Session 3: Monitoring and advanced diagnostics to enable AM fundamental understanding –

Direct Energy Deposition and Electrospinning

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Direct Energy Deposition

Laser Nozzle
Laser Beam
Shielding-/Carrier Gas
Metallic Powder

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Hybrid Additive and Subtractive Machining

Prototypes and small series production of complex lightweight and integral parts for:
1) Die & Mold
2) Aerospace
3) Automotive
4) Medical

Repair of Turbine and Die & Mold Components

Repair of damaged and worn components for:
1) Medical
2) Die & Mold
3) Aerospace
   (e.g. Blade Tip Repair)

Corrosion and Wear Resistant Coatings

Partial coatings and complete part coatings (corrosion and wear resistant):
1) Mould Making
2) Off Shore Drilling
3) Machine Tool
4) Medical

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The flexibility of the additive manufacturing via laser powder nozzle is combined with the precision of the cutting technology.

- The workpiece can be built-up in several steps. Intermediate milling operations are possible.
- Machining of large, complete workpieces
- Repair of turbine components, repair in die & mold, technical and wear resistant coatings
• Far Field Electrospinning – achieve fast deposition of nanofibers

- Near Field Electrospinning takes a random deposition process and converts it into a controlled additive manufacturing process.

Near Field Electrospinning
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2x speed
2s wait at corner
Current Industrial Applications of Electrospinning

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3D cell scaffolds for cell growth and drug testing. (Electrospinning Company)

Battery Separators (Elmarco)

Air Filters (Elmarco)

AVflo™ Vascular Access Grafts with multilayer structure (Nicast)
• Overview of DED and Electrospinning

• Process Parameters and Their Influences
• Sensing and Characterization Methods
• Process Control

• Research Needs
Process Parameters

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- **Powder Deposition Parameters**
  - Powder Flow Rate
  - Shield Gas Flow Rate
  - Powder Shape/Size/Type
  - Nozzle Type

- **Laser Parameters**
  - Laser Spot Size
  - Laser Scanning Speed
  - Laser Power
  - Laser Type

- **Geometric Parameters**
  - Hatch Spacing
  - Layer Height
  - Build Geometry
  - Build Strategy

- **Substrate Parameters**
  - Substrate Surface Condition
  - Substrate Temperature
  - Substrate Size
Effect of Powder Mass Flow Rate on Microstructure

- Porous holes
- Solid layer
- Microcracks

0.8 g/min 1.58 g/min 3.15 g/min

Effect of Powder Mass Flow Rate on Clad Quality

- 20 g/min
- 50 g/min
- 80 g/min


[2] Used with permission from DMG Mori
Effect of Shield Gas Flow on 8620 Steel Build Quality

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Laser Power

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[1] Experimental study of effects of main process parameters on porosity, track geometry, deposition rate, and powder efficiency for high deposition rate laser metal deposition, Zhong et al., Journal of Laser Applications, 2015

Effect of Scan Speed and Laser Power on Ti-6Al-4V Build Microstructure

The effect of laser power and traverse speed on microstructure, porosity and build height in laser-deposited Ti-6Al-4V, Kobryn, Scripta Materialia, 2000
Effect of Part Geometry on Porosity

Shell Build 304L SS

Block Build 304L SS

Quantitative characterization of porosity in stainless steel LENS powders and deposits, Susan, Materials Characterization Vol 57, 2006
Build Strategy
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Effect of Deposition Direction on Microstructure

Outline

• Overview of DED and Electrospinning

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Approaches

- Imaging
  - Infrared (IR) and visible-wavelength cameras

- Emission detection
  - Variations of optical pyrometry or spectroscopy

Methods

- **Electronic scale**: change of weight of metal powders in the hopper
- **Optoelectronic sensor**: laser energy decreased with increasing powder delivery rate

![Fig. 1. Powder delivery rate sensor. (a) Schematic of the powder delivery rate sensor. (b) Setup of the powder delivery rate sensor.](image)

![Fig. 2. Output performance of the powder delivery rate sensor.](image)

 Bulk Ultrasonic Wave Speed Variation with Porosity in LENS® Manufactured CoCr Sample

In-situ X-ray diffraction (XRD) on rapidly heated and cooled Ti alloys

Leinenbach, C., LANL Workshop, Santa Fe, 20/21.07.2015
Novel submicron X-ray microscopy for sub-surface imaging and reveals 3D microstructure

Outline

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Layer Height Control

Control of melt pool temperature and deposition height during direct metal deposition process, Song, et al., The International Journal of Advanced Manufacturing Technology, 2012

With Control

Without Control
Deposit experiences increased heating during build

Deposit experiences stable heating at reduced levels
• Overview of DED and Electrospinning

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• Process Control

• Research Needs
Near Field Electrospinning takes a random deposition process and converts it into a controlled additive manufacturing process.

Unique in-situ monitoring requirements due to printing via continuous nano and micro fiber deposition.

System typically operates using open loop control.

Metrology and characterization done after deposition via SEM.


(A) Deposition of single fiber, scale bar: 100 μm (B) structure deposition, scale bar: 100 μm (C) Microscopic image of deposition process, scale bar: 25 μm
• **Process parameters**: electric field strength, flow rate, deposition speed, and evaporation rate.

• On line **diagnostic requires** high magnification and high temporal resolution of deposition process over large areas.
  - Fiber diameters range from ~ 5 nm to tens of microns.
  - Collector speeds up to 100s of millimeters per second
  - Areas of tens of centimeters.

• **Monitoring of fiber** in flight: diameter, speed, orientation

Current in-situ sensing limited to environmental control (humidity, temperature), electrical current, and limited optical feedback.

Real-time optical monitoring of Taylor cone to assure continuous deposition and estimate fiber diameter.

Relation between electric current and fiber morphology

• Production of copper nanofiber webs via two-step pyrolysis of PVA and copper acetate webs deposited by electrospinning.
• High fiber density leads to resistance reduction
• High transparency and conductivity.


Printing of nano and microchannels

Deposition of nanofibers on patterned silicon collector

Cell Scaffolds with excellent spacing control printed via near field melt electrospinning
NFES Setup

(a) Electric field simulation: electric potential contours, electric field streamlines, and electric field arrows. (b) Comparison of the horizontal component of the electric field along the central axis when the guiding electrode is not present and when a 5 V potential is applied to it.

Results show increased repeatability in deposition when secondary electrode is used.

Proposed stationary electrode ring design with four independent potentials.

Results show increased fiber deposition control when secondary electrode is used.

Proposed piezo actuated electrode ring design at a single potential.

Electrospray assisted Langmuir-Blodgett assembly

Nie, H.L. et al., *JACS*, 2015 137, 10683
• Overview of DED and Electrospinning

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• Process Control

• Research Needs
* Given that AM enables the realization of both design geometry and multi-material characteristics, how do we develop digitally compatible computational design tools that address and integrate multi-material and geometric information into the design of manufacturing process considering uncertainties?
Thermal History: IR Camera
Tool Path and Build Geometry
Preprocessing and Calibration

Local non-equilibrium solution
- Porosity
- Grain size
- Orientation
- Phase %
- Residual Stress

Microstructure: SEM, TEM, FIB, Ultrasonic NDT

Mechanical Properties: Tensile, Shear, Charpy, etc.

Simulation Driven

Topological Design

Coupled Thermal-Microstructure Evolution

Preprocessing and Calibration

Simulation Driven Process Design

Property Prediction

Image/Process-Based Constitutive Modeling

FEA Mesh

Microstructure Reconstruction

Process Design

Process Parameters

Thermal Modeling
Identify key unknown parameters in the material model

**Physics-based Models**

- Beam Power
- Scanning Speed
- Powder Feed Rate

**Thermal Model**
- Thermal conductivity
- Cooling rate
- Thermal expansion coefficient

**Surrogate Models**

**Bayesian Inference**

**Sensor Signals**

**Parameters Updating**

Posterior distribution
• Geometric and experimental information can be saved in a compact format which is used to generate simulation mesh, store simulation results and material performance prediction.

• High throughput and memory bandwidth of massively parallel GPUs can be leveraged.
* Given that AM enables the realization of both design geometry and multi-material characteristics, how do we develop digitally compatible computational design tools that address and integrate multi-material and geometric information into the design of manufacturing process considering uncertainties?

* Many of the limitations of AM can be effectively addressed with predictive simulation paired with equipment innovation, effective process control and a strong understanding of the processes, materials, and properties involved.
TYPE OF MANUFACTURING

DISTRIBUTED

1800 AD
Self-reliance

CONCENTRATED

2000 AD
Reliance on others

DISTRIBUTED + CONCENTRATED

2100 AD

CURRENT FORCES NOW AT WORK

• Globalization
• Cyber Infrastructure
• Technological Advances
• Mass Customization / Personalization
• Emergence of Point-of-use Technologies

Rapid Flexible Manufacturing
Support from NIST, NSF, DOD and DMG MORI

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THANK YOU
Stratonics Therma Viz System
Northwestern Engineering

Temperature & Dimensional Metrics:
- Heating & Cooling Rates
- Peak Temperatures
- Melt Pool Size & Global Heat Flow

Control of Process Parameters:
- Laser Power
- Deposit Speed
- Powder Rate

Computer

Laser

Melt Pool Sensor

Global Heat Flow Sensor

Focused laser beam
Converging powder streams
Substrate
Deposition surface
x-y motion