Powder Bed Additive Manufacturing of Titanium: Aerospace Opportunities and the US Supply Base

26 Sept 2016

Adam Pilchak, Jon Miller, and Eddie Schwalbach

AFRL/RXCM
Acknowledgements

AFRL RXCM:
  Mike Groeber, Kevin Chaput, Todd Butler, Sean Donegan

AFRL ManTech:
  Mary Kinsella, Mark Benedict

Builds:
  ORNL, GE and Sigma Labs
Aerospace Applications of AM

• Aerospace Community
  – Practically all sectors are actively evaluating AM:
    structure, propulsion, space, munitions, electronics, human system
  – Depending on application, a variety of implementation paths are possible:
    tooling, prototypes, design iteration, production parts
  – Some aspect of Material, Process and Component Qualification is required
    for nearly every implementation path

• AM Aerospace Opportunities
  – Functionally-embedded structures
  – Expanded geometric complexity
  – Required component re-design
  – Low production quantities
  – Mass customization
  – Non-critical parts

Source: Wohlers Associates
**Benefits and Challenges**

**AF Benefits:**
- Reduced lead time and cost for small production runs → Aircraft Availability & Sustainment Affordability
- Mass customization and enabling geometric complexity → Adaptive Warfighter & Energy Efficiency
- Weight reduction via part consolidation/material substitution → Reduced Sustainment Burden & Energy Efficiency

**Technical Challenges:**
- Unquantified material quality with undefined inspection protocols to meet aerospace structural requirements
- Highly variable material properties and lack of statistical databases for design
- Lack of standardized process controls typically required for structural applications
- Inadequate cost models for representation of post-processing requirements — Inspection, Machining, and Heat Treatment
Enhanced Component Performance
Multiple component families’ geometries are constrained by conventional manufacturing capabilities, including non-structural parts, complex propulsion parts, heat exchangers, space parts.

Opportunities:
- High-Value, Low-Production Geometries
- Expanded Component Geometries
- Weight Reduction via Consolidation
- Reduced Dev. Cycle / Rapid Design Iteration

Potential for
- System Design Cycle Reduction
- Lead-Time Improvements
- Component Performance Benefits

Functionally-Embedded Structures
Opportunities:
- Reliable, integrated electronics printed directly on structure
- Conformal antennas adapted into load-bearing structure
- Distributed electronics for flight-control feedback and structural health monitoring

Potential for
- Simplified Mfg., New Sensing, Improved System Performance

Replacement Parts for Sustainment
Re-manufacture of components with obsolete manufacturing routes or low production volumes are expensive and have long lead times due to tooling requirements of conventional mfg. processes.

Opportunities:
- Tools, Fixtures & Prototypes
- Temp. Replacement Parts
- Unintended Spares & Obsolescence Replacement

Potential for
- Improved Lead Times
- Reduced Cost (LRP)

System Affordability
Opportunities:
- Low Production Volume Components
- Parts Customization and Consolidation
- Lean Parts Management
- Parts on Demand

Potential for
- Total Life Cycle Cost Reduction
- Lead-Time Improvements
- Simplified Manufacturing Routes

Component Repair
Current Issues:
- Current parts NOT designed FOR repair
- Unvalidated processes and inspections

Potential for
- Organic or Local Mfg Repair
- Reduced Sustainment Burden

AFRL
Qualification of AM for Critical Structures

AFRL is the material and process qualification protocol thought leader for critical AF aerospace applications

- AFRL contributes to development of:
  specs, standards, and qualification methods
- Entire community defining certification process
- Significant material integrity risks
- Need new quality assurance methods

Conventional NDE & CT Evaluation

Process Complexity, Monitoring & Control

Highly Variable Material Properties
Process Complexity
Length & Time Scales

Temporal

Solid

Powder

IR Intensity

Time [s]

Contours

Melting

Post-heats

Pre-heat

Spread powder

Complex thermal history
Solidification event ≈1 μs
Full build ≈1 day

Spatial

Build (40 parts)
Part (300 layers)
Layer (150 tracks)
Track

Wide range of spatial scales, complex build can easily have 10km of track

0.2m
15mm
15mm
≈150μm

0.2m
15mm
15mm
≈150μm

50μm
Process Complexity
Geometry Variations & Process Changes

Arcam A2 e-beam powder bed fusion: Ti-6Al-4V

- Notional parameters uniform throughout bed
- Local processing parameters changed by system in response to geometry
- 3D maps of processing parameters generated via ORNL code

**Conditions/Parameters (Normalized to Region A)**

<table>
<thead>
<tr>
<th></th>
<th>Region A</th>
<th>Region B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>20</td>
<td>107.6</td>
</tr>
<tr>
<td>Power/$P_A$</td>
<td>1</td>
<td>4.67</td>
</tr>
<tr>
<td>Spot Velocity/$V_A$</td>
<td>1</td>
<td>8.10</td>
</tr>
<tr>
<td>Line Velocity/$V_A$</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Scan time/$t_A$</td>
<td>1</td>
<td>0.636</td>
</tr>
<tr>
<td>Energy density/$E_A$</td>
<td>1</td>
<td>0.556</td>
</tr>
</tbody>
</table>

Property variations observed with...
- Different orientations (build direction debits)
- Thicknesses within a “Region” (1-5 mm)
- “Region A” to “Region B” (machine algorithm)
- Powder Lot Variations & Recycle Strategies
- Machine S/Ns, Machine Models, Vendors
  …not to even count process knob changes…
E-Beam Process-Structure-Properties

**Processing**
Implicit changes in conditions via geometry affect melt pool geometry

**Structure**
Change in Texture across regions

**Properties**
Texture variation results in tensile property variations across regions
Direct Metal Laser Sintering (DMLS)
EOS M280 Machine
Striping & Hatching Enabled
Stripes Rotate 67° Per Layer

Path plan for a single layer colored by elapsed time

Zoom of 10mm diameter cylinder

Stripes Typically 1s-10s of mm
Stripes Processed in Serpentine Manner
Laser Moves ~1 m/s
Laser Crosses Stripe in ~1/200 s
Fundamental Research: Pedigreed Data Processing – Structure – Properties

Data collected at GE (AFRL contract)    EOS M280    Ti-6Al-4V

Control Spatial Processing Variation → Control Structure

Post-Build Defect Characterization

CAD Geometry

Laser Position(t)

Laser Properties

Voids & Stripe Boundaries

Temp v. Time Profiles

Processing Frequency

Defect Frequency

Processing -Structure Maps

DARPA

AFRL
Designing for AM: AFRL Vision
Adaptive 3D Digital Architecture

- Process Planning
- Process Modeling
- Process Monitoring
- Topology Optimization
- NDE Modeling
- Geometry & Design Rules
- Outcome Modeling & Characterization
- Nondestructive Inspection
• Great Opportunities exist for Additive Manufacturing of Ti alloys
  – Need to find the right ones that balance risk and value proposition
• There has been significant progress in understanding process control & integrity
  – Significant geometry influences in addition to classic process-structure-property relationships
• Need Data Tools to manage the extensive spatially resolved data
  – Need to deal with significantly different spatial and temporal scales