Expedited Fabrication of SiC Mirrors

Approved for Public Release
09-MDA-4521 (1 JUN 09)
377ABW-2009-0561 (1 JUN 09)
Third Wave Systems
Minneapolis, MN USA
AdvantEdge Machining Modeling Environment

**AdvantEdge FEM**
- Micro/detailed cutting tool analysis
- Forces, temperature, heat flow
- Chip formation
- Work hardened layer, residual stress

**AdvantEdge Production Module**
- Macro/process level analysis
- Cycle time reduction
- Maximizes machine utilization
- Load balancing
- Chatter
Customer Profile

Primarily aerospace, defense, automotive, and tooling companies looking to:

• Reduce machining cycle time
• Improve part quality
• Reduce weight
• Improve costs
TWS Productivity Center
Plymouth, MN

- Part design
- First part prototype production
- Material modeling
- Simulation validation
- Residual stress characterization
- Tool life testing
- Machinability testing
- Computing resources

Mori Seiki NH 6300
## Government Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Awarded</th>
<th>Source</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>SBIR Phase I - Nickel Alloy Machining for Jet Engines</td>
<td>2009</td>
<td>DLA</td>
<td>Awarded</td>
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<tr>
<td>STTR Phase II - Freeform Optical Systems for Defense Systems Optics</td>
<td>2009</td>
<td>MDA</td>
<td>In Process</td>
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<tr>
<td>SBIR Phase II - Composite Drilling</td>
<td>2009</td>
<td>DLA</td>
<td>In Process</td>
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<tr>
<td>SBIR Phase III - Titanium Integral Bladed Rotor (IBR) Machining Transition Program</td>
<td>2008</td>
<td>Air Force</td>
<td>In Process</td>
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<tr>
<td>SBIR Phase II - Large Web, Deep Pocket Titanium &amp; Aluminum Bulkheads</td>
<td>2008</td>
<td>NAVAIR</td>
<td>In Process</td>
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<tr>
<td>SBIR Phase I - Conformal Sensor Window</td>
<td>2008</td>
<td>NAVAIR</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I - Precision Aluminum Milling Techniques</td>
<td>2008</td>
<td>NAVSEA</td>
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<tr>
<td>SBIR Phase I - Composite Drilling</td>
<td>2007</td>
<td>DLA</td>
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<tr>
<td>SBIR Phase I - Innovative Computer Aided Manufacturing</td>
<td>2007</td>
<td>Army</td>
<td>Complete</td>
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<tr>
<td>STTR Phase I - Freeform Optical Systems for Defense Systems Optics</td>
<td>2007</td>
<td>MDA</td>
<td>Complete</td>
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<td>BAA - Advanced Modeling Technology for Large Structure Machining</td>
<td>2006, 2007</td>
<td>Army</td>
<td>Complete</td>
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<td>SBIR Phase II - Expedited Fabrication of Conformal Window for ABL</td>
<td>2006</td>
<td>MDA</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I and II - Thin Wall Bulkhead &amp; Firewall Machining</td>
<td>2005, 2006</td>
<td>NAVAIR</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I and II - Titanium Integral Bladed Rotor (IBR) Machining</td>
<td>2005, 2007</td>
<td>Air Force</td>
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<tr>
<td>SBIR Phase I - Improved Core Milling Process</td>
<td>2005</td>
<td>Navy</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I and II - Residual Stress and Part Distortion Modeling</td>
<td>2003, 2005</td>
<td>NSF</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I and II - Machining of Ceramic Materials</td>
<td>2003, 2004</td>
<td>MDA</td>
<td>Complete</td>
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<tr>
<td>SBIR Phase I and II - High Speed Machining of Titanium</td>
<td>2002, 2004</td>
<td>Air Force</td>
<td>Complete</td>
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<tr>
<td>Metals Affordability Initiative</td>
<td>2001</td>
<td>Air Force</td>
<td>Complete</td>
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<tr>
<td>ATP (Advanced Technology Project) - Hard Turning Project</td>
<td>2000</td>
<td>NIST</td>
<td>Complete</td>
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Expedited Fabrication of SiC Mirrors

**Business Approach:**
- Partner with Dr. John Patten and Western Michigan University

**Innovation:**
- Apply ductile mode machining (DMM) methodology to the production of optical quality ceramic surfaces

**Objectives:**
- Demonstrate feasibility of DMM by producing 6” diameter SiC mirror.
Expedited Fabrication of SiC Mirrors

**SBIR Phase II Project Goals**

- Develop and validate modeling technology for production-level ductile mode machining of window and mirror materials
- Fabricate scaled prototype window via DMM
- Determine production-level process conditions for SiC mirror and fabricate via DMM
Expedited Fabrication of SiC Mirrors

DMM Benefits

• Reduce fabrication times by 50% by reducing/eliminating lapping, grinding, polishing for mirrors

• Virtually eliminate surface and subsurface flaws

• Achieve higher part quality with surface roughness down to 10 nm RMS range

• Apply to mirrors, lenses, radomes, semi-conductor substrates
Ductile Mode Machining Overview

- Machine below critical feed threshold (<100nm)
- Brittle materials behave in ductile manner – similar to metals
- Higher material removal rate than conventional grinding/lapping/polishing
- Diamond tools
- Superior surface finish
Ductile Mode Machining Overview

**Ductile:**
Long continuous chips

**Brittle:**
Powdery chips

<table>
<thead>
<tr>
<th>Material</th>
<th>DMM Threshold</th>
<th>Silicon Nitride</th>
<th>Silicon</th>
<th>Silicon Carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 40 µm</td>
<td>&lt; 1 µm</td>
<td>&lt; 500 nm</td>
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</table>
DMM Process Benefits

- Reduced Prototyping Times by 50% for Windows and Mirrors
- Higher Part Quality w/ Surface Roughness in the 0.010-0.050 μm Range
- Improved Manufacturing Yields
- Reduced Cycle Time of Brittle Part Manufacturing
- Virtually Eliminate Surface and Subsurface Flaws

ENABLING TECHNOLOGY

Third Wave AdvantEdge FEM Machining Model
- Ductile Mode Pressure-Sensitive Brittle Material Constitutive Model
- Brittle Mode Continuum Damage Model
- Micrometer Machining Process Model

TARGET MACHINING PROCESS

- Ductile mode machining of brittle materials

PHYSICS

High pressure induced phase transformation

Metallurgical phase of brittle material (ductile)

Brittle mode

Poor Part Quality and Process Performance
Western Michigan University Test Facility

Universal Micro-Tribometer (UMT)

SiC disc immersed in polishing fluid

Tool clamped on holder

SiC disc holding fixture
Ductile Regime Modeling

- Drucker-Prager Model
- Yield surface is pressure dependent – critical for modeling material with disparate tensile and compressive yield strengths
- Johnson and Holmquist (2002) have used similar model in FEM simulations of advanced ceramic armor impact
Simulations of Test Cutting Conditions

**SiC CVD Machining Simulations**

- Simulations show change in pressure contours with change in rake angle

*Ductile Mode Chip*
Simulations of Test Cutting Conditions

SiC CVD Machining Simulations

- Effect of different feeds on pressure for -45 degree rake tool

Ductile Mode Chip
Simulations of Test Cutting Conditions

SiC CVD Machining Simulations

- Effect of different feeds on pressure for -60 degree rake tool

Ductile Mode Chip
Production of 2” Prototype SiC Mirror

Surface finish achieved: <35nm

<table>
<thead>
<tr>
<th>Sample</th>
<th>CVD Coated 2” SiC (POCO)</th>
</tr>
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<tbody>
<tr>
<td>Tool Used</td>
<td>Single Crystal Diamond Tool 3mm Nose Radius</td>
</tr>
<tr>
<td>Lubricant Used</td>
<td>Master Polish (Polishing Fluid)</td>
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Production of 6” Prototype SiC Mirror

Surface finish achieved: <10nm

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Tool Wear

Favorable, progressive, even tool wear

Tool edge with 3mm nose radius

Tool cutting edge after machining
Infrasil 2000 Window Machining

- Chips formed are continuous and solid, indicating DMM