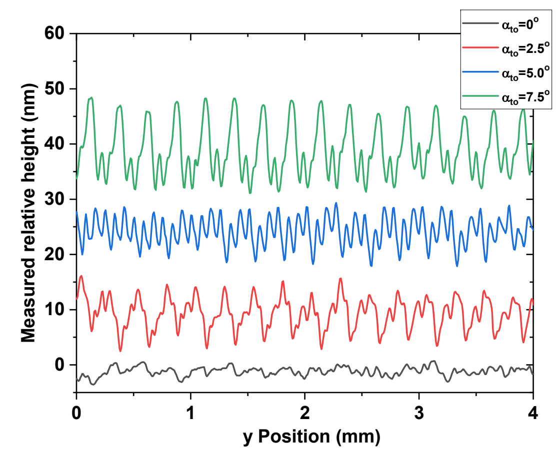
Simulated Feed Ripples from TIF spots



Solid lines = from measured TIF spots
Dashed lines = from smoothed TIF spots

$$h(y) = -\int \frac{dh(y+V_f t)}{dt}dt = -\sum_i \frac{dh(y+iy_f)}{dt}\frac{1}{R_t}$$

Measured Feed Ripples within trench

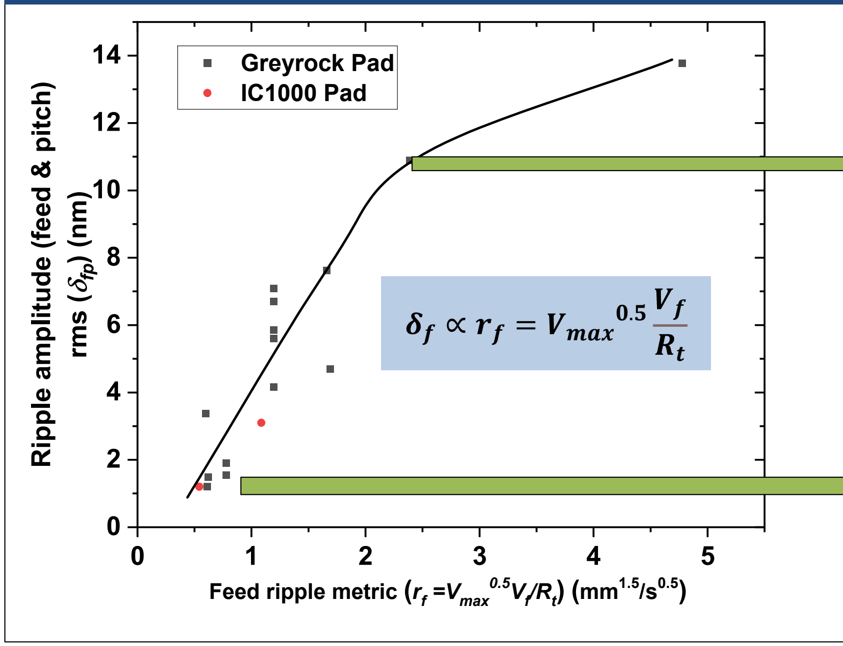


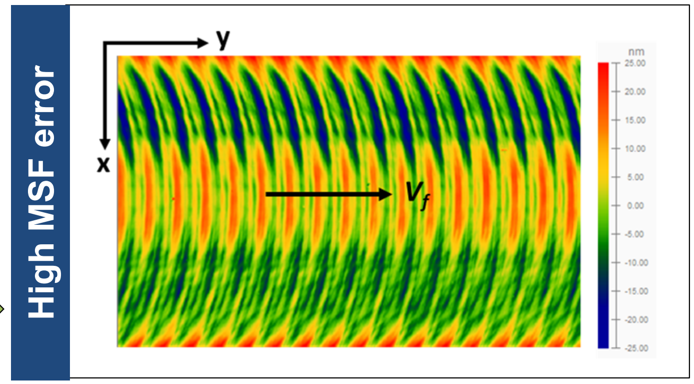
- **Simulated feed ripples have similar amplitude & spatial scale length (determined by feed per rotation, y_f) as the measured data**
- **Simulated feed ripples from smoothed TIF spots show large reduction in amplitude**

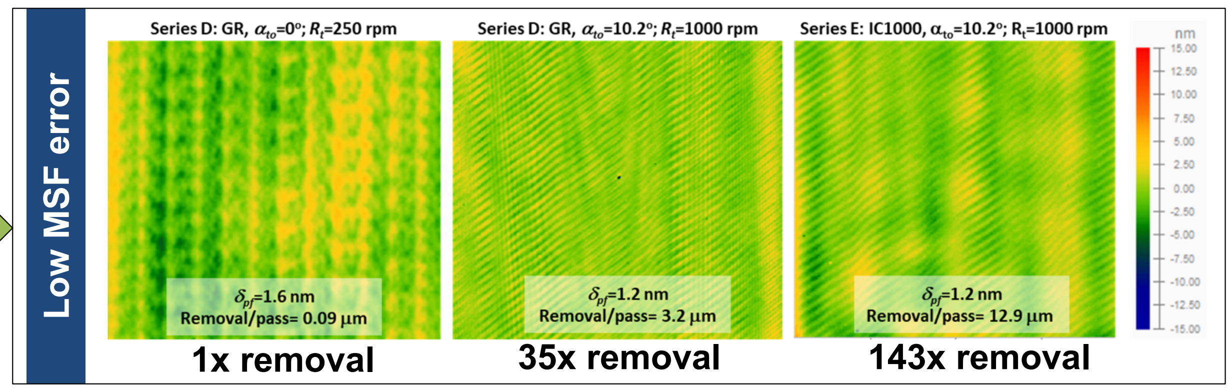
Removing removal nonuniformity of the pad (e.g., nonporous pads) may allow for significant feed ripple reduction

Using process parameters that meet relative pitch step & feed ripple metric criteria, low MSF error can be achieved over a large range of material removal rates!

Overall ripple amplitude or MSF error (rms) vs feed ripple metric (r_f) when $x_s/a_t \leq 0.2$



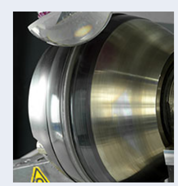




Combined feed & pitch ripple in a patch can be minimized when
$x_s/a_t \leq 0.2$ and $r_f \leq 0.7$ $mm^{1.5}/s^{0.5}$

General process route for making a freeform optic

+ Strategy to improve workpiece quality and/or reduce process time

	1. Coarse Grind	2. Fine Grind	3. Bulk Etch	4. Grayout	5. Smoothing I	6. Figure Correction I	7. Smoothing II	8. Figure correction II
Type	Grinding	Grinding	Chemical	Polishing	Polishing	Polishing	Polishing	Polishing
Purpose	Shape within 2-3 um	Shape within 1-1.5 um	Reduce polishing amount	Rapidly remove Gray	Remove grinding ripples (mid-spatial)	Figure to within ~300 nm PV	Remove polishing ripples (mid-spatial errors)	Surface figure to within <50 nm rms
LLNL Machine	Satisloh	Satisloh	Static bulk etch station	OptiPro Belt Polishing	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Satisloh + ASI-Q Metrology	Q-flex MRF + ASI-Q Metrology + white light interferometry
Example	Cup or Wheel, Diamond 50 um 	Cup or Wheel, Diamond 15 um 	Buffered Oxide Etch	CEO Belt 	Multi-layer Pad/foam, CeO_2 	Hemi Pad/foam, CeO_2 	Multi-layer Pad/foam, CeO_2 	MRF ribbon, CeO_2 
	Required	Required			Required	Required		Required

1) Improved Figure Correction
Increase TIF determinism & repeatability

2) Minimize mid-spatial generation
Reduce ripple magnitude

3) Improve Smoothing
Increase ripple convergence & minimized figure degradation

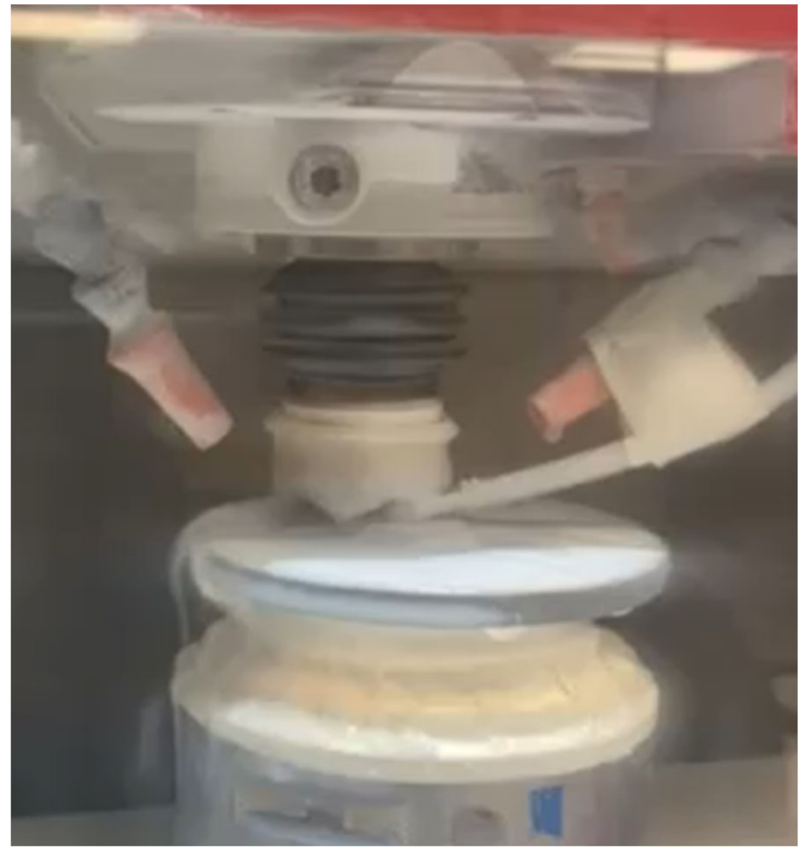
We have developed a new smoothing tool that removes mid-spatial error rapidly with little surface figure degradation

Smoothing Tool Design Evaluated

Table 1. Description of the Various Smoothing Tools (25 mm in Diameter) Utilized for the Polishing Experiments

	(A) Pitch/felt Yellow	(B) IC1000 Black	(C) Notched IC1000 Black	(D) Grooved IC1000 Yellow	(E) Grooved IC1000 Blue
					
Top Layer					
Material	Gugolz 73/felt	IC1000 PU	IC1000 PU	IC1000 PU	IC1000 PU
Pattern	none	none	notched	grooved	grooved
Thickness, t_{pad} (mm)	1.5	1.0	1.0	1.5	1.5
Modulus, E_{pad} (MPa)	8[a]	360	360	360	360
Bottom Layer					
Material	Foam	Foam	Foam	Foam	Foam
Thickness, t_{foam} (mm)	6.0	7.5	7.5	6.0	6.0
Modulus, E_{foam} (MPa)	2.2	0.13	0.13	2.2	5.3
Testing Hypothesis	Viscoplastic top leading to smaller figure degradation	Control for (C)	Notches leading to enhanced ripple removal with minimum surface degradation	Higher modulus underlayer: Optimize for RR and MSF ripple removal	Higher modulus underlayer: Optimize for RR and MSF ripple removal

PU = polyurethane pad
[a]Estimated from reported shore hardness of 79.



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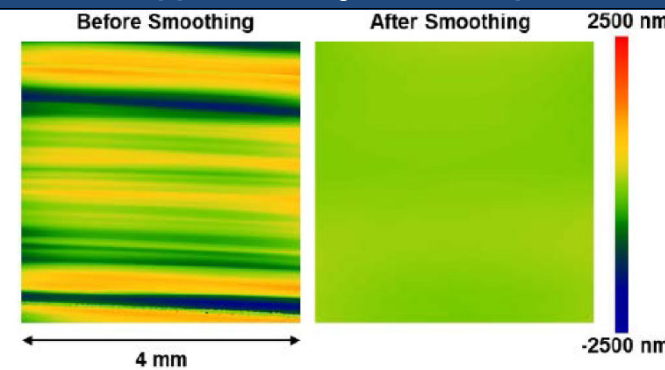
Ripple Convergence Example



Ripple reduction with smoothing

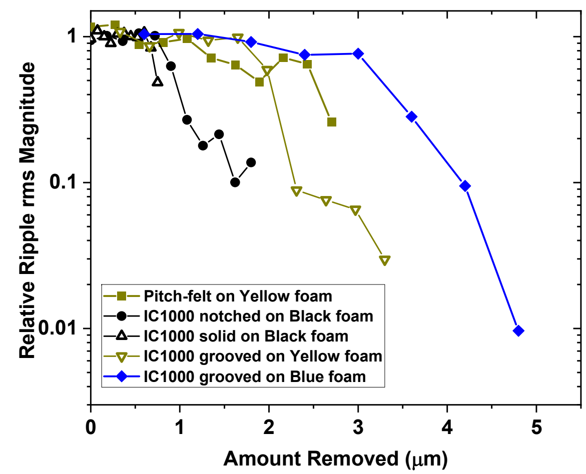
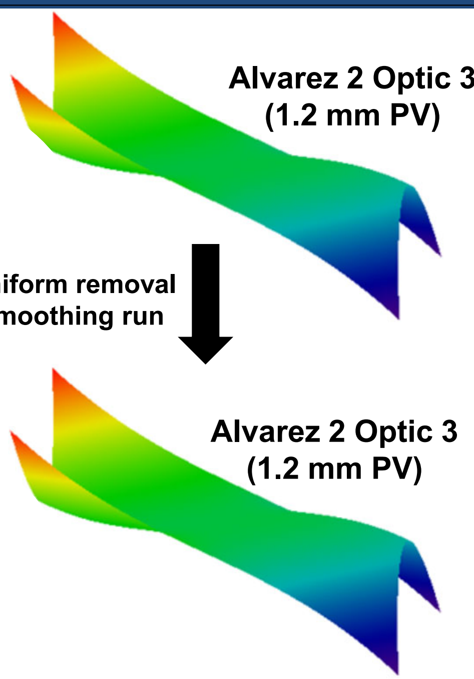


Figure degradation experiments surprisingly show that IC1000/blue foam smoothing tool is the most effective

Figure Degradation Experiment

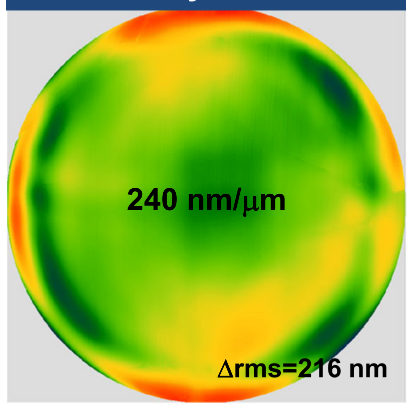


$$\Delta SF = (SF_i - SF_f)/\ RR$$

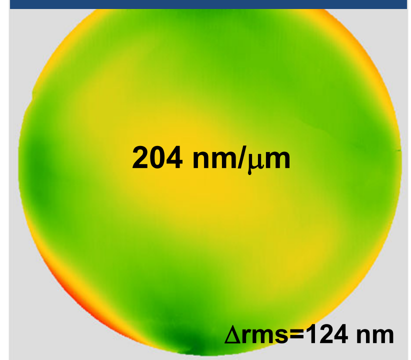
Initial Surface Figure | Final Surface Figure | Removal Rate

Normalized Figure Degradation Results (ΔSF)

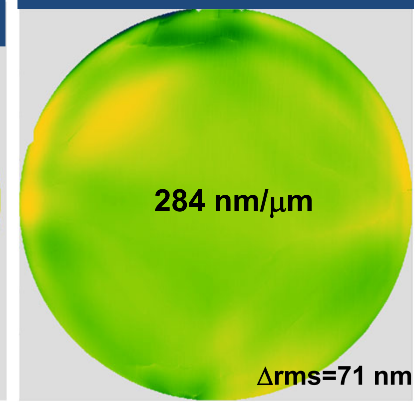
Pitch/felt/yellow foam



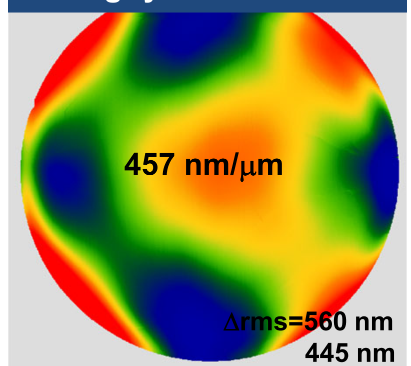
IC1000notched/black foam



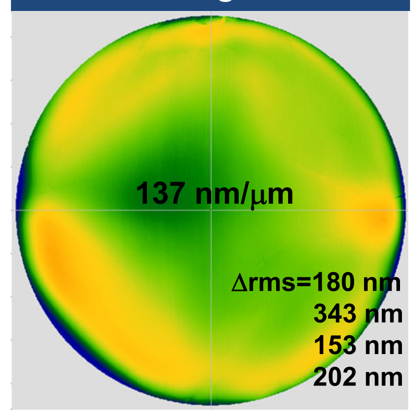
IC1000 solid/black foam



IC1000 solid gr/yellowfoam



IC1000 solid gr/bluefoam



Two tools & DC

-7 µm to 3 µm; 90 mm aperture

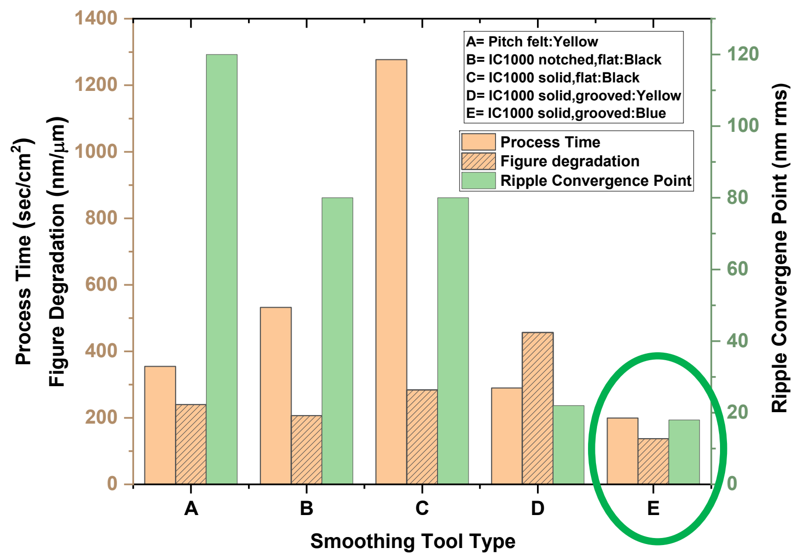
“Solid IC1000 grooved; Blue Foam” tool shows that best overall performance as a smoothing tool

Smoothing tool objective:

- **To rapidly perform gray-out & remove grinding ripples with minimal surface figure degradation**

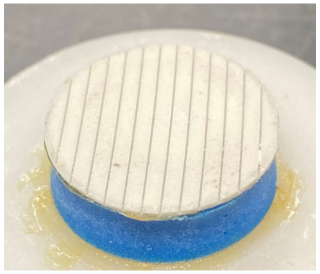
Metric	Description	Units	Target value
1) Process time	Related to removal rate	sec/cm^2	8 hrs/part
2) Figure degradation	Change in figure per removed amount	nm/μm	<1000 nm overall
3) Ripple Convergence point	Ripple roughness remaining	nm rms	<30 nm

Smoothing tool performance comparison



	Tool top	Tool Back	Rotation Rate	Process Time	Ripple Convergence	Figure degradation
			rpm	sec/cm2	rms (nm)	rms nm/um removed
A	Pitch felt	Yellow	250	355	120	240
B	IC1000 notched, flat	Black	250	532	80	207
C	IC1000 solid, flat	Black	250	1277	80	284
D	IC1000 solid, grooved	Yellow	250	290	22	457
E	IC1000 solid, grooved	Blue	250	200	18	137

Best performing smoothing tool

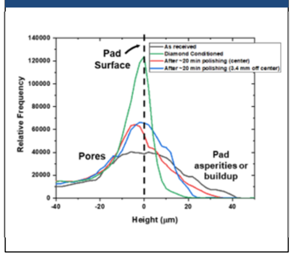


25 mm

Practical process rules/tools have been developed for more deterministic removal functions (magnitude & shape) and surface figure (including MSF errors)

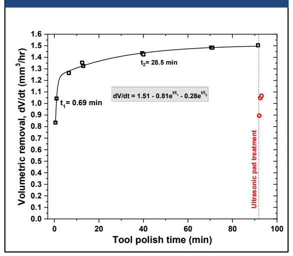
Increase determinism & stability

Diamond condition tool



Improves volume removal stability

Tool pre-polish

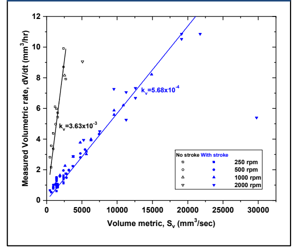


Improves volume removal stability

Precision tool length/ radius measurement

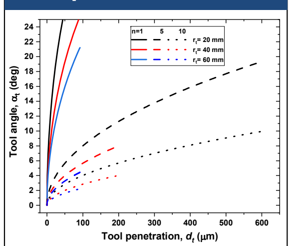
Improves volume removal & contact width precision

Volumetric Rule-of-thumb



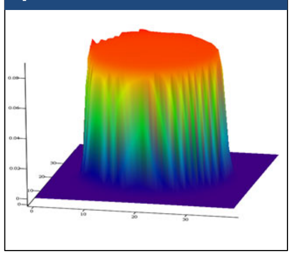
Determines optimum tool parameters (r_t, d_t, α_{to})

Buckling & trench shape rule-of-thumb



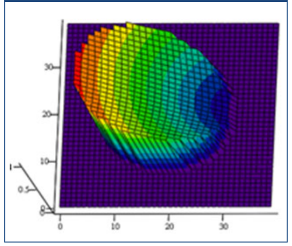
Determines optimum parameters (r_t, d_t, α_{to}) & trench cross section

Hydrodynamic pressure contribution



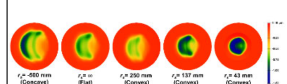
Determines ideal tool mechanical properties and foam thickness

3D Kinematics (relative velocity dist)



Predicts general shape of TIF

Workpiece-Lap Mismatch Model



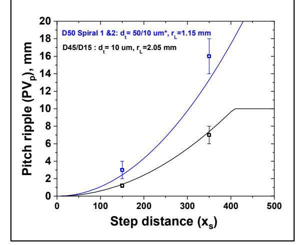
Improves precision in shape removal for curved surfaces

Reduce MSF errors

Tool porosity & PSD

Guides pad selection and expected PSD

Grinding Pitch ripple reduction

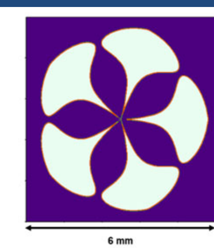


Reduces mid-spatial frequency (MSF) error

Smoothing tool design

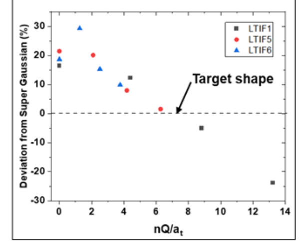
Reduces mid-spatial frequency (MSF) error w/o figure degradation

Tool Petalap



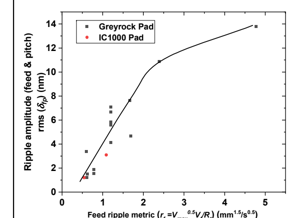
Controls trench cross section

Trench shape & polishing pitch ripple



Determines ideal TIF trench shape to reduce MSF error

Polishing ripple reduction



Determines process conditions to reduces MSF error

General process route for making a freeform optic

+ Strategy to improve workpiece quality and/or reduce process time

	1. Coarse Grind	2. Fine Grind	3. Bulk Etch	4. Grayout	5. Smoothing I	6. Figure Correction I	7. Smoothing II	8. Figure correction II
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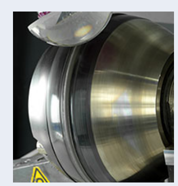
Example	Cup or Wheel, Diamond 50 um 	Cup or Wheel, Diamond 15 um 	Buffered Oxide Etch	CEO Belt 	Multi-layer Pad/foam, CeO_2 	Hemi Pad/foam, CeO_2 	Multi-layer Pad/foam, CeO_2 	MRF ribbon, CeO_2 
	Required	Required			Required	Required		Required

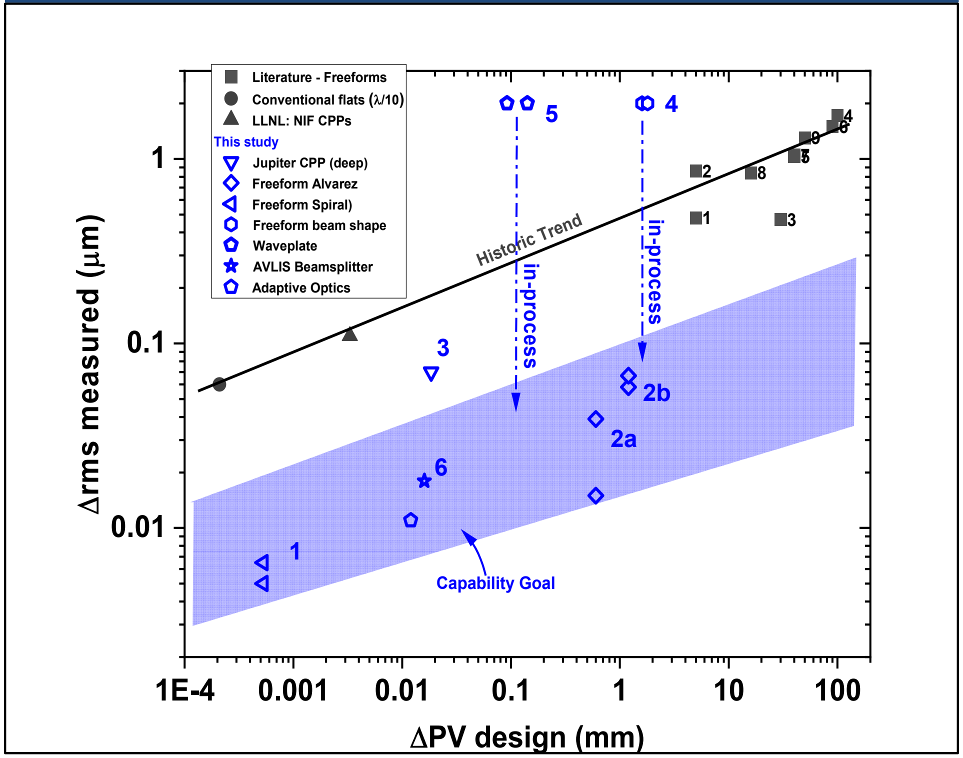
1) Improved Figure Correction
Increase TIF determinism & repeatability

2) Minimize mid-spatial generation
Reduce ripple magnitude

3) Improve Smoothing
Increase ripple convergence & minimized figure degradation

Our goal is to fabricate mm to cm scale PV freeform designs with ~10x reduction in typical deviation from target shape

Optical specification parameter space

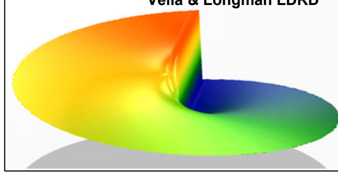


PV: Design Peak-to-valley of full optic
Δrms: Measured rms deviation from target surface figure

1. Spiral Optics

Δrms=5.0 nm

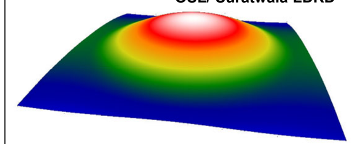
PV= 119 μm; 0.5 μm
Max slope=1.6 μm/mm
Quartz/Fused Silica (100-150 mm)
Vella & Longman LDRD



4. Beam Shapers

Δrms= In process

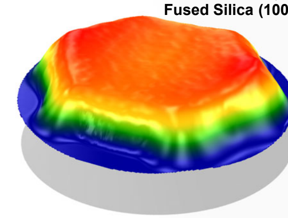
PV= 1500 μm
Max slope=37 μm/mm
Fused Silica (100 mm)
OSL/ Suratwala LDRD



7. Adaptive optic test

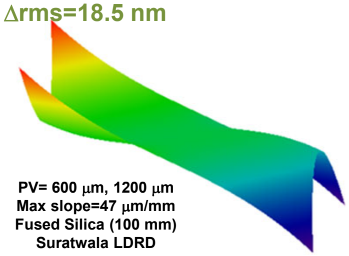
Δrms=11 nm

PV=12 μm
Max slope= XX μm/mm
Fused Silica (100 mm)



2. Alvarez Lens

Δrms=18.5 nm

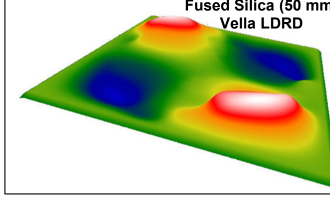


PV= 600 μm, 1200 μm
Max slope=47 μm/mm
Fused Silica (100 mm)
Suratwala LDRD

5. Waveplates

Δrms= In process

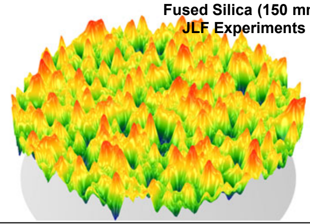
PV= 141 μm
Max slope=26 μm/mm
Fused Silica (50 mm)
Vella LDRD



3. JLF 2 mm CPPs

Δrms=70 nm

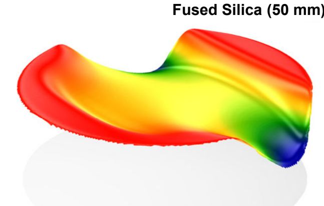
PV=18 μm
Max slope= 2.7 μm/mm
Fused Silica (150 mm)
JLF Experiments



6. Beamshaper

Δrms=18 nm

PV=16 μm
Max slope= XX μm/mm
Fused Silica (50 mm)



Ref: G. Matthews, SPIE 10448 2017; D. Walker, SPIE 5869 2005; Blalock, SPIE 9575 2015; Kong, IEEE 33(4) 2010; J. Menapace (Jupiter CPP)

For further details…

1. T. Suratwala, et. al. “Smoothing tool design and performance during sub-aperture glass polishing” *Applied Optics* 62(8) 2061-2072 (2023).

2. T. Suratwala, et. al. “Understanding the tool influence function during sub-aperture belt-on-wheel glass polishing” Applied Optics 62(1) 91-101 (2022).

3. T. Suratwala, “Understanding & reducing mid-spatial frequency ripples during hemispherical subaperture tool glass polishing” *Applied Optics* 61(11) 3084-3095 (2022).

4. N. Ray, et. al. “Modeling the hydrodynamic impact on the tool influence function during hemispherical subaperture optical polishing” *Applied Optics* 61(18), 5392-5400 (2022).

5. T. Suratwala, et. al., “Effect of workpiece curvature on the tool influence function during hemispherical sub-aperture tool glass polishing” *Applied Optics* 60(4) 1041-1050 (2021).

6. T. Suratwala, et. al. “Mechanisms influencing & prediction of tool influence function spots during hemispherical sub-aperture tool polishing on fused silica” *Applied Optics* 60(1) 201-214 (2020).

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