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   Recent Developments in the UltraForm Finishing and UltraSurf Measuring of Axisymmetric IR Domes

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   OptiPro demonstrated the polishing and measurement of a glass tangent ogive using their previously developed belt polishing equipment and their latest UltraSurf measuring equipment. The surface roughness of the new splice-less belts showed a 8 to 9 Angstrom surface roughness. New tool path options were also demonstrated that compensate for radial and angle errors during polishing. Test ellipsoids were polished with the new tool path correction that improved surface accuracy from 5.23 micrometers peak to valley to 1.38 micrometers. The UltraSurf non-contact metrology system was used to measure the surface accuracy of a small convex dome and the surface accuracy and thickness of the as-ground ogive.

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**Abstract**

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Recent Developments in the UltraForm Finishing and UltraSurf Measuring of Axisymmetric IR Domes

Mirror Technology SBIR/STTR Workshop
June 8, 2010

David Mohring, Mike Bechtold, Scott Bambrick
Scott DeFisher, Shai Shafrir, Jayson Tierson

OptiPro Systems, LLC
Ontario, NY 14519
(585) 265-0160
UltraForm Finishing and UltraSurf Measuring of Axisymmetric Domes

**OptiPro Systems, LLC**
**Ontario, NY**

**INNOVATION**

The UltraForm Finishing (UFF) and the UltraSurf platforms developed by OptiPro Systems deterministically polish and measure complex aerodynamic and conformal shapes made of difficult to manufacture glass, crystal and ceramic materials.

**ACCOMPLISHMENTS**

- 2008 OSA – Paul Forman “Excellence in Engineering Award” for first affordable Computer Controlled Optical Machining Center.
- Optical fabrication companies and prime contractor suppliers are embracing the new technology to cost effectively manufacture axisymmetric domes and optics for newly designed defense systems.
- The integration of the UFF (CNC controlled finishing platform) and the UltraSurf (Automated non-contact measurement device) provides a deterministic fabrication solution for a wide range of newly developed windows, domes and mirrors.

**COMMERCIALIZATION**

- **UltraForm Finishing (UFF)**: Asphere, Axisymmetric Dome, Freeform Polisher
  - Private Sector installations at Universities, Material manufacturers and Precision optical component manufacturers
- **UltraSurf**: Non-Contact Asphere, Axisymmetric Dome measurement platform
  - Private Sector Asphere and Dome Measurement System will be available by July 2010
- Primary market focus is on companies engaging in the optical fabrication and measurement of spherical domes, aspheres, parabolic mirrors, torics and conformal/freeform shapes.
- Private sector investment into the UFF and UltraSurf platforms has been through Beta site partners and production level machine purchases.
- OptiPro Systems, LLC has alliances with material manufacturing firms who require new manufacturing techniques to test and enhance their prototype components and determine the pathway to production level quantities.

**GOVERNMENT/SCIENCE APPLICATIONS**

- Contract Numbers W31P4Q-05-C-R048 and W31P4Q-04-C-R101 awarded by the Defense Advanced Research Projects agency (DARPA); and Contract Numbers N68936-10-C-0094 and N68936-08-C-0050 awarded by the Navy Engineering Logistics Office and NAVAIR.
- Toric, Acylinder and other freeform/conformal geometric shapes made from Si and SiC are potential applications.
- Fabrication methods: Corrective Optics for Conformal Windows and Domes, NAVAIR Contract N68936-09-C-0016.
- OptiPro’s deterministic fabrication and metrology solutions result in dramatic cost savings due to cycle time reductions and improved surface qualities.
- Materials Include: Spinel, ALON™, CeraLumina™, Si, SiC, ceramics & standard optical glasses

Date: June 8, 2010
Optical Fabrication History

- **SX Optical CNC Machining Centers**
  - Defense Advanced Research Projects Agency, DARPA
  - Developed with the Center for Optics Manufacturing, Kodak and DARPA
  - Machines sold to fabrication companies and DOD Prime Contractors

- **ePX Spherical High Speed Optical Dome Polisher**
  - High Speed Polishing of JAGM Spinel and AlON Domes
  - Machines sold to fabrication companies and DOD Prime Contractor vendors

- **UFF UltraForm Finishing 5-Axis Polisher**
  - Initial prototype developed with Army Contract DAAE30-95-C-0091 SBIR
  - CeraLumina (PCA) Ogive production with Navy Contract N68936-08-C-0050 SBIR
  - Machines sold to fabrication companies and DOD Prime Contractor vendors
  - Materials include: Optical Glass, PCA, ALON, Spinel, Si, SiC, IR Material
  - Shapes include: Domes, Aspheres, Ogive, Non-Axisymmetric freeform

- **UltraSurf 5-Axis Non Contact Metrology System**
  - Development with Naval Air Systems Command Contract N68936-07-C-0046 SBIR
  - Prototype platform for Dome, Ogive, Asphere and Freeform/Conformal surfaces
CNC Fabrication Equipment

- eSX
- ePX
- UFF
- SXL

Dome
Ogive
Conformal

Large UFF
## Materials

<table>
<thead>
<tr>
<th></th>
<th>CeraLumina™</th>
<th>Spinel</th>
<th>Sapphire</th>
<th>ALON™</th>
<th>SiC</th>
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</thead>
<tbody>
<tr>
<td>Grain Size (microns)</td>
<td>0.4</td>
<td>100-200</td>
<td>2-5, 40-100</td>
<td>150-250</td>
<td>0.2 – 4.5</td>
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<tr>
<td>Hardness (Hv) Kgf/mm²</td>
<td>2284</td>
<td>1350</td>
<td>1700</td>
<td>1560</td>
<td>2800</td>
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<tr>
<td>Fracture Toughness (K) MPa•m1/2</td>
<td>3.3</td>
<td>2.2</td>
<td>3.6</td>
<td>2.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>

### Standard Optical Material
- ULE & Zerodur
- Fused Quartz
- BK7 & Pyrex

### Finishing Importance
- Transmissive and reflective surface wavefront
- Strength enhancement in brittle materials
- Contamination issues during coating
Dome High Speed Polishing Challenges

- Material removal & cycle time
- Grain highlighting
- Wavefront distortion
- Determinism

- Fixtures
- Spindle loads
- Tool Clearances
- 1:1 tool to part size
High speed polishing platform

Machine Features
- High Torque Spindles
  - 1.3 Kw to 5.0 Kw
- High Pressure thru the tool slurry
- Tool Truing Process with variable toolpath & infeed
- Work envelope optimized for dome process fixtures
- Dome polish software customization
  - Easy Setup
  - User interface design with motion feedback & control
  - Work piece/Tool collision detection
Hemi-Dome Fixtures

Polish grinding damage out of a 7” diameter dome
90-120min
Wavefront over 70mm aperture

2 mm thick Dome

½ wave PV

.06 wave rms
UltraForm Finishing

- 5 axis CNC Platform: 3 Linear X,Y,Z and 2 Rotary B and C
- Industrial Fagor 8070 CNC Control with User Friendly GUI
- On-Board metrology for removal function and preliminary part measurement
- Bound/Fixed abrasive with Coolant & Slurry containment - feed systems
UFF Solution

- Polish, fine ground spherical, aspheric, freeform and plano surfaces (*No pre-polishing requirements*)
- 2 different length arms, the long extension arm of the wheel allows finishing inside deep concave ogive missile domes
- Wide variety of Ultrawheel durometers and diameters and abrasive belts
- Long belt lengths with a variety of finishing materials and slurries allows for a more deterministic polishing process
- On-board metrology for work piece and removal function analysis
- Intuitive Graphical User Interface with surface correction algorithms
UltraForm Finishing polishes using a precision controlled belt
- Fixed abrasive cerium oxide, alumina and diamond belts
- Conventional polyurethane pad belts with abrasive slurries
Laser Probing the tool insures process repeatability
  - The exact location of the tool in the X and Y axis
    - This allows for the best possible centering
  - The exact size and shape of the tool
    - This allows for the tool to be modeled as accurately as possible
UFF removal function is measured in situ w/noncontact optical sensor

- Non-contact chromatic confocal imaging optical sensor (collimated white light) for 3D surface metrology
- Innovative non-contact technique for 3D metrology recommended by the ISO 25178 international standard.
Glass Tangent Ogive 2009

- Block on ID Fixture
- Rough and Fine Grind OD
- Move Fixture with Ogive to UltraForm Polishing Machine
- Polish OD
- De-block

June 8, 2010
Glass Tangent Ogive 2010

Rough and Fine Grind OD

Move Fixture with Ogive to UltraForm Polishing Machine
Fused Quartz Glass Ogive processed from solid block to expedite the work piece requirements for metrology tests
Recent Developments in UFF

- New Splice-less belt designs
- R-Theta error correction algorithm solution
- Conformal optics Ellipsoids, Toroids and Aspheric Cylinders using raster algorithm solution
- Cost reduction in production aspheres
Splice-less Belts

- BK7
- Spray on slurry
- 8-9 A RMS surface roughness
Tool Path Options includes “R” & “Theta” error corrections

**R-Theta**

- Tool traverses left to right
- Best for rotationally symmetric shapes

- “R” Errors
- “Theta” Errors
R-Theta results example for BK7

• Initial Surface
  • PV: 0.793 \( \lambda \)
  • RMS: 0.208 \( \lambda \)

• Final Surface
  • PV: 0.119 \( \lambda \)
  • RMS: 0.018 \( \lambda \)
Results – Ellipse Raster 2009

Simulation: 5.1μm

GPI PV: 5.23μm
Results – Ellipsoid Raster 2010

Ellipsoid From 2 Years Ago
Cost Reduction in Production Aspheres

Define-AspherePro

Grind-eSX or SXL 5 axes grinder

Measure-OptiTrace 5000

Finished Asphere

Polish- UltraForm Finishing (UFF)

Transfer measured data to UFF

1-2 polishing iterations and ship!
UltraSurf Metrology

- 5-Axis Non-Contact Measuring System
- Utilizes Various Non-Contact Probes
- All Air Bearing Axes
- Linear Motors
- Brushless DC Rotary Motors

<table>
<thead>
<tr>
<th>Axis:</th>
<th>X, Y, Z</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel:</td>
<td>200 mm</td>
<td>360°</td>
<td>360°</td>
</tr>
<tr>
<td>Resolution:</td>
<td>5 nm</td>
<td>0.018 second</td>
<td>0.009 second</td>
</tr>
<tr>
<td>Accuracy:</td>
<td>25 nm</td>
<td>0.09 second</td>
<td>0.045 second</td>
</tr>
<tr>
<td>Max. Velocity:</td>
<td>30 mm/s</td>
<td>6 RPM</td>
<td>6 RPM</td>
</tr>
</tbody>
</table>
UltraSurf Dome, Ogive and Freeform
Typical UltraSurf Measurement

Concentric rings on a rotationally symmetric part

Spacing Can Be Dynamically Controlled
### Optical Probes

Currently testing and implementing these 2 non-contact probe styles. Other probes may be utilized on the UltraSurf.

<table>
<thead>
<tr>
<th>Probe</th>
<th>Measurement Range</th>
<th>Focal Distance</th>
<th>Focal Point Diameter</th>
<th>Angular Tolerance</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>Scan Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumetrics</td>
<td>12 µm – 15 mm</td>
<td>25 mm or 50 mm</td>
<td>100 µm</td>
<td>2 °</td>
<td>200 nm</td>
<td>30 nm</td>
<td>1 - 50 Hz</td>
</tr>
<tr>
<td>STIL</td>
<td>300 µm</td>
<td>5 mm</td>
<td>10 µm</td>
<td>25 °</td>
<td>90 nm</td>
<td>10 nm</td>
<td>50 - 2000 Hz</td>
</tr>
</tbody>
</table>

**Probes:**
- OptiGauge
- OP300VM
Process Flow For Measurement

Mount Part
- Use any desired method

Enter Shape Parameters
- Radius
- Coefficients
- Point Spacing

Center/De-Tilt
- Easy to use manual alignment table

Sensor Alignment
- Using the non-contact probe

Run the Scan
- UltraSurf automatically performs measurement

View the Data
- UltraSurf software reconstructs the data using triangle-based interpolation
Small Dome, Convex Surface Error

UltraSurf

Stitching Interferometer

UltraSurf CX Dome Surface Error

Stitching Interferometer CX Dome Surface Error
Large Dome, Surface Error

Convex

Concave

Surface Error Projected over Dome
Large Dome, Thickness

Overall Dome Thickness

Curve Mismatch, 97 µm
Wedge or Piston

Thin Center, Thick Edge
Ogive Results

Large, Fine Ground Ogive
Ogive Surface Results

Outside Surface Error

Inside Surface Error

Note Grinding Fixture Features
Ogive Thickness Result

Isometric view of thickness map

Top Down View
Collaborative Cost Optimization

Optical Designers → Material Manufacturers

Optical Fabrication & Metrology Equipment

Optical Manufacturing Vendors → Prime Contractors
Workpiece Diameter Range of 10-500mm, max weight of 170 kg
- Work Spindle 1-250 rpm
- Tool Spindle 100-12,000 rpm
- Quickchange Tooling
- Vacuum Workholding
- 48” x 28” x 20” XYZ Axes travels
- B-Axis ±90°, C-Axis 0° to 360°
- Automatic Tool Changer
- Tool/Workpiece Probe
- User Friendly Operator Screens
- Built in Electronic Spherometer
- Ethernet communications
- Fagor 8070 5-axis CNC Control

Online in July 2010
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