Update on NDE for Powder Bed Fusion and Direct Energy Deposition

AMC Meeting at EWI

16 July 2015

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Outline

- Paper study – “Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures”. EWI project 55028GTH.
- Current projects
  - Project 55488GTH, “Non-Destructive Evaluation of Complex Metallic Additive Manufactured Structures” – X-ray CT
  - Project 55139GTH, “Advanced Eddy Current Techniques for Characterization of Additive Manufacturing Metal Components”
  - Project 55110CSP, “Refining Microstructure of AM Materials to Improve Non-Destructive Inspection (NDI)” – phased array UT
Project 55028GTH

Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures – Paper Study
Team and Acknowledgments

- Lead Organization – EWI
- Sponsored by Air Force Research Laboratory through America Makes
Problem and Objectives

 Problem - Process scale, geometric complexity, and limitations of current NDI techniques present technical challenge in adoption of AM technologies
  – Defects sizes tend to scale with the process (e.g. powder, beam size)
  – Wide range of geometric complexity in AM parts today
  – Little work to date to characterize NDI techniques as they apply to metal AM parts.

 Objectives
  – Evaluate capabilities of existing NDE and applicability to complex shape AM
  – Select possible NDE techniques for post-process inspection
  – Identify technical gaps
  – Recommend future near- and far-term work on NDE optimization and validation for AM components
Results

- Reviewed metal powder bed fusion processes and types of defects observed in literature
- Identified two potential processes for fabrication of aerospace components – laser powder bed fusion (L-PBF) and electron beam powder bed fusion (EB-PBF)
- Developed scheme for grouping part complexity
- Reviewed existing NDE techniques in both existing and emerging fields
- Down-selected NDE techniques
- Identified technical gaps
- Proposed plan to address technical gaps
AM Flaws and Conditions

- Typical flaws for L-PBF and EB-PBF
  - Pores – too high energy input and/or lower speed, gas trap
  - Balling – increased O₂, layer thickness, and laser speed
  - Lack of fusion - too low energy input and/or higher speed
  - Inclusions – inadequate cleaning
  - Cracking and delamination – high thermal and residual stresses

- Others
  - Residual stresses and possible distortion – low geometrical stiffness or thin walls, overhang structure,
  - Surface roughness
  - Microstructure, phase composition, anisotropy

- Small flaw sizes in range of beam size 50 to 100 µm pose additional challenges
AM PBF Processes and Flaws

<table>
<thead>
<tr>
<th>Process</th>
<th>Beam Size (µm)</th>
<th>Powder Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB-PBF</td>
<td>100-500[^2,3]</td>
<td>(50[^4])</td>
</tr>
</tbody>
</table>


Surface Breaking/Linear Defects – Cracking [8]

Surface Roughness [9]

Delamination

6-14 µm L-PBF, 25-97 µm EB-PBF
Group 4 and 5 most complex. Traditional subtractive fabrication technologies not applicable.

Group 4 and 5 expected to be most difficult to NDE after fabrication.
## NDE Technique vs. Geometric Complexity Matrix

<table>
<thead>
<tr>
<th>NDE Technique</th>
<th>Geometry Complexity Group</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>VT</td>
<td>Y</td>
<td>Y</td>
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<tr>
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<td>ACPD</td>
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<td>Y</td>
</tr>
<tr>
<td>ET</td>
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<td>Y</td>
</tr>
<tr>
<td>AEC</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PAUT</td>
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</tr>
<tr>
<td>UT</td>
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<td>Y</td>
</tr>
<tr>
<td>RT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>X-Ray CT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>X-Ray Micro CT</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Key:**
- Y = Yes, technique applicable
- P = Possible to apply technique given correct conditions
- NA = Technique Not applicable

**Notes:**
- (a) Only surfaces providing good access for application and cleaning
- (b) Areas where shadowing of acoustic beam is not an issue
- (c) External surfaces and internal surfaces where access through conduits or guides can be provided
- (d) Areas where large number of exposures/shots are not required

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VT – Visual testing  
LT - Leak testing  
PT – Penetrant Testing  
PCRT - Process Compensated Resonance Testing  
EIT - Electrical impedance tomography  
ACPD - Alternate Current Potential Drop  
ET - Eddy Current Testing  
AEC - Array Eddy Current Testing  
PAUT - Phase Array Ultrasonic Testing  
UT - Ultrasonic Testing  
RT - Radiographic Testing  
X-Ray CT - X-Ray Computed Tomography  
X-Ray Micro CT - X-Ray Microfocus Computed Tomography
X-ray CT may be applicable to geometries up to Group 5 complexity. Potential resolution in range from 50 to 100 µm for AM defect detection and shape validation.

Enhanced VT, PCRT, flexible AEC and flexible PAUT - potential to inspect components up to Group 3 when coupled with advanced tools for data acquisition, processing and imaging.

Specialized - potential applications for microstructure and residual stress characterization of AM parts.

- UT - acoustic attenuation and velocity
- Electromagnetic - conductivity and/or magnetic permeability mapping

In the long term, proven medical techniques may be transferred and adapted to examine AM components after fabrication

- X-ray CT
- UT pulse-echo and through transmission tomography
- Emission tomography
Technical Gaps

- Limited number of studies investigating NDE for post process inspection of AM components
- Performance of NDE techniques, even most promising, cannot be reliably evaluated or anticipated when testing AM components
- Challenge presented by most complex AM parts (e.g., Group 4 and Group 5) - not adequately addressed

Three significant technical gaps:
  - Limited number of NDE studies for AM
  - Limited scope of NDE studies for AM
  - Challenges of part complexity for existing subtractive technologies
Methodology to Address Technical Gap

- To apply NDE technique:
  - Method and operator must be systematically qualified/quantified in defect detection, characterization, and sizing
  - Requirements depend on industry

- Conduct Technical Justification (TJ) and Practical Trials [13]
  - Introduction with description of inspection and quantification objectives
  - NDE procedure and personnel certification
  - Training information and requirements
  - TJ expand to include
    - Overview of procedure from previous quantification efforts
    - List of affected essential parameters
    - Predictions by computer modeling (model assisted probability of detection included)
    - Experimental evidence from previous qualification or quantification activities

- TJ outcome - Does NDE system meet the inspection objective?
  - POD, accuracy of sizing, false call rate, discontinuity location accuracy, characterization, and resolution in terms of interacting discontinuity separation
Recommendations – Near Term

- Prepare methodologies and conduct comprehensive studies for Group 4 and 5 components, evaluating:
  - X-ray CT performance
  - PCRT as high speed screening technique

- Prepare methodologies and conduct comprehensive studies for Group 1-3 components for small surface and subsurface tight planar flaws, evaluating:
  - Flexible AEC
  - Flexible PAUT

- For NDE monitoring and evaluation of microstructure, strain, anisotropy, hardness and residual stresses, investigate correlation to electrical conductivity, magnetic permeability, acoustic velocity, acoustic attenuation and others.
Recommendations – Far Term

- Optimize further qualified advanced NDE techniques for complex geometries to reduce cost and increase speed of inspection
- Prepare or update codes, standards and specifications for NDE of AM components after fabrication
- Evaluate feasibility and transition emerging and advanced NDE technologies from medical (e.g., pulse-echo and through transmission ultrasonic tomography) or other industries, where applicable.
- Evaluate performance of emerging and advanced NDE techniques for examination of flight critical AM components
Report in Public Domain

AFRL-RX-WP-TR-2014-0162

AMERICA MAKES: NATIONAL ADDITIVE MANUFACTURING INNOVATION INSTITUTE (NAMII)
Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

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JUNE 2014
Interim Report

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References

Project 55488GTH

Non-Destructive Evaluation of Complex Metallic Additive Manufactured Structures
Team and Acknowledgments

- Lead Organization – EWI
- Sponsored by Air Force Research Laboratory through America Makes
Problem and Objectives

Problem
- Lack of NDE techniques for examination of typical flaws in AM components
- Only X-ray CT possible for complex geometries

Objectives
- Select aerospace components made of Ti64 and In718 with desired complexity
- Conduct X-ray CT following AM fabrication process
- Evaluate X-ray CT flaw detection and sizing capabilities
Approach and Progress

◆ Approach
  – Two materials – Ti64 and In718
  – Two technologies – direct metal laser melting (DMLM) and electron beam melting (EBM)
  – Flaws will be implanted in coupons and components
  – Computer simulation to optimize experimental matrix
  – Destructive testing to validate X-ray CT capabilities

◆ Progress
  – Complex geometry components being selected
  – Prepared flaw matrix with 32 coupons per material - 24 coupons with 135 subsurface and surface flaws, other coupons with porosity and artificial flaws
  – Conducted initial modeling for optimization
Progress

Possible Components

X-ray CT of Lattice Structure

Coupon X-ray CT Modeling

60 kV
Project 55139GTH

Advanced Eddy Current Techniques for Characterization of Additive Manufacturing Metal Components
Team and Acknowledgments

- Lead Organization – EWI
- Sponsored by NIST, Engineering Laboratory, Intelligent Systems Division, Additive Manufacturing
Summary

**Problems**
- Small features and defects generated during L-PBF pose unique challenges for process inspection and monitoring
- Lack of adequate NDE techniques for examination before, during and after AM component fabrication

**Objectives**
- Develop eddy current techniques for characterization of AM materials – before, during and after fabrication
- Build computer models for prediction of sensors response to typical AM discontinuities and conditions
- Develop and optimize software and sensor modules to enable imaging and measurement of AM material properties inside and outside L-PBF test bed

**Approach**
- Experimental specimens for equipment development and test
- Measurement of electromagnetic properties of feedstock and fused metal
- Computer simulation for sensor and technique optimization
- Laboratory system integration
- Demonstration in laboratory environment
Project 55110CSP

Refining Microstructure of AM Materials to Improve Non-Destructive Inspection (NDI)
Team and Acknowledgments

- Lead Organization – EWI
- Sponsored by Lockheed Martin and America Makes
Problem and Objectives

Problem

- Reliable NDE required during optimization and microstructure refining of Ti64 direct energy deposition (DED) process
- Attenuation of ultrasound energy is relatively low and non-uniform or anisotropic in alloy prior to beta anneal
- After beta anneal, grain size and grain orientation have an even greater effect on attenuation.
- Diffraction and scattering have major impact on ultrasonic waves as they propagate through material
- Diffraction causes redirection of the sound wave resulting in missed flaws and inaccuracy in flaw location
- Scattering reduces the signal-to-noise ratio and rapidly reduces sound energy resulting in high attenuation of the received signal that can exceed 18dB or greater

Objectives

- Develop matrix phased array (MPA) ultrasonic sensor and technique
- Evaluate MPA capabilities by detecting 3/64” diameter FBH for each process variant and compare with baseline process
Example of Attenuation Variations

Max. Attenuation Variation Within Sample (dB) = 9.1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Value</th>
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<tbody>
<tr>
<td>Maximum Amp. (% FSH)</td>
<td>80</td>
</tr>
<tr>
<td>Minimum Amp. (% FSH)</td>
<td>28</td>
</tr>
<tr>
<td>Average (% FSH)</td>
<td>50</td>
</tr>
<tr>
<td>Median (% FSH)</td>
<td>48</td>
</tr>
</tbody>
</table>
Off-the-shelf MPA sensor used for initial scans did not produce satisfactory results

New MPA sensor designed and fabricated to provide smaller, more uniform beam spot

Based on modeling results, smaller beam could allow more sound energy to propagate through columnar grain structure with less noise

Models also predicted that new MPA sensor would produce signal amplitude from 3/64” FBH ~18 to 20dB greater than off-the-shelf sensor
New vs Off-the-shelf Sensor on Beta Annealed Part

Base Gain = 52 dB

Off-the-shelf Sensor

Base Gain = 52 dB

FBH

12 dB added to compensate for attenuation (23 dB + 12 dB = 35 dB)

New Sensor

Base Gain = 35 dB

FBHs

12 dB added to compensate for attenuation (23 dB + 12 dB = 35 dB)
Conclusions

- MPA ultrasonic technology allows reliable inspection of AM Titanium parts with reduced noise level
- MPA sensor covers large area reducing inspection time, while still maintaining relatively small beam size throughout thickness
- MPA is promising technology for inspection of parts made with EB-DED process
- Sensor and technique optimization may be required for different geometries
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