MRF and Subaperture Stitching: manufacture and measure more optics, more accurately

Presented By:
Jean Pierre Lormeau
QED European Business Manager
QED Technologies International Inc.
www.qedmrf.com
Presentation topics

🔹 MRF:
  - A Little History
  - MRF general principles and benefits
  - Examples of applications

🔹 Stitching Interferometry
  - Motivation
  - General principles
    - Spheres
    - Aspheres
  - Examples of applications
Early Evolution of MRF

From R&D to Commercial Product

1993

QED Q22 - X/Y

Prototype

1996

COM Trough Machine

1998

QED Q22 Prototype

2000
MRF Platform Portfolio

Evolution to Larger Optics…

~100 mm

~200 mm

~400 mm

~1000 mm

~750 mm

~2000 mm
Magnetorheological Finishing (MRF®)

What is MRF?
- Very deterministic polishing & figuring technology
- MRF tool is stable, conformable & predictable w/ high peak removal rates
- Part Ø from ~5 mm to ~2 m
- Multi-axis CNC machine bases
  - Rotational polishing
  - Raster polishing

**Tool is based on fluid**
- Conforms perfectly to any shape
- Fluid can be monitored & maintained

**Fluid changes viscosity in magnetic field**
- Stiffened near optic to create high shear removal function

**High automated, metrology-driven process**
How MRF Works…

- Random arrangement of particles
- Field creates stiff structure of iron particles
  - Forces water and abrasives to top, thin layer
- Converging gap is created
  - Cores are formed, creating sheared layer of fluid
  - Pressure gradient is formed
  - High-velocity, shear-based removal is created
Schematic of MR Finishing Interface

MRF “Spot” Creation

Lens
Moving Wall
MR Fluid

Magnetic Field

Removal spot
How MRF works…
Forces acting in polishing

**Conventional Polishing**

- Abrasive Particle
- Load
- Workpiece
- Pad

An abrasive particle is embedded in a rigid pad, which supports the particle load. The normal force (~0.01 N) is significant enough to cause surface indentation and scratching.

**MRF**

- Workpiece
- Hydrostatic Pressure
- Magnetic buoyant force
- MR Fluid Core

100 - 150 μm

Because the particle/surface contact area is small, the hydrostatic pressure results in insignificant normal force (~10⁻⁷ N). The buoyant force (~10⁻⁹ N) is also too small to cause appreciable indentation.
Understanding Potential for Corrosion

Specific surface area of iron particles ~ 1m\(^2\)/g

Surface area of iron particles in 1 liter of MR fluid ~ 4000 m\(^2\)

Surface area of a football field = 5500 m\(^2\)

The surface of iron particles is constantly attacked by abrasive particles resulting in intensive erosion and corrosion.
MR Polishing Fluid Composition

- The stabilizer is a key element in MR fluid development.

- It helps to resolve a contradiction between requirement high concentration of iron particles low fluid viscosity.

- Also, it is responsible for fluid sedimentation stability, re-dispersability, corrosion control.
Family of Aqueous MR Polishing Fluids

With one charge of fluid removal rate stability is provided for at least 3 weeks
How MRF works…
Fluid delivery system

MRF Delivery system is “heart” of machine
- Creates stable, continuous, flow of MR fluid
MRF – Removal mechanism summary:
Shear stress creates material removal!

- MRF is fluid based
- MR Fluid properties are precisely controlled
- MRF tool is subaperture
- The MRF subaperture tool is insensitive to Z-Axis errors
- MRF material removal mechanism is based on shear stress
- MRF end result is predicted and achieved
What Can MRF Do?

- **Improve** form/figure/waveform
  - High convergence
    - 5-10x improvement in 1 iteration
  - $\lambda/20$, $\lambda/50$...as good as your metrology

- **Improve** roughness
  - Typically ~ 0.5 nm RMS

- **Improve** surface integrity
  - Remove subsurface damage
  - Remove stress
  - Increase laser damage resistance
Examples of MRF applications

- Large Face Sheet
- 300mm Si Wafers
- Shear Plate TWF Correction
- Dove Prisms
- Steep Concave
- Laser Rods
- Lightweight Primary Mirror
- Lightweight SiC Mirror
- Meter-Class Aspheres
- Novel Geometries
- Steep Aspheres
- High Aspect Ratio Optics
- Calcium Fluoride
- Sapphire Windows
- Off-axis Zerodur Component
Where does MRF fit in?

- Glass/Plastic Molding
- Aspheric Grinding
- Single Point Diamond Turning (SPDT)
- Computer Controlled Polishing (CCP)
- Magnetorheological Finishing (MRF)
- Ion Beam Finishing (IBF)
Typical correction of form error

Polishing

Material: Borofloat C-10+ fluid
50 mm wheel
2 mm edge exclusion

- 50 mm convex sphere, RC 99.96. Boro Glass
- Figure $< \lambda/10$ over full aperture (PV = 0.0707 wv)
- Figure $< \lambda/20$ over 49 mm (PV = 0.044wv, 0.5 mm edge exclusion)
Convex CaF$_2$ Sphere $\Phi \sim 25$ mm, $R \sim 310$ mm

**Before MRF**

PV = 0.171 wave
RMS = 0.026 wave

**Final Figure**

PV = 0.073 wave
RMS = 0.006 wave

4 Iterations, 20 min
10 mm phase correctors, create a perfectly bad surface

**Desired Figure**
2.6 μm PV
818 nm rms

**Actual Figure**
2.6 μm PV
811 nm rms

**Difference Map**
50 nm PV, 9 nm rms
Example Rod Correction

- Transmitted wavefront improved by ~9x
- MRF offers robust, reliable process for correcting material inhomogeneities

**Before**

TWF PV = 0.44\(\lambda\)

**After**

TWF PV = 0.05\(\lambda\)
Corrected rods dramatically improve laser performance

- Improvement in far field intensity distribution of CLARA laser system
  - MRF induced perfectly bad surface on single rod face to compensate for inhomogeneity
  - System divergence went from unusable to nearly diffraction limited
NIF Continuous Phase Plates (CPP)
Capability Unique to MRF

- Computer generated topographical profiles are designed to achieve required energy contours for laser beam
- 430x430 mm fused silica plates with “mountains & valleys” “microns” high and “mm-cm” wide
- A good example of a “perfectly bad surface” that MRF can help make
CPP Imprinting Process
Step #1 – Large Spot – Low order imprinting

- 150 mm square sample (~1/3 x 1/3 of a whole plate)
- Initial polishing with large wheel imprints “lower” order error
  - High removal rate “roughs out” the CPP pattern
  - Tool size: ~30 mm
  - Up to 6 \( \mu \)m of removal in some locations on the surface
CPP Imprinting Process

Step #2 – Small Spot – Imprinting the fine features

Final Polishing with small wheel imprints “higher” order error, tool size: ~3-4 mm
Q22-2000F: Meter-class figure correction

- MRF polishing of primary mirror
- **Mirror Details**
  - Outer Diameter: ~1.1 m (~43”)
  - Inner Diameter: ~0.1 m (~4”)
  - Concave Radius of Curvature: ~3 m (~120”)
  - Material: Zerodur-like
**Q22-2000F: Meter-class figure correction**

- Only 20 hours of polishing time
- Only 2 iterations of MRF

<table>
<thead>
<tr>
<th>Initial</th>
<th>Final</th>
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<tr>
<td>RMS = 80 nm (~l/7)</td>
<td>RMS = 9 nm (~l/70)</td>
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*Fast Convergence on Meter-Class Optics!*
**SPDT + MRF**

- **2-step process only**
- **Fully Deterministic**
- **For Turnable materials**
  - E.g. higher precision IR

Diagram showing the process:
- Molding
- Grinding
- SPDT
- CCP
- MRF
- IBF

Steps:
- Blank
- Near Net Shape
- Precision Optic
- High Precision Optic
Concave SPDT Si Sphere $\phi \sim 17 \text{ mm}, R \sim 20 \text{ mm}$

Before MRF

**S/N 2**

Figure After 1 iteration

4.5 min

**S/N 5**

Figure After 1 iteration

3.9 min
MRF Removes the Diamond Turning Marks

Before MRF

After MRF

Color
No Color
Latest MRF Development

- **Q-flex MRF Platform**
  - Modular
  - Production oriented

- **Flexible optics production**
  - Plano, Sphere, Asphere,
  - Cylinder, prism
  - Freeform
Motivation for Sub-aperture Stitching Interferometry

“If you can’t measure it, you can’t make it”

- Corollary: the quality and flexibility of your measurement limits the quality and variety of optical surface you can make – particularly if you have an exceptional deterministic polishing tool at hand...

- And therefore we want our metrology to be:
  - Full aperture, for deterministic correction of the whole surface
  - Accurate, to achieve tighter optical specifications
  - High resolution, to correct edges and other small features
  - Flexible, to minimize custom tooling and lead time even for aspheres

- Subaperture stitching can address all these needs
Full vs. sub aperture metrology

Myth #1: If all subapertures pass spec, the full aperture passes

- Subaperture QA may be appropriate for a few applications
- Full aperture metrology necessary for deterministic finishing and quality insurance

Subapertures (all pass a $\lambda/10$ PV, $\lambda/100$ rms spec)

On axis
- PV 34
- rms 5.7

Off-center (up)
- PV 38
- rms 4.5

Off-center (right)
- PV 44
- rms 5.4
Are you measuring what you think you are?

**Myth #2: if the measurement is \( \lambda/10 \), the part is \( \lambda/10 \)**

Two-sphere calibration

- **PV**
  - 48
  - 26
- **rms**
  - 8.3
  - 2.0

Difference from SSI reference

full aperture  mismatch  reference
QED Stitching History

- QED has successfully developed subaperture stitching interferometry for a variety of uses:
  - 2004: SSI® for large aperture spheres/flats
  - 2007: SSI-A® for mild aspheres without null lenses
  - 2009: ASI® for high-departure aspheres without null lenses
Subaperture Stitching systems

- Precision Multi-axis motion control platform
  - SSI-A and ASI w/o VON: 6 axes
  - ASI: 11 axes
- 4” or 6” interferometer
- QED control software: automation + advanced algorithms + Variable Optical Null technology

Stitching advantages

- Cost-effective measurement of larger optics, full aperture
- Automatic, inline calibration of systematic error
- Increased lateral resolution
- Measures aspheres without dedicated nulls!
SSI & ASI measurement process for spheres

1. Specify surface to test
2. Select transmission sphere and define lattice
3. Locate central null
4. Move to lattice position
5. Auto-null
6. Measure
7. Stitch

Fully automated process
The SSI & ASI measure spherical parts that a 6” interferometer cannot test

- **Large numerical aperture**
  - Ø 36 mm R -18 mm
    - NA: 1 (90°)
  - Ø 36 mm R 18 mm
    - NA: 1 (90°)
  - Ø 9 mm R 4.5 mm
    - NA: 1.0 (90°)
  - Ø 59 mm R 30 mm
    - NA: 0.98 (79°)

- **Large clear aperture**
  - Ø 300 mm
    - R 350 mm
  - Ø 225 mm
    - R 350 mm

- **Higher CA**
- **Higher NA**

*conventional capability*
- 4” interferometer
- 6” interferometer

*SSI capability*
- 4” recommended
- 6” recommended

*NA=1 (convex hemisphere)*

radius of curvature (mm)
Aspheric testing

- State of the art with out stitching – interferometer null test
  - Standard methods require dedicated test optics to be made
    - Computer-generated hologram (CGH)
    - Refractive, or sometimes reflective, null
  - Disadvantages: Lead time, cost, accuracy, and convex parts

- Stitching employs a non-null test for aspheres
  - Flexible: no dedicated null optics needed!
  - Current ASI capability up to ~650 micrometer of departure from best fit sphere
    - More possible as QED continues to develop the technology
What is a non-null test?

- The reference wavefront does not match the surface
  - A perfect surface produces fringes in a non-null test
  - Test rays will not trace back on themselves ⇒ “retrace” error

Null test: sphere

Null test: asphere

Non-null test
SSI-A The first solution for aspheres

No null optics required!!
Increasing measurable aspheric departure: how does it work?

 Three key issues to address
  - Fringe resolution – use slower TSs (higher magnification) & stitch
  - Retrace error – automatically model and compensate w/ stitching
  - Remove nominal shape – precise motion + auto-compensation

Asphere w/ ~80 λ departure from bfs (~320 λ from vertex sphere)
SSI-A example & cross test with CGH

- R -310 mm; CA 110 mm; ~30 l from bfs.
- 33 subapertures (10-15 minutes) w/ f/3.2 TS
- Good agreement with CGH cross test
  - but higher resolution & easier calibration!

Stitch map (+lattice)
SSI-A example (2)

- R = 226 mm; CA 100 mm; ~25 l from bfs.
- Secondary mirror for the PICTURE / SHARPI sounding rocket programs
- Good agreement with vendor’s null test
  - But again, note the finer structure resolved

Null test data courtesy of Jay Schwartz, L3-SSG-Tinsley

Test part courtesy of Scott Antonille, NASA Goddard

Scale +/- 12.5 nm

Conic null test

Stitch map
ASI: Variable Optical Null Device

Interferometer

Interferometer

Variable Optical Null device
Our Particular VON

- Counter-rotating optical wedges

- By varying the total wedge angle and tilt, the VON produces low-order aberrations:
  - Astigmatism, coma, trefoil

- Flat surfaces only, simple mechanical motions
Variable Optical Null Configurations

- No Tilt
- No Wedge
- Tilt only
- Tilt and Wedge

Small spherical
mostly astigmatism
mostly coma
coma and astigmatism
Sub-aps with or without VON

Without VON

With VON
1000 Wave Asphere Example

- 118 mm CA
- 72 mm vertex radius
- 656 micron departure from best fit sphere
- High NA and aspheric departure make this asphere difficult to measure with other techniques
Impact of the VON on the example

- Only need to match the low-order aberrations of each subaperture, producing resolvable fringes over entire field
- Combine measurement of residuals with nominal wavefront of VON
Actual subaperture measurements show good agreement with model (small differences due to alignment, figure error on part)

Use stitching algorithms to refine the nominal wavefront
Example of High Resolution Stitch

2k x 2k stitch
2.6 million pixels!

Center 10mm
(data refitted)
Lateral Resolution Comparison

Center 10mm aperture with 36 Zernike terms removed

400 x 400 pixel stitch

2000 x 2000 pixel stitch
Lateral Resolution Comparison

10mm aperture offset by 15mm, with 36 Zernike terms removed

400 x 400 pixel stitch

2000 x 2000 pixel stitch
Results with MRF® Correction

- Part had low figure error, but high mid-spatial frequency content
- ASI + MRF successful at measuring and improving the surface

Initial condition (rms = 7.4nm)

After single MRF correction (rms = 2.6nm)
Conclusion

The use of subaperture stitching interferometry allows for:

- Full aperture coverage on 200 mm+ lenses
- Higher lateral resolution
- Increased accuracy
- Aspheric measurements without dedicated nulls up to 1000 waves of departure from best fit sphere for the ASI

Combining Subaperture Metrology capability with the unique efficiency and performance of MRF provides unmatched capabilities both in R&D and production.