Additive manufacturing of metallic materials

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Vision
The Nation’s Premier Laboratory for Land Forces.

Mission
DISCOVER, INNOVATE, and TRANSITION Science and Technology to ensure dominant strategic land power

Making today’s Army and the next Army obsolete
ARL S&T Campaigns

Human Sciences
Fundamental understanding of Warfighter performance enhancement, training aids, and man-machine integration.

Information Sciences
Fundamental understanding of information generation, collection, assurance, distribution, and exploitation.

Sciences for Lethality & Protection
Fundamental understanding of emerging technologies that support weapon systems, protection systems, and injury mechanisms affecting the Warfighter.

Sciences for Maneuver
Fundamental understanding of the design, integration, control, and exploitation of highly adaptive platforms in complex environments.

Computational Sciences
Fundamental understanding of computer hardware, high efficiency algorithms, and novel mathematical methods.

Materials Research
Fundamental understanding of structural, electronic, photonic, and energy materials & devices.

Extramural Basic Research
Steering and oversight of the systematic study to increase fundamental knowledge and understanding in physical, engineering, environmental, and life sciences related to long-term national security needs.

Assessment and Analysis
Quantitatively assess the development and application of analytical tools and methodologies to quantitatively assess the military utility of Army, DoD, and select foreign combat systems.

ARL Campaign Publications: http://www.arl.army.mil/publications
Key Focus Areas for Transformational Materials Science

**Modeling & Simulation**
- Multi-Scale Modeling
- Link Scales
- Solve Modeling Gaps

**Synthesis & Processing**
- Efficient Process Scaling
- Reduced Cost
- Advanced Manufacturing

**Advanced Characterization**
- Microstructural & Property Characteristics
- Processing-Property-Microstructure Relationships

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**Army Need** | **Transformational Materials Science** | **Army Payoff**
VISION: Provide the Army with advanced materials and manufacturing science based solutions that increase the lethality and survivability of the warfighter through reduced weight, increased functionality and improved reliability.
Coupling design, novel materials, and advanced manufacturing

Mission:
Develop innovative processing & agile manufacturing technologies for rapid delivery of technology and materials to enable Warfighter Capabilities in a persistent conflict environment.

Capabilities:
- Manufacturing Science
- Material System Integration
- Material Selection and Trade Studies
- Manufacturing Readiness Assessments
- Warfighter Protection
- Non-destructive Evaluation (NDE)
- Military Specifications
- Additive Manufacturing

Innovative Processing

Agile Manufacturing

Rapid Transition

Near Net Shape Processing

MIL Specs & Standards

Topography Optimization

Design

Manufacturing

Handheld
Open Campus: Building the Ecosystem

- Army Leadership Support
- Collaborative Mechanisms
  - Cooperative Research and Development Agreements (CRADAs)
  - Patent License Agreements
  - Educational Partnerships
  - Partnership Intermediary Agreements
- Opportunities Advertised
  http://www.arl.army.mil/opencampus/
- Openly Sharing Technical Strategies
- Infrastructure
  - Enhanced Use Lease
  - Collaborative Network and Data Sharing
  - Layered Security
- People
  - Flexible Work Places and Schedules
  - Sabbatical Leave
  - Entrepreneurial Separation
- Open Campus Open House

> 200 People Into and Out of Laboratory Under Open Campus Pilot So Far
> 60 CRADAs, 28 Academic and 32 Industry
The BIG Army vision

- Expeditionary
- Reduce the logistical tail
- Adaptive to location. … jungle, mountain, desert, etc.
- Adaptable, configurable
- Real-time, on-time, on demand
  - manufacturing
- Point of use; In-field
- Organic capability
- Realize light weighting
- Complex manufacturing
- Man-machine interface
- Unmanned vehicles

AM is Agile Manufacturing!
The REF inserted two (2), 20-foot, containerized mobile Expeditionary Labs, or Ex Labs, to deploy to units in isolated locations. Each lab includes a Stratasys Fortus 250mc 3-D printer, a computer numerical control milling machine, an array of fabrication tools, electrical diagnostic equipment, software programs and a global communications system to connect forward teams directly with REF leadership and other partners.

The REF owns five (5) 3-D printers -- the two in Afghanistan and three at its headquarters at Fort Belvoir, Va. -- all of which print solely in plastic polymers, suitable for prototyping. While the labs can create one-off, low-volume orders for simple, plastic components, REF prototypes are typically the first step and often require external validation and manufacturing.
Photo-Polymerization

- Modified Stereolithography
- Particle Alignment
- Multi-material
- Pseudo Composite Systems

ARMY BENEFIT

Dual Micro-Dispensing System

- 1cps to 1,000,000 cps materials
- Resolution +/- 1µm accuracy
- Surface scan for topology guidance
- Fiducial recognition system
- Open access motion control

ARMY BENEFIT

Vat Polymerization

- X/Y Resolution 50µm
- Z Resolution 25µm
- Parallel Cure Mechanism

ARMY BENEFIT

Integrated Materials on Arbitrary Structures

Rapid Fabrication of Electronics

Spatially Varied Material Properties
6 - Axis Heterogeneous System

- 1 cps to 1,000,000 cps materials
- Resolution +/- 1µm accuracy
- Surface scan for topology guidance
- Fiducial recognition system
- Open access motion control
- Inverse Kinematics Enabled

For references, contact POC Larry R. Holmes, Jr. larry.r.holmes.civ@mail.mil
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Direct Metal Laser Sintering @ ARL

ProX 100: 4x4x4” Build Volume
ProX 300: 10x10x10” Build Volume
Full Volumetric Control of Build Parameters

**ARMY BENEFIT**

- Reduce logistics tail
- Mission readiness → “good enough” parts
- Optimized Structural Components → Light Weighting!
- Reduce Number of Parts in Complex Systems → Reduce Cost!
- Integrated Design of Materials and Manufacturing → Unique and Local Control of Microstructures and Properties!
Energy Density

- Laser Speed (v)
- Laser Power (P)
- Hatching Distance (h)
- Laser Defocusing
- Powder Layer height (LT)

\[
ED = \frac{P}{vLT}h
\]

Melt Pool Formation


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**ARL DMLS EFFORTS**

### Manufacturing
- **Powder Bed**
- **Powder Fed**
- **Novel Metals AM**
- **Benchmarking**
- **Post-Processing (HT, HIP, Machining, Surface Finish)**
- **Qualification and Certification**

### Characterization
- **In-situ Sensing and Control**
- **Laser**
- **Feedstock**
- **AM Components**
  - Mechanical Properties
  - Porosity/Defects, Residual Stresses, Distortions/Geometry
- **Processing/Microstructure/Property Relations**

### Modeling and Simulation
- **Design Tools**
  - Topology Optimization
  - CAD
  - Physics based Support Structures
- **Performance**
  - FEA
  - Microstructure based Prediction of Mechanical Properties
- **3D Scanning and CAD Generation**
- **Process Models**
  - Micro Scale (Powder/Meltpool)
  - Solidification, Thermodynamics, Phase Field, Microstructure Prediction and Evolution
  - Continuum
  - Process Modeling, Thermal Histories, Residual Stresses, Distortion, Microstructure based Prediction of Mechanical Properties

### Materials/Feedstock Development
- **Optimized alloy design**
- **Computational Thermodynamics**
- **Powder production**
- **Cryomilling and Atomization**

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**MATERIALS AND MANUFACTURING SCIENCE**
- AM Research

**EXPEDITED MANUFACTURING IN-THEATER CAPABILITIES**

**APPLICATIONS**
- High Performance Structural Components

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**Defects**

Porosity
Unmelted particles
Lack of fusion

**Anisotropy**

<table>
<thead>
<tr>
<th>Material</th>
<th>Grade 2 RD</th>
<th>Grade 2 TD</th>
<th>Grade 4 RD</th>
<th>Grade 4 TD</th>
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<tbody>
<tr>
<td>Conventional yield stress (MPa)</td>
<td>330</td>
<td>404</td>
<td>473</td>
<td>592</td>
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<tr>
<td>Ultimate tensile true stress (MPa)</td>
<td>518</td>
<td>508</td>
<td>727</td>
<td>797</td>
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<tr>
<td>Uniform elongation (%)</td>
<td>10.9</td>
<td>7.4</td>
<td>14.7</td>
<td>14.1</td>
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<tr>
<td>Fracture strain (%)</td>
<td>40</td>
<td>35</td>
<td>41.7</td>
<td>22</td>
</tr>
</tbody>
</table>

**Part/geometry dependence**

Ni based

R.C. Buckingham et al. / Mat. Sci & Eng A 654 (2016) 317–328

MIL-DTL-12560K
Take away message
AM parts may not have properties matching conventional manufactured parts, yet, but compared to other technologies AM is in its infancy.
**Novel materials**

In house development of high strength alloys, novel strengthening mechanisms, design and control of microstructures

**UCF gas atomization facility**
- UHP Ar or N2 for atomizing gas
- Temperatures up to 1650°C
- Produce ~2 kg powders/run
- ~50% yield for ≤75 μm particles
  - System is easily cleaned

**Optimization and design of lightweight alloy feedstocks for AM**

**Feasibility study of high strength FeZrNi alloy**
Predictability
- Void
- Porosity
- Thermal Gradient
- Residual Stress
- Thermal Fatigue
- Performance

μ-metallurgy
- μ-Solidification
- μ-Phase Transition
- μ-Diffusion
- μ-Segregation
- μ-Aging

Abaqus FEM Solver
- Thermodynamics
- Kinetics
- Solute Redistributions
- Residual Strain
- Thermal Strain

Process Characterization

Beam Traverse Time / Path

Temperature

Process Monitoring
Optical, Thermal, & Acoustic sensing

Powder & bulk: CT, OM, SEM, TEM, EBSD, FIB, micro-mechanical test, nano-indentation, XRD
Processing/Microstructure/Property Relations

High Resolution Surface Metrology

Effect of Process Parameters on Residual Stresses/Distortion

Mechanical Testing and Fracture Analysis

Effect of Process Parameters on Tensile Behavior of 17-4 SS
Rapid DOE for process parameter optimization

**Microstructure by design**

- **Large grains in local regions**
- **Small grain regions**
Development of processing parameters
Single pass characterization

128.63 μm
39.41 μm
147.33 μm
26.27 μm
163.34 μm
39.86 μm

50 mm/s Bead
Development of processing parameters
Single pass characterization

Continuous

50 mm/s
150 mm/s
250 mm/s
350 mm/s

Irregular

450 mm/s
850 mm/s
Balling

1150 mm/s
Development of processing parameters
Hatching Distance Test Results

50 mm/s
25 μm

150 mm/s
75 μm

250 mm/s
50 μm

350 mm/s
100 μm
Design for AM (DFAM)

Is the traditional design optimal?

The ultimate goal: Achievable through topology optimization

Can we use/develop multi functional materials?

How can we manufacture for better properties and more complicated designs?

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Technical Introduction: Topology Optimization

POC Dr. Andrew Gaynor

Design Domain

Conventional low-weight design – driven by traditional manufacturing

Topology optimized design: ~42% stiffer for same weight

Topology optimized design: ~48% lighter for same (elastic) stiffness

Design Evolution

F

red = solid
blue = void
Topology Optimization: An organic computational design method for extreme light-weighting

Direct Control over Feature Size

32% weight reduction

Increased Complexity, Increased Performance:
With AM Complexity is “free”

Experimental validation of process specific manufacturing constraints is critical!
Overhang Angle Constraint

Issues if not supported: Energy from melting/sintering cannot adequately dissipate away and large residual stresses develop creating curling.


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Simply-Supported Beam Example

L

\[ H = \frac{L}{6} \]

Build Direction

Build Plate

POC Dr. Andrew Gaynor
NDE: ARL CT Systems

**Bruker Skyscan 1172**
- Power: 20-100 kV, up to 10W
- Sample size < 26 mm
- Minimum voxel size: 0.5 um
- Resolution: approximately 5 um

**Zeiss Xradia 520 Versa**
- Power: 30-150 kV, up to 10W
- Sample size < 300 mm
- Minimum voxel size: 70 nm
- Resolution: 0.7 um
- Phase contrast enhancement

**NorthStar X5000**
- Power: 25-225 kV, up to 320 W
- 450 kV, 700 or 1500 W
- Sample size 16”
- Minimum voxel size: ~20 um
- Non-cabinet system
- Enhanced speed detector

**POC Dr. Jennifer Sietins**
Quantitative CT Analysis

Quantification of Defects (Pores)

Quantification of Dimensional Fidelity

POC: Dr. Jennifer Sietins
Quantification of distortion

3D Digital Image Correlation (DIC) to quantify effect of laser scan strategy on residual stress/distortion
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Integrated Computational Materials Engineering for Virtual Manufacturing of Army Components and Systems

Primary processing (casting model)

Secondary processing (thermo-mechanical model)

Processing/microstructure/properties relations (microstructure based models)

Integrated Computational Materials Engineering for Virtual Manufacturing

Manufacturing based performance (structural models)

As built performance modeling for: Optimized design, light weighting, reduced cost (materials and manufacturing)
Enhanced protection, lethality, and mobility

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1. Microstructure characterization $f(\text{weld conditions, material, } t)$

2. Identify constitutive behavior

3. Validation of constitutive models (JC) including progressive damage and failure

4. Coupon level blast simulation and experimental validation

5. Sub and full scale welded hull simulations
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Additive Manufacturing M&S

Porosity
Phase Transformations
Residual Stresses
Delaminations
Distortions
Metal Tearing

Casting/Solidification Components
Precipitates
Inclusions

Thermo-Mechanical Components
AM Process Model

Thermal Histories

Interface Design & Effects

Melt Pool Physics in DMLS
Powder Production (e.g. atomization)

King, W., et al, Mat. Sci. and Tech, (31) 2015
AM Process Modeling

- In house development and external collaboration to develop validated ICME framework for AM
  - Thermal history and residual stresses
  - Microstructure evolution including defects

Simulate to optimize process parameters so that you **know** you will manufacture:

**THIS** Ahead of Time! **NOT THIS**
ARL ICME for AM Roadmap

**AM workflow**
- AM Alloy development
- Powder feedstock production

**AM workflow**
- Manufacturing
  - Mechanical performance and requirements
- Part performance

**Design**
- Materials
- Manifacture
- Topology Optimization

**Macro**
- Computational thermodynamics
  - CFD and microsolidification of atomization process
- Computational thermodynamics
  - FEA Thermal histories of builds
  - Residual stresses/distortions

**Meso**
- Powder scale models
  - Powder packing, powder melting and re-solidification, phase field, microstructure evolution
- Micro
  - Prediction of microstructure (grain size, phase composition and distributions, porosity)

**Micro**
- Local effects of microstructure (grain size, texture, anisotropy, defects, etc)

**Part performance**
- Predicting mechanical properties

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Current Critical AM Technology Gaps

- Melting and solidification of existing metal AM processes results in sub-optimal microstructures with inferior properties not suitable for use in Army applications.
- Currently no suitable commercial AM processes available for structural ceramics
- Limited control of processing-structure-property-performance relationships