Penn State
Applied Research Lab
Laser Additive Manufacturing Technology

Presented at:
Direct Digital Manufacturing of Metallic Components Workshop

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Tom Donnellan

May 11, 2010
Established in 1945 by the Navy
Largest Interdisciplinary Research Unit at Penn State – 1,200+ faculty/engineers, staff, students and 350,000 sq.ft.
Classified facilities and programs to SCI
Research expenditures FY 2009: $165M
Designated a University Affiliated Research Center by DoD in 1996

As a University-Affiliated Research Center (UARC) ARL Penn State…
“…maintains a special long-term strategic relationship with DoD for technology development and engineering applications.”
MISSION
To be the preeminent source of innovative technologies-materials, process, manufacturing, design and logistics technologies for affordable, high performance DoD platform structures and systems.

Materials Processing
- Material Design and Characterization
- Process Development
- Advanced Coatings

Advanced Composites
- Marine, Land, and Aerospace Systems
  - Design and Analysis
  - Materials Char./Qual.
  - Process Optimization
  - NDE, Repair

Laser Processing
- Laser Physics
- Process Technology
- System Integration

Manufacturing Systems
- Automated Conceptual Design/Trade Space Exploration
- Simulation and Modeling for Manufacturing
- Shearography, Spectrometry, Inspection, NDT
- Environmental Technology

Systems Operations & Automation
- Condition Based Maintenance
- Sense and Respond Logistics
- Integrated Health Management

MAJOR PROGRAMS
iMAST, Drivetrain Technology Center,
DTRA University Partnership, Laser Processing Consortium
Materials and Manufacturing
Laser Processing
Technology Development & Implementation

Technology Development

- Improved Process Understanding
- Process Sensing and Control
- Material Response Models
- Process Development: New Hybrid Processes

Transition to Industry

- 1990
  - Application of LASCOR (U.S.S Mt. Whitney)
- 2000
  - Laser Deposition for Commercial Applications (NUWC - Keyport)
- 2010
  - Laser Repair of Undersea Components (NUWC - Keyport)
  - Portable Laser Repair for VLS Components (Pearl Harbor NSY)
Flexible Fabrication of Titanium (Acquisition Cost and Schedule)

Acoustically Tailored Structures (Tailorability)
  - Modeling and Simulation

AV-8B Compressor Blade Repair (TOC)

Discussion Topics/Technology Needs
Flexible Fabrication of Titanium

Background

- Work on Metal Deposition Processes – 1980s

- Work on Rapid Prototyping Technologies – 1980 & 1990s
  - Stereo lithography

- DARPA/ONR Interest in Cost Reduction of Ti Components
  - Flexible Fabrication of Titanium Program
    - Dr. R. Crowe (DARPA) and Dr. G. Yoder (ONR)
    - APL/JHU, ARL/PSU, MTS
Flexible Fabrication of Titanium

First DARPA Free Forming System
Flexible Fabrication of Titanium

- Powder feeding was perfected for titanium alloys in argon atmosphere
  - Made billets and rudimentary shapes
  - Characterized material via chemical and mechanical testing
  - Performed economic analysis
Flexible Fabrication of Titanium

Approximately 12 inches
Flexible Fabrication of Titanium Ti-6-4 Microstructures

Ingot 022396: Blended Ti-6Al-4V, L2

Ingot 032296: Pre-Alloyed Ti-6Al-4V, L2

Ti-6Al-4V Typical Thick Section Casting

Ti-6Al-4V Typical Thin Section Casting
### Flexible Fabrication of Titanium Chemical Analysis, Pre-alloyed

<table>
<thead>
<tr>
<th>Element</th>
<th>Powder, wt. %</th>
<th>Laser Formed*, wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>3.97</td>
<td>3.80</td>
</tr>
<tr>
<td>Al</td>
<td>6.20</td>
<td>5.91</td>
</tr>
<tr>
<td>Fe</td>
<td>0.232</td>
<td>0.199</td>
</tr>
<tr>
<td>O</td>
<td>0.230</td>
<td>0.237</td>
</tr>
<tr>
<td>N</td>
<td>0.032</td>
<td>0.037</td>
</tr>
<tr>
<td>H</td>
<td>0.012</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* Vacuum Mill Anneal, 1450°F (788°C) 2 hrs., argon quench

Interstitial contamination low, manageable
Flexible Fabrication of Titanium

In situ alloy fabrication possible
Flexible Fabrication of Titanium Mechanical Properties

Laser Formed Fatigue Test Results

![Graph showing laser formed fatigue test results with data points for various categories such as Cast, Wrought, and Cast+HIP. The graph plots Max Stress (MPa) against Fatigue Life (Nf, cycles).]
### Method #1:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning Volume, in³</td>
<td>8,640</td>
</tr>
<tr>
<td>Beginning Mass, lbm</td>
<td>1,391.0</td>
</tr>
<tr>
<td>Rough Machining</td>
<td></td>
</tr>
<tr>
<td>Plate Volume, in³</td>
<td>1,728.0</td>
</tr>
<tr>
<td>Rib Volume, in³</td>
<td>396.0</td>
</tr>
<tr>
<td>Cross-rib Volume, in³</td>
<td>45.3</td>
</tr>
<tr>
<td>Rough Volume, in³</td>
<td>2,169.3</td>
</tr>
<tr>
<td>Rough Ending Mass, lbm</td>
<td>349.2</td>
</tr>
<tr>
<td>Mass removed by machining, lbm</td>
<td>1,041.8</td>
</tr>
<tr>
<td>Machining time, hours</td>
<td>115.8</td>
</tr>
<tr>
<td>Total time, hours</td>
<td>118.8</td>
</tr>
<tr>
<td>Cost Estimates</td>
<td></td>
</tr>
<tr>
<td>Thick plate</td>
<td>$32,342</td>
</tr>
<tr>
<td>Rough machining</td>
<td>$9,500</td>
</tr>
<tr>
<td>Time per unit (hours)</td>
<td>118.8</td>
</tr>
<tr>
<td>Cost per unit</td>
<td>$41,842</td>
</tr>
<tr>
<td>Units per year</td>
<td>32.3</td>
</tr>
<tr>
<td>Total cost per year</td>
<td>$1,352,988</td>
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<tr>
<td>Acceptable units per year</td>
<td>29.1</td>
</tr>
<tr>
<td>Total acceptances (pounds)</td>
<td>10,164</td>
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<tr>
<td>Cost per pound accepted</td>
<td>$133</td>
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</table>

### Method #2

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Plate volume (in³)</td>
<td>1,728</td>
</tr>
<tr>
<td>Ribs additive deposit (in³)</td>
<td>396</td>
</tr>
<tr>
<td>Ribs additive deposit (pounds)</td>
<td>63.8</td>
</tr>
<tr>
<td>Cross-ribs additive deposit (in³)</td>
<td>45</td>
</tr>
<tr>
<td>Cross-ribs additive deposit (pounds)</td>
<td>73</td>
</tr>
<tr>
<td>Total additive deposit (pounds)</td>
<td>71.0</td>
</tr>
<tr>
<td>Powder usage (pounds)</td>
<td>88.8</td>
</tr>
<tr>
<td>Plate (pounds)</td>
<td>278.2</td>
</tr>
<tr>
<td>Total (pounds)</td>
<td>349.2</td>
</tr>
<tr>
<td>Deposit time (hours)</td>
<td>22.2</td>
</tr>
<tr>
<td>Total job time (hours)</td>
<td>25.2</td>
</tr>
<tr>
<td>Cost Estimates</td>
<td></td>
</tr>
<tr>
<td>Laser operator</td>
<td>$630</td>
</tr>
<tr>
<td>Assistant laser operator</td>
<td>$394</td>
</tr>
<tr>
<td>Thin plate</td>
<td>7,025</td>
</tr>
<tr>
<td>Powder</td>
<td>2,664</td>
</tr>
<tr>
<td>Argon</td>
<td>1,060</td>
</tr>
<tr>
<td>Helium</td>
<td>13</td>
</tr>
<tr>
<td>Process electricity</td>
<td>$266</td>
</tr>
<tr>
<td>Cooling electricity</td>
<td>$117</td>
</tr>
<tr>
<td>Metal waste disposal</td>
<td>18</td>
</tr>
<tr>
<td>Heat treatment</td>
<td>349</td>
</tr>
<tr>
<td>Laser maintenance</td>
<td>427</td>
</tr>
<tr>
<td>Other equipment maintenance</td>
<td>222</td>
</tr>
<tr>
<td>Floor space</td>
<td>$123</td>
</tr>
<tr>
<td>Depreciation expense</td>
<td>$2,304</td>
</tr>
<tr>
<td>SUBTOTAL</td>
<td>$15,612</td>
</tr>
<tr>
<td>Time per unit (hours)</td>
<td>25.2</td>
</tr>
<tr>
<td>Cost per unit</td>
<td>$15,612</td>
</tr>
<tr>
<td>Units per year</td>
<td>121.9</td>
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<tr>
<td>Total cost per year</td>
<td>$1,903,162</td>
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<tr>
<td>Acceptable units per year</td>
<td>109.7</td>
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<tr>
<td>Total acceptances (pounds)</td>
<td>38,317</td>
</tr>
</tbody>
</table>
| Cost per pound accepted         | $50         

Buy-to-fly

Conventional - $133/lbs.

Laser Deposition - $50/lbs.
**Monolithic alloys**
- Ti-6Al-4V
  - Powder
  - Elemental powder blends
- Nickel-aluminum-bronze (NAB)
- $\gamma$-TiAl (Ti-47-2-2)
- 17-4PH stainless steel
- Alloy 625
- Alloy 690

**Composite/Graded**
- NAB graded to Alloy 625, 17-4PH SS, W
- 308SS/Stellite 6 layered
- CP Ti + W particle composite
Submarine propellers are NAB engineered structures which are long lead items for platform.


Laser additive manufacturing: cost and schedule benefits for submarine propeller applications.
## NAB Process & Properties

<table>
<thead>
<tr>
<th>Condition</th>
<th>Test Direction</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>% elong (2 in.)</th>
<th>% R of A</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>Y</td>
<td>665</td>
<td>265</td>
<td>25.0</td>
<td>23.8</td>
</tr>
<tr>
<td>N₂</td>
<td>Y</td>
<td>645</td>
<td>261</td>
<td>21.0</td>
<td>22.4</td>
</tr>
<tr>
<td>N₂</td>
<td>Y</td>
<td>665</td>
<td>256</td>
<td>26.0</td>
<td>26.0</td>
</tr>
<tr>
<td>N₂</td>
<td>Y</td>
<td>648</td>
<td>242</td>
<td>26.0</td>
<td>27.2</td>
</tr>
<tr>
<td>Ar</td>
<td>Y</td>
<td>679</td>
<td>271</td>
<td>27</td>
<td>27.2</td>
</tr>
<tr>
<td>Ar</td>
<td>Y</td>
<td>689</td>
<td>296</td>
<td>23</td>
<td>23.8</td>
</tr>
<tr>
<td>Ar</td>
<td>Z</td>
<td>662</td>
<td>268</td>
<td>30.0</td>
<td>27.9</td>
</tr>
<tr>
<td>Ar</td>
<td>Z</td>
<td>662</td>
<td>270</td>
<td>26.0</td>
<td>28.6</td>
</tr>
<tr>
<td>Ar</td>
<td>Z</td>
<td>662</td>
<td>268</td>
<td>27.0</td>
<td>28.6</td>
</tr>
<tr>
<td>Ar</td>
<td>Z</td>
<td>655</td>
<td>265</td>
<td>29.0</td>
<td>28.6</td>
</tr>
<tr>
<td>ASTM B148</td>
<td></td>
<td>585 (min)</td>
<td>240 (min)</td>
<td>15 (min)</td>
<td></td>
</tr>
</tbody>
</table>

Specimen locations, 3 shown, but may be adjusted
Free-Forming process has potential to
- Produce parts with material properties superior to cast parts for less cost/schedule (reduce critical path by 1 year)
- Make a variable property blade for structural acoustic tailoring
- Make a thick NAB “skin” with internal void for treatment
Structural-acoustic design is important in determining the sound radiation from underwater vehicles.
Single blade spanwise material property variations:

\[ E \rightarrow 10 \text{ to } 50 \text{ Msi} \]

\[ \rho \rightarrow 0.12 \text{ to } 0.37 \text{ lb/in}^3 \]

Predicted radiation efficiency reductions of first five modes up to 10 dB relative to NAB

“Optimum” case

Structural Acoustics Analytical Results
How can these optimized designs be fabricated?

Design 1 – 2.2 dB Reduction

Addresses trailing edge forcing function

Design 2 – 1.3 dB Reduction

Reduces radiation efficiency – Less sound for the same vibration

Solution: Laser Additive Manufacturing
Issues with LAM of Graded Structures

- Need for better understanding of process
- Need for better control of process
Development and Validation of LAM Process Models

Beam - Material Interaction

Incident Beam from Nd:YAG Laser (Wavelength of 1.06 µm)

Powder Bed With Size Distribution of 74 to 177 µm (90/200 Mesh)


Transport Models

Conduction

2040 µm Powder Layer

R. W. McVey, Penn State University, 2007

Microstructure Models

Thermodynamic

A4Si + 0 wt. % WC System

A4Si + 10% TiC System

S.S. Babu and R.P. Martukanitz, 2006

Morphology

Heat and Mass Transfer

Absorbtion Coefficient

Irradiation Time [s]

M. Keller and S.M. Kelly, ICALEO 2006

A.C. Naber, Penn State University, 2005.
Understanding Microstructure Evolution During LAM of Ti-6Al-4V

Decreasing Heat Input

Basketweave-α

“Colony-α”
2009 DURIP Award - Installed December 2009

OPTOMEC Laser Engineered Net Shaping (LENS™) System

Features:
- Dual powder feeders.
- Material grading capability
- Single and multi-mode fiber capable
- Closed-loop melt-pool control.
- Inert processing chamber.
- Specifically designed deposition heads.

Addresses many of the shortfalls of previous ARL tool.
LAM-Based Repair of Compressor Blades in the AV-8B Harrier

- F402 engine compressor blade tips in the AV-8B become worn, resulting in a performance decrease, requiring replacement.
- FRC-East estimates that Rolls-Royce will not be able to meet their demand for new (replacement) compressor blades, potentially impacting force application. Costs associated with replacing worn blades is $929K/year.
- FRC does not have reliable NDT capability to detect porosity at the required levels.
Key Technology Solutions:

- Key Technologies:
  - Laser Additive Manufacturing
    - H&R Technology, Huffman Corp., Optemec Inc.
  - High Resolution Ultrasonic Inspection

- Gaps and Barriers:
  - Repair
    - Standardized evaluation of repair properties.
    - Development of systems for repair of compressor blades.
    - Qualification testing.
  - Inspection
    - Ability to detect 0.005 in. defect at 90% POD at 95% confidence interval.
Process Development

Repair Vendor A
- Ribbon

Repair Vendor B
- Powder

Repair Vendor C
- Powder

Proof of Concept Repairs on Stage 3 Compressor Blades
Metallurgical Coupon Dimensions

As-Provided Coupon

As-Repaired Coupon

Vendor A

Vendor B

Vendor C
Microstructures appear to be indicative of non-equilibrium phases as a result of rapid cooling.
**Project:** A2177F402 Compressor Blade Repair and Inspection

**Objective:** Demonstrate that repaired properties do not pose a flight risk through the execution of an approved, evaluation and pilot-qualification test plan.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Value</th>
<th>Requirement Threshold Value</th>
<th>Requirement Objective Value</th>
<th>How to Measure (quantity per repair process)</th>
<th>Date to be Achieved</th>
<th>Achievement History</th>
<th>How Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair Chemistry</td>
<td>AMS 4999 Specification</td>
<td>meet</td>
<td>meet</td>
<td>Bulk and Interstitial Element Composition of Repair Metallurgical Coupon (2)</td>
<td>1 mo ARS MAR 10</td>
<td>75% of Samples Rec'd</td>
<td>-</td>
</tr>
<tr>
<td>Repair Metallurgy</td>
<td>AMS 4999 Specification</td>
<td>Transformed α + β microstructure in fusion zone; no alpha case; no cracking.</td>
<td>meet</td>
<td>Repair Metallurgical Coupon (2)</td>
<td>1 mo ARS MAR 10</td>
<td>75% of Samples Rec'd</td>
<td>-</td>
</tr>
<tr>
<td>Tensile-X</td>
<td>AMS 4911</td>
<td>meet</td>
<td>exceed</td>
<td>Repair Test Coupon (3)</td>
<td>3 mo ARS MAY 10</td>
<td>75% Samples Rec'd</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\sigma_Y \geq 120$ ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{UTS} \geq 130$ ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\epsilon_F \geq 10%$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile-Z</td>
<td>AMS 4911</td>
<td>meet</td>
<td>exceed</td>
<td>Repair Test Coupon (3)</td>
<td>3 mo ARS MAY 10</td>
<td>75% of Samples Rec'd</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\sigma_Y \geq 120$ ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{UTS} \geq 130$ ksi</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>$\epsilon_F \geq 10%$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexural Fatigue</td>
<td>Fatigue Life Curve of Unrepaired Test Coupon</td>
<td>meet</td>
<td>exceed</td>
<td>Fatigue Life Curve (10^5 to 10^7 cycles) Repair Test Coupon (9)</td>
<td>6 mo ARS AUG 10</td>
<td>75% of Samples Rec'd</td>
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<tr>
<td>Component Frequency Analysis</td>
<td>New Unrepaired HPC Blade</td>
<td>No effect of repair on frequency response</td>
<td>NA</td>
<td>Repaired HPC Blade (TBD)</td>
<td>MAY 11</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Continued next slide….*
Laser Additive Manufacturing has potential for cost and schedule benefit for Navy, DoD, and commercial applications

- Performance/cost trade based selection of candidate components
- Repair/replacement benefits for maintenance community

Laser Additive Manufacturing has unique benefit in tailored structures

- Design of a multi-alloy components which can be made for about the same cost as a monolithic structure
Starting Material
- quality, cost, availability

Application Guidelines
- multifunctional structure design development

Equipment Design Features
- scalability
- process control

Certification Protocol Development