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

*Direct Energy Deposition and Electrospinning*

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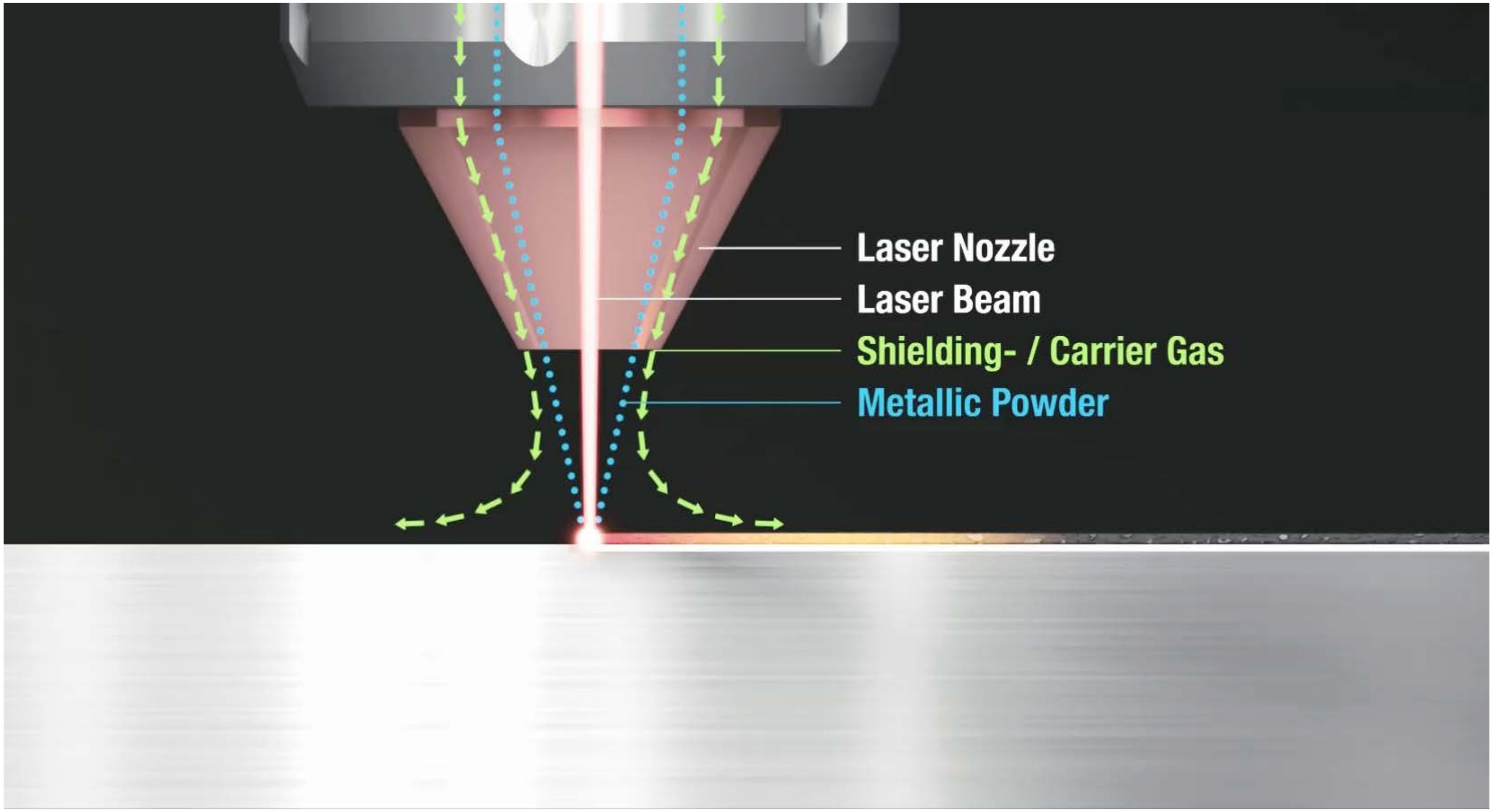
NORTHWESTERN UNIVERSITY

# Direct Energy Deposition

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# DED Industrial Application

## Hybrid Additive and Subtractive Machining

Prototypes and small series production of complex lightweight and integral parts for:

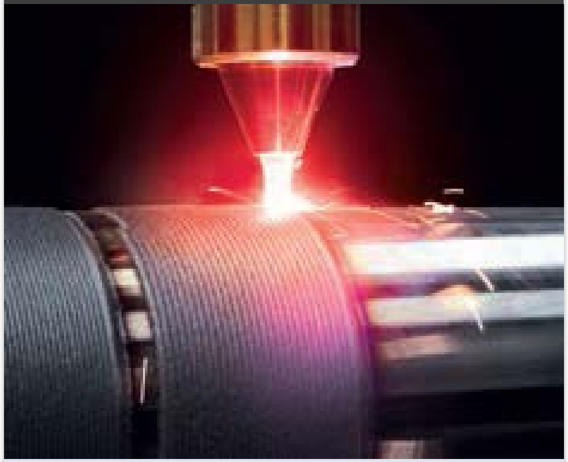
**1) Die & Mold**
**2) Aerospace**
**3) Automotive**
**4) Medical**

## 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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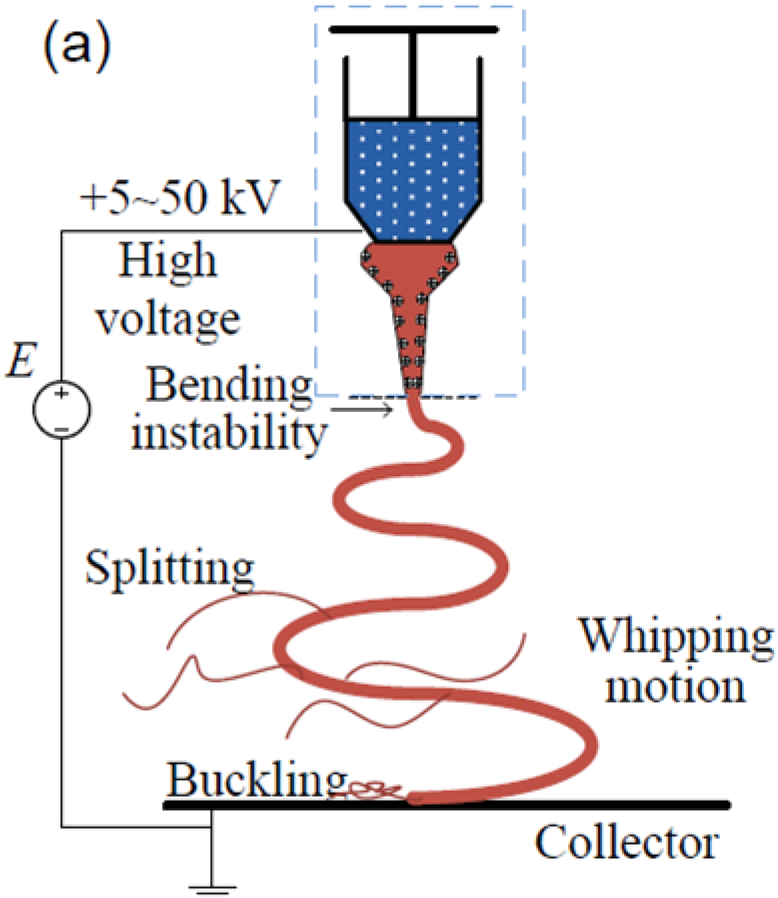
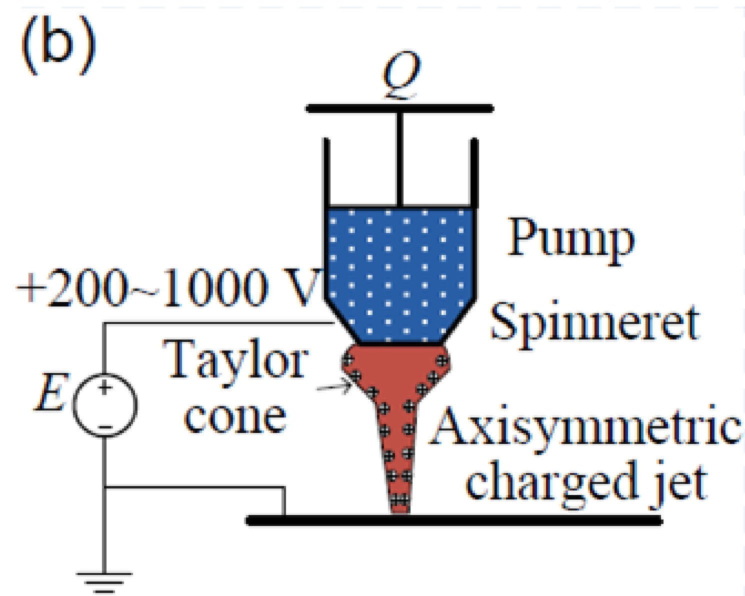
- **The flexibility of the additive manufacturing via laser powder nozzle is combined with the precision of the cutting technology**
- The workpiece can be built-up in several steps. Intermediate milling operations are possible.
- Machining of large, complete workpieces
- Repair of turbine components, repair in die & mold, technical and wear resistant coatings

# Electrospinning



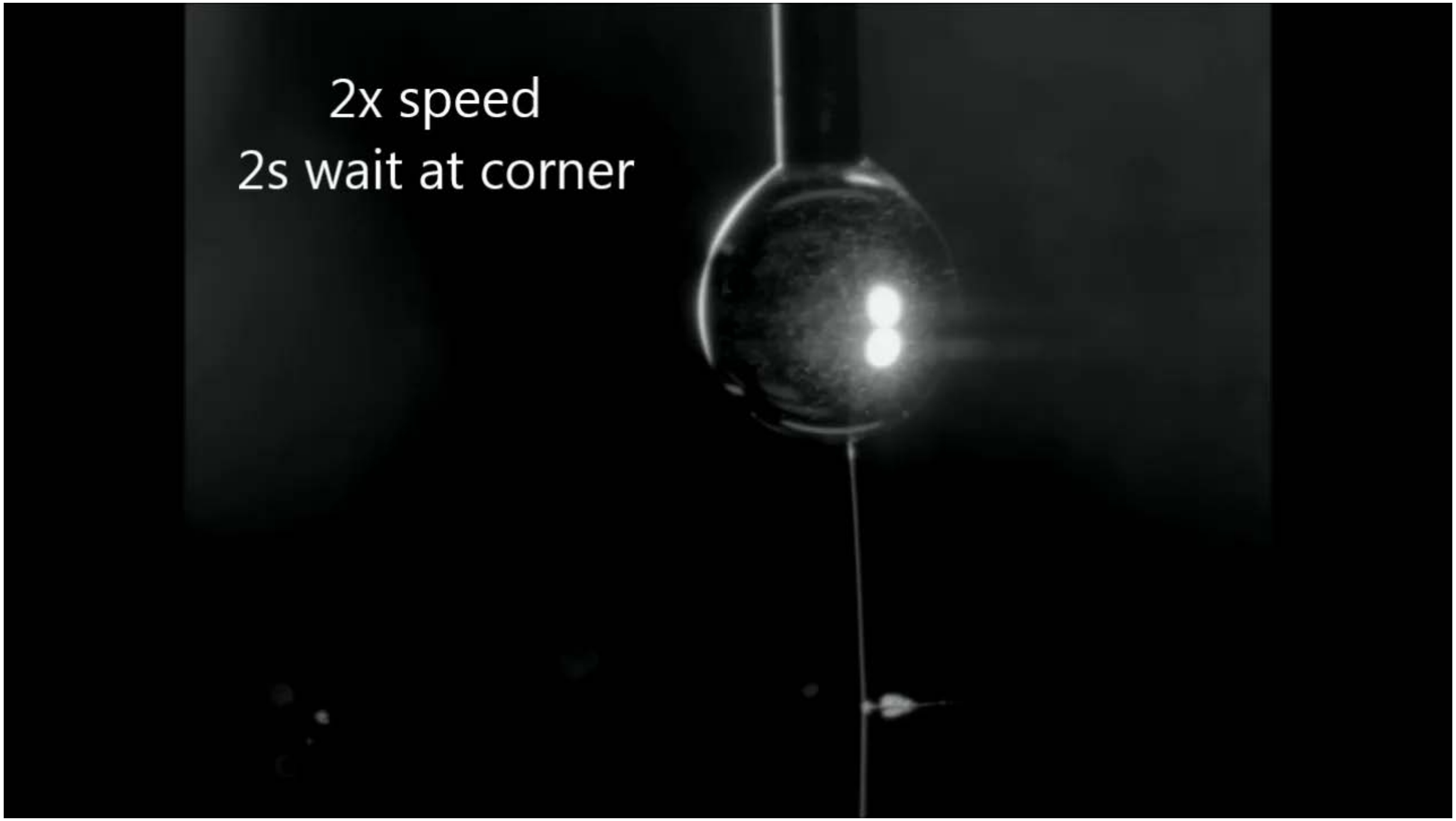




- Far Field Electrospinning – achieve fast deposition of nanofibers

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

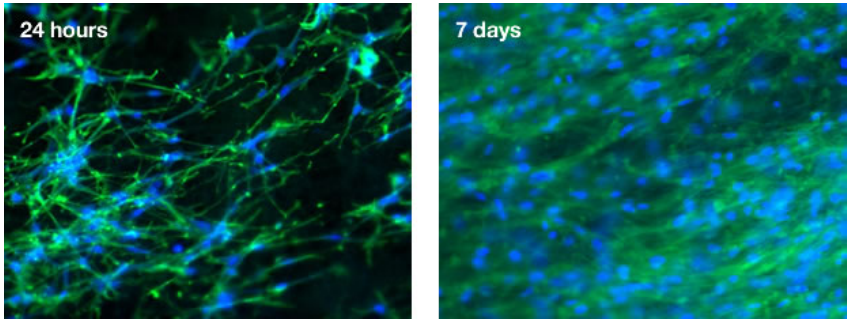
Sun, Daoheng, et al. "Near-field electrospinning." *Nano letters* 6.4 (2006): 839-842.

# Near Field Electrospinning

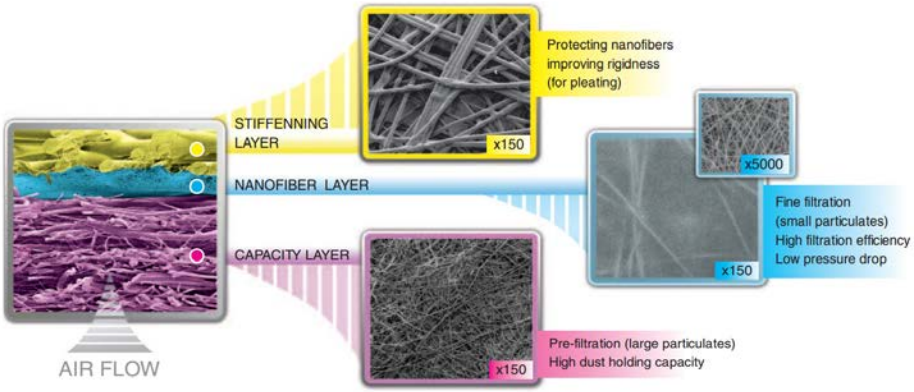



Nicolas Camilo Martinez Prieto, Jian Cao, Jiaxing huang, Kornel Ehmann, Northwestern AMPL 2015

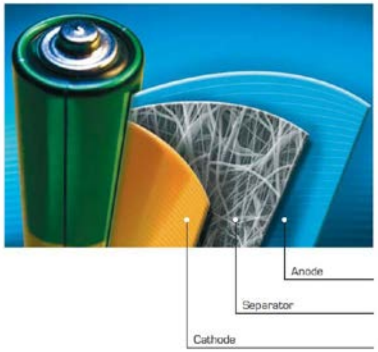
# Current Industrial Applications of Electrospinning



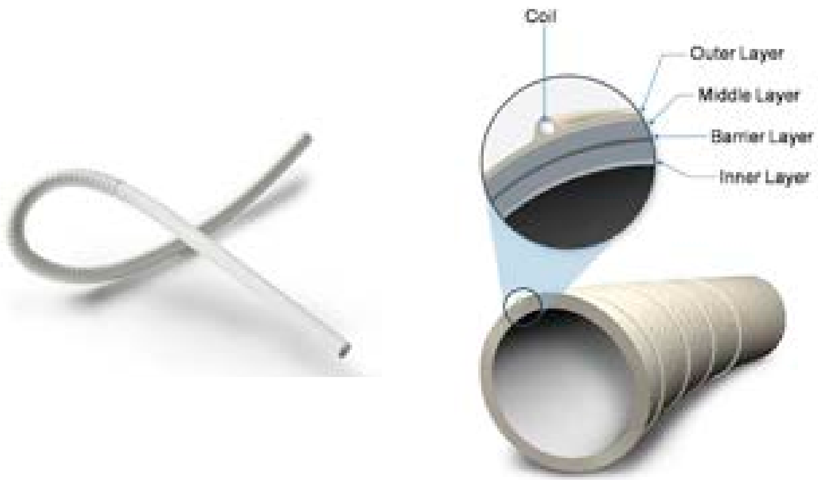

3D cell scaffolds for cell growth and drug testing. (Electrospinning Company)




Air Filters (Elmarco)




Battery Separators (Elmarco)




AVflo™ Vascular Access Grafts with multilayer structure (Nicast)

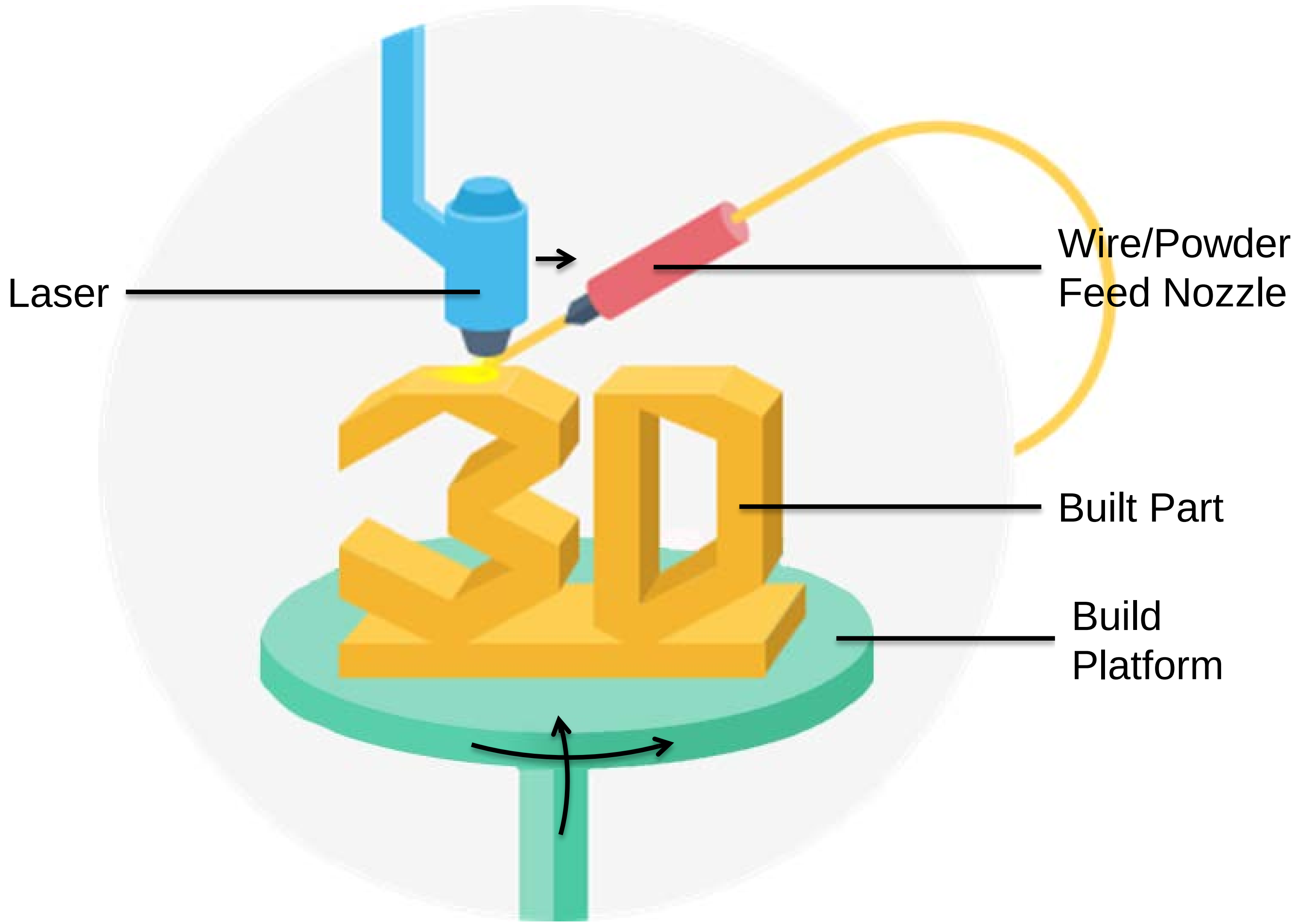
# Outline

- **Overview of DED and Electrospinning**

- **Process Parameters and Their Influences**
- **Sensing and Characterization Methods**
- **Process Control**

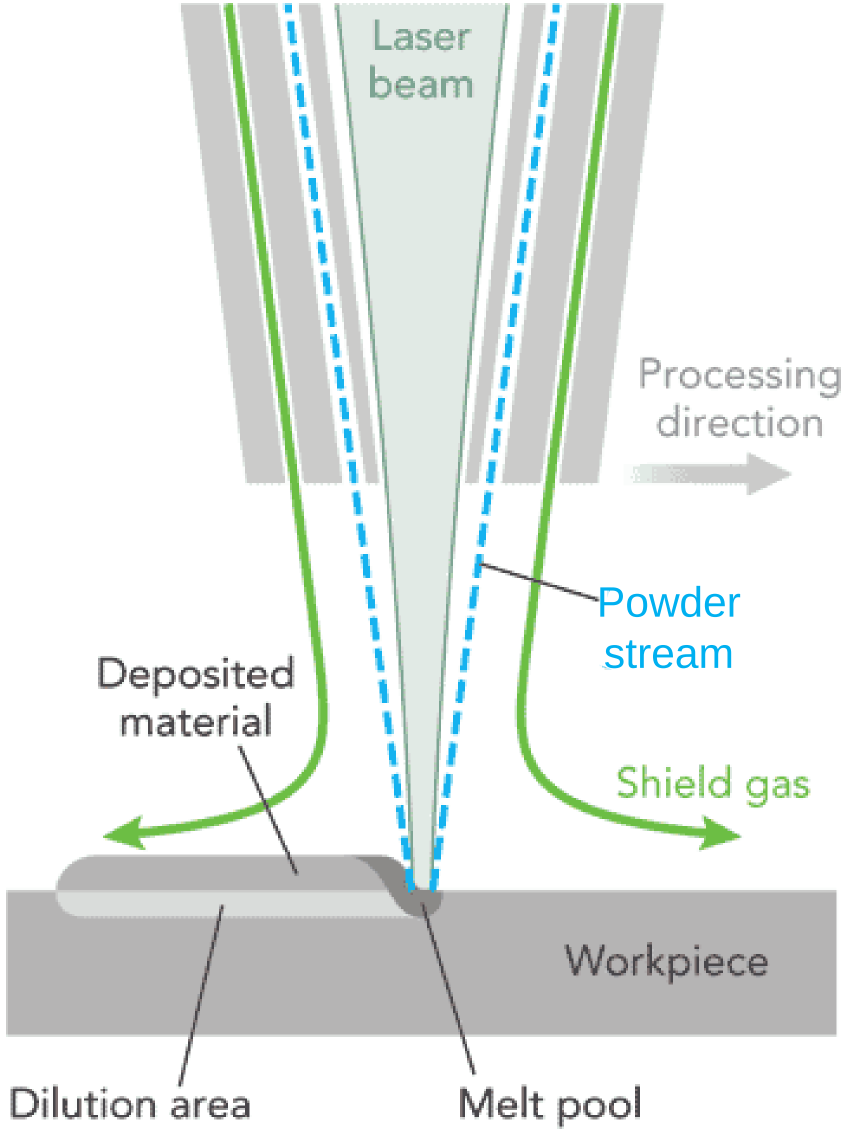
- **Research Needs**

# Direct Energy Deposition

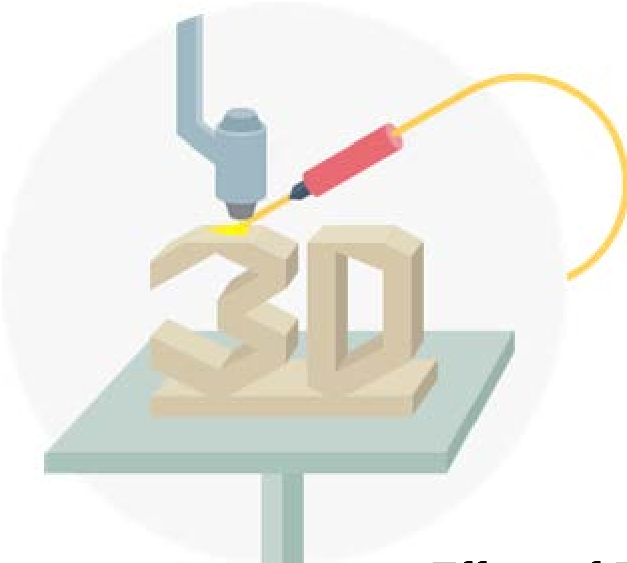


# Process Parameters

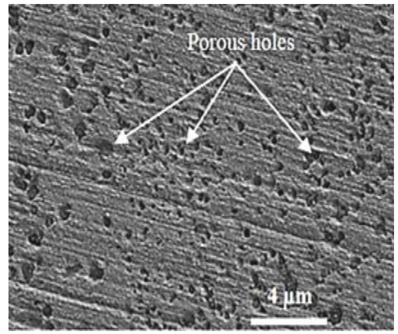
- **Powder Deposition Parameters**
  - **Powder Flow Rate**
  - **Shield Gas Flow Rate**
  - **Powder Shape/Size/Type**
  - **Nozzle Type**
- **Laser Parameters**
  - **Laser Spot Size**
  - **Laser Scanning Speed**
  - **Laser Power**
  - **Laser Type**
- **Geometric Parameters**
  - **Hatch Spacing**
  - **Layer Height**
  - **Build Geometry**
  - **Build Strategy**
- **Substrate Parameters**
  - **Substrate Surface Condition**
  - **Substrate Temperature**
  - **Substrate Size**



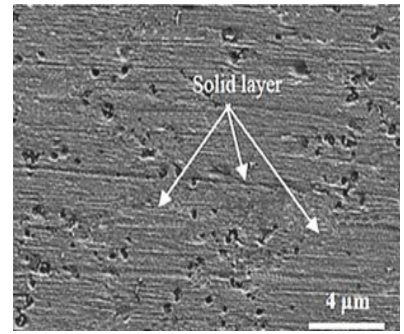
# Powder Flow Rate



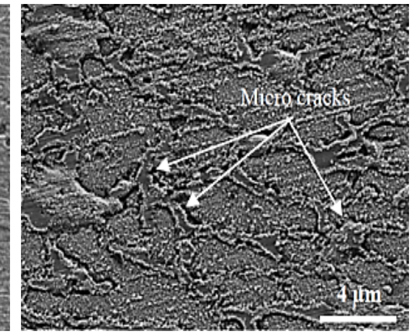
## Effect of Powder Mass Flow Rate on Microstructure[1]




0.8 g/min

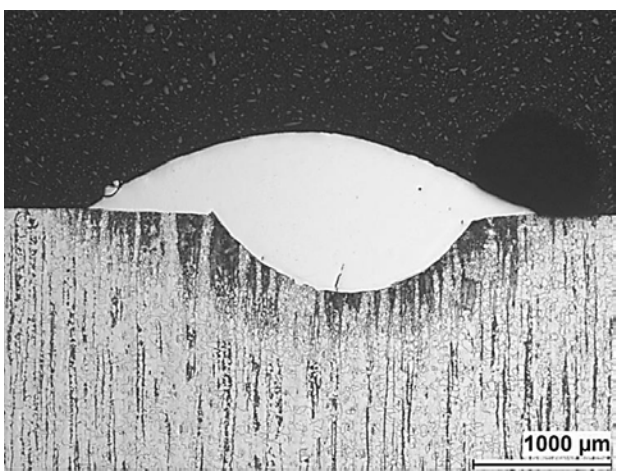



1.58 g/min

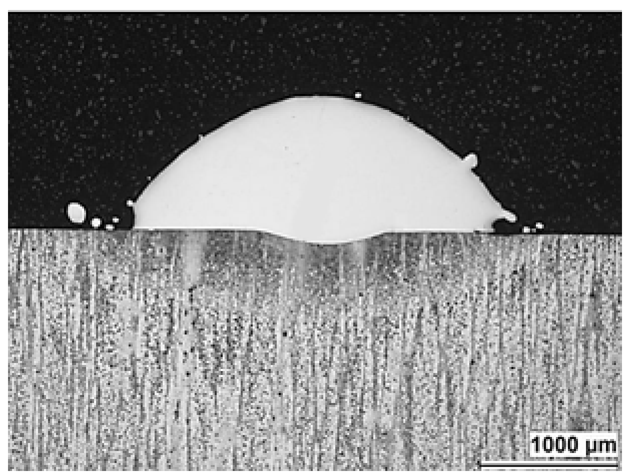



3.15 g/min

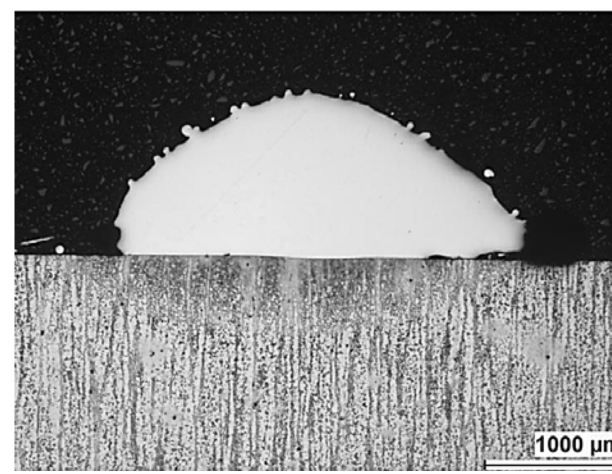
## Effect of Powder Mass Flow Rate on Clad Quality [2]




20 g/min



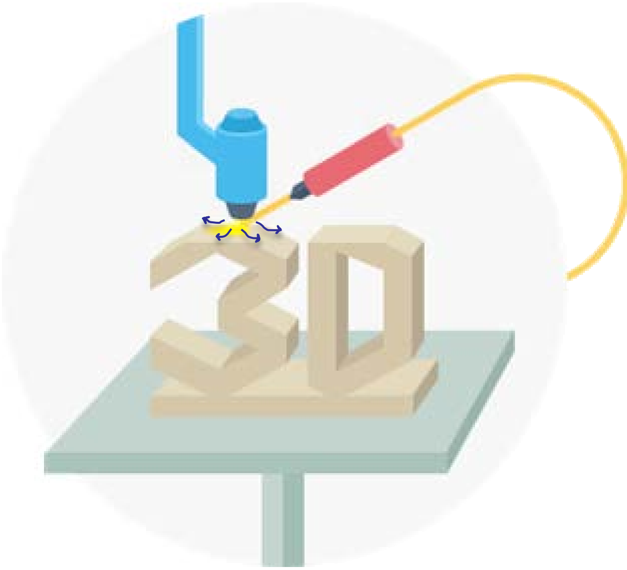

50 g/min




80 g/min

*[1] Influence of Process Parameters in the Direct Metal Deposition of H13 Tool Steel on Copper Alloy Substrate, Imran et al., Proceedings of the World Congress on Engineering Vol III, 2010*
*[2] Used with permission from DMG Mori*

# Shield Gas

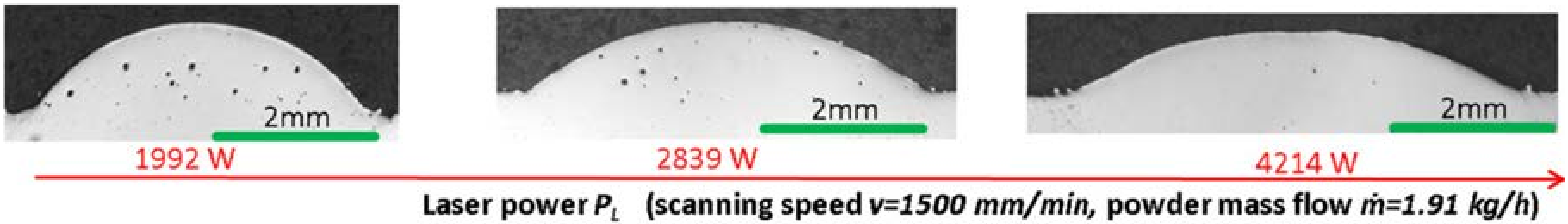



Sufficient
Shield Gas Flow

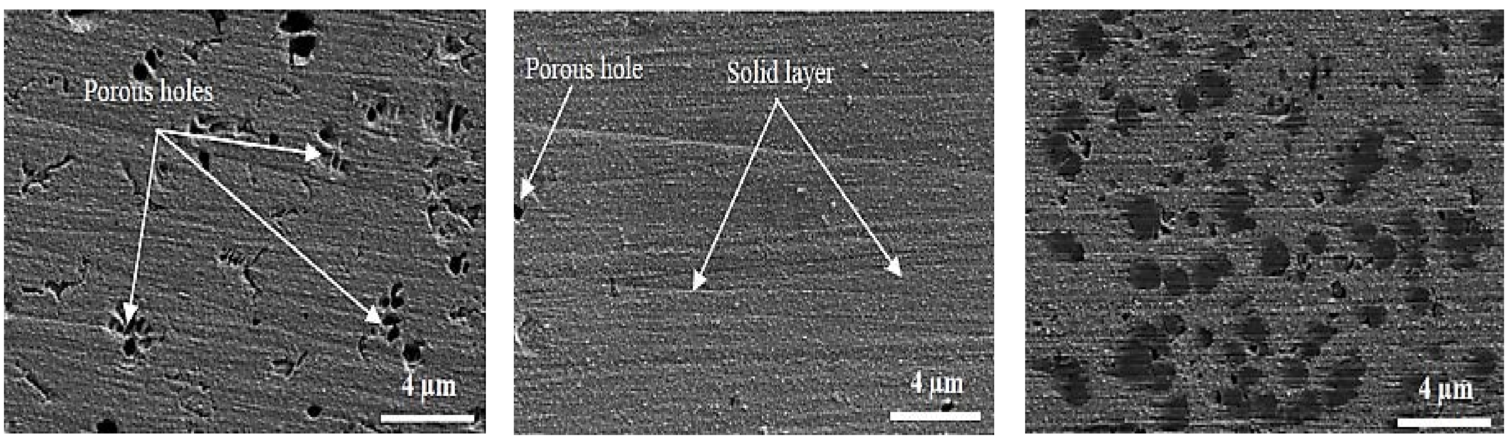
Insufficient
Shield Gas Flow

**Effect of Shield Gas Flow on 8620 Steel Build Quality**

# Laser Power




[1]

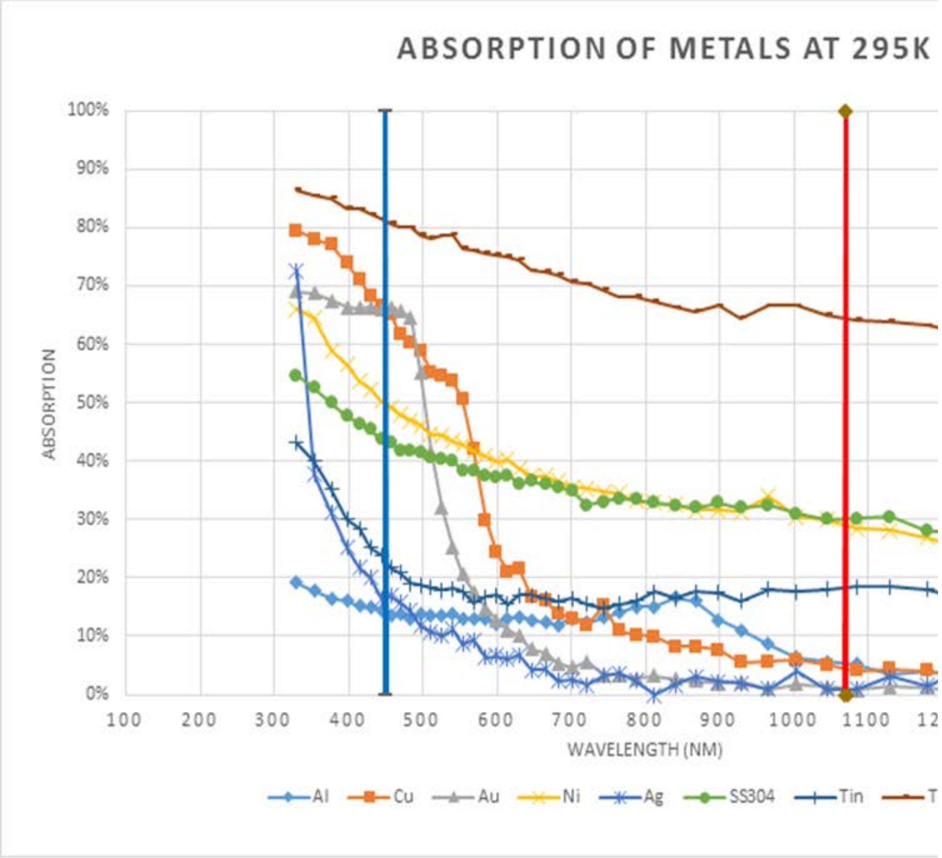


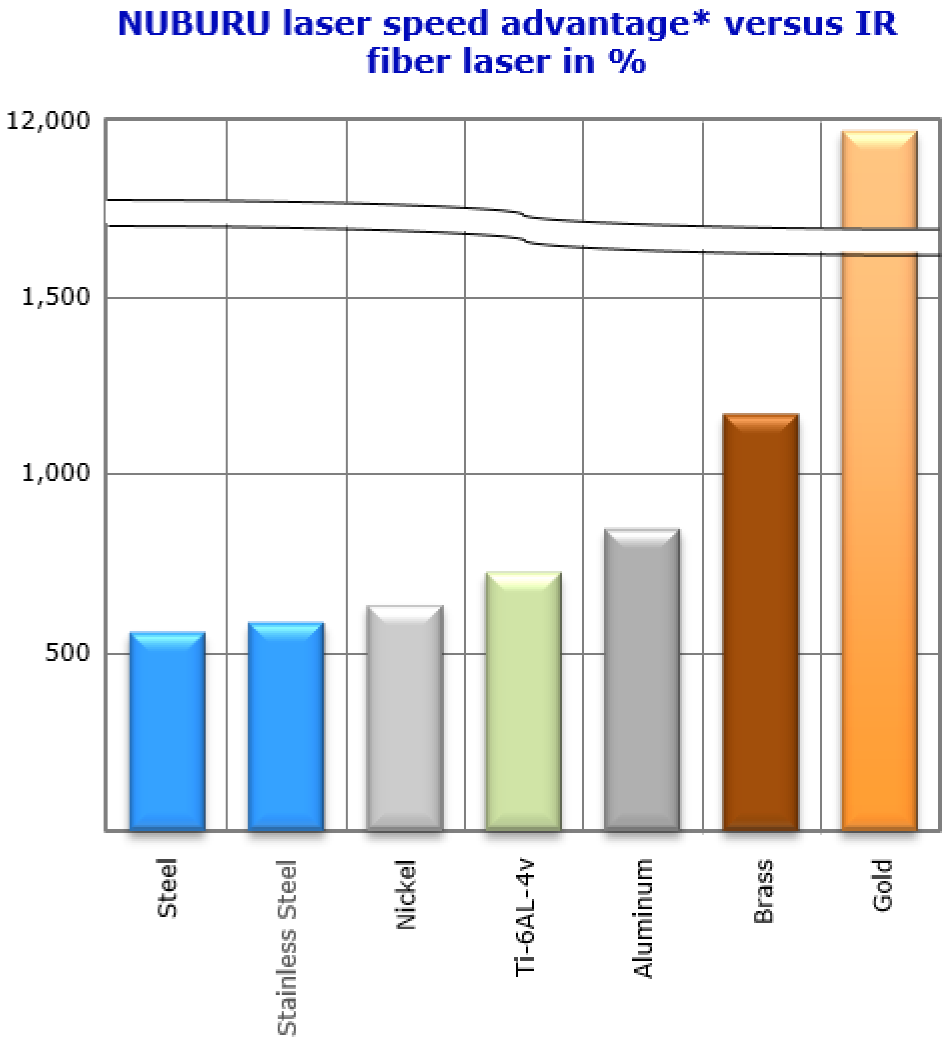

**4 kW** **3 kW** **2 kW**

[2]

*[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*
*[2] Influence of Process Parameters in the Direct Metal Deposition of H13 Tool Steel on Copper Alloy Substrate, Imran,* Proceedings of the World Congress on Engineering, *2010*

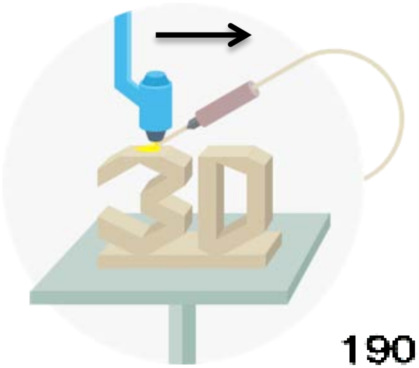
# Laser Type



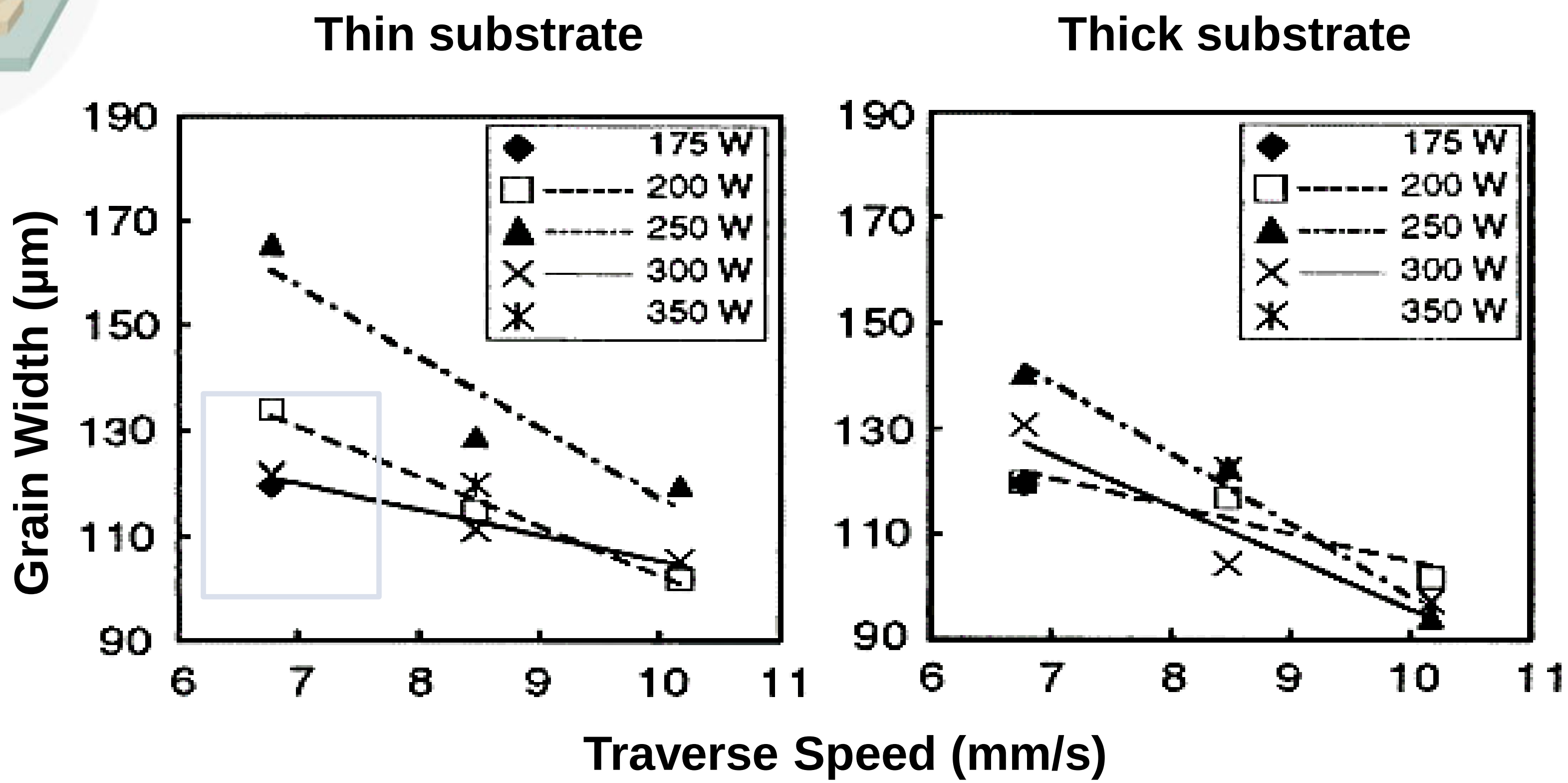




NUBURU

# Laser Feed Rate

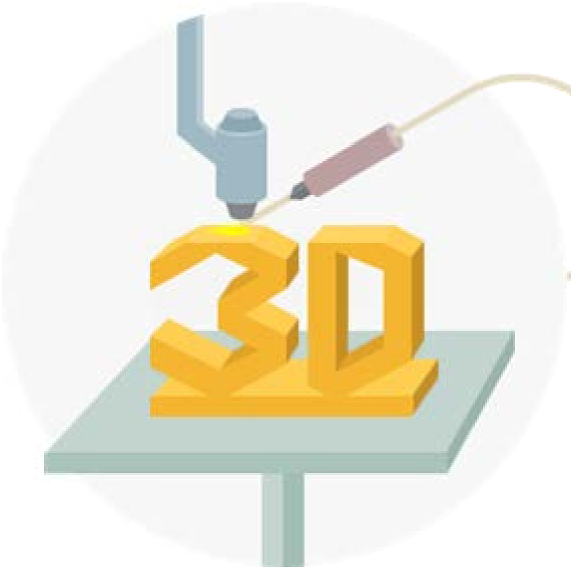


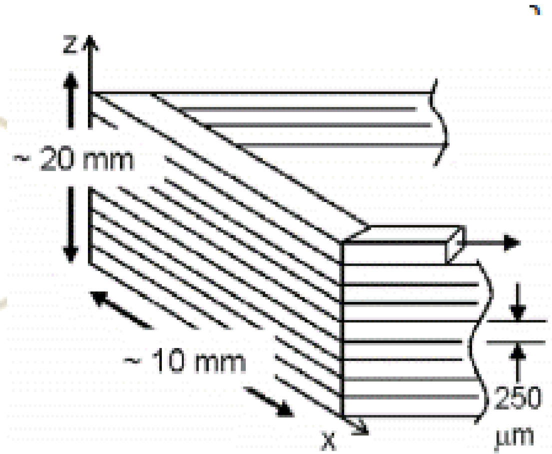
## Effect of Scan Speed and Laser Power on Ti-6Al-4V Build Microstructure



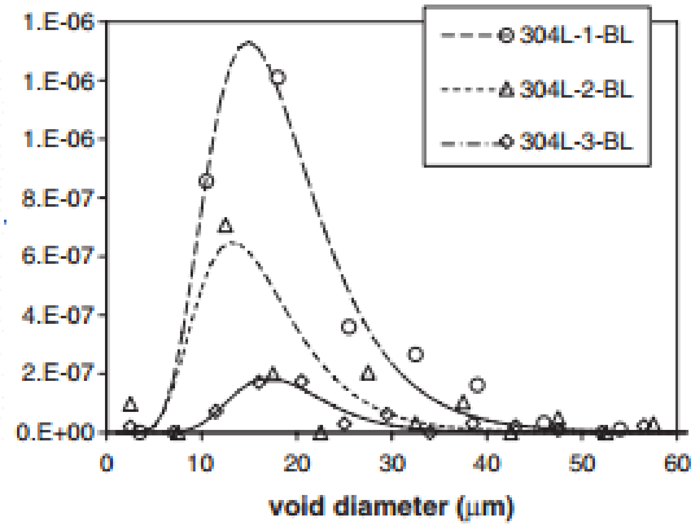

*The effect of laser power and traverse speed on microstructure, porosity and build height in laser-deposited Ti-6Al-4V, Kobryn, Scripta Materialia, 2000*

# Build Geometry

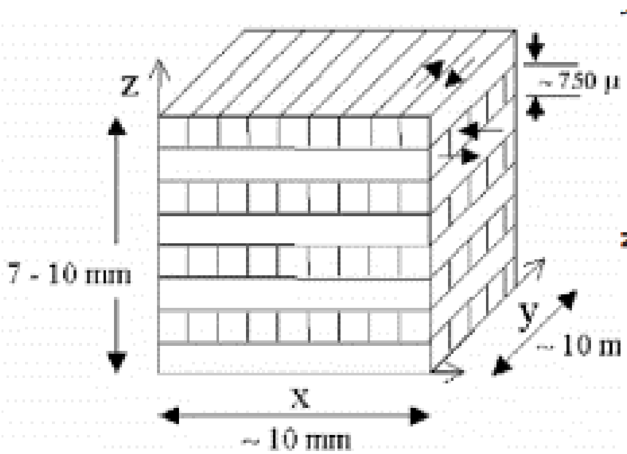




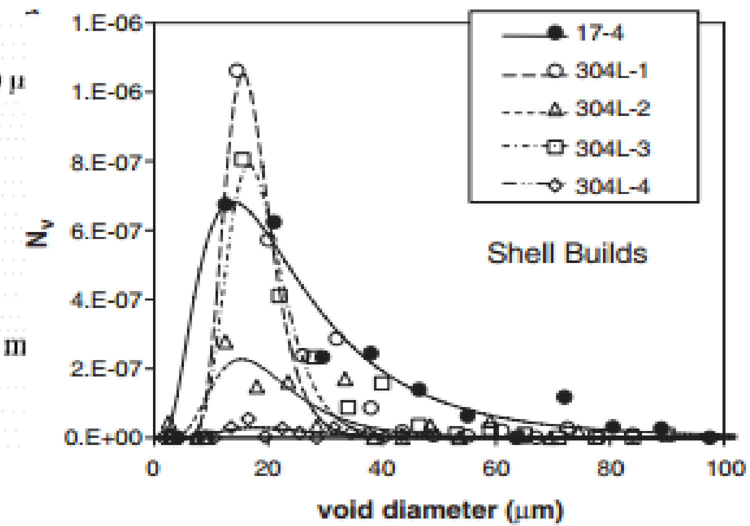

**Shell Build 304L SS**




**Effect of Part Geometry on Porosity**



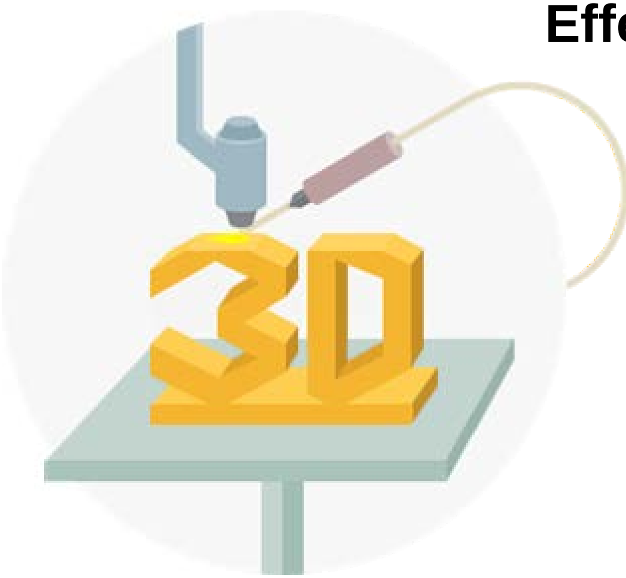

**Block Build 304L SS**

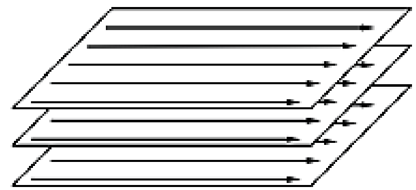



*Quantitative characterization of porosity in stainless steel LENS powders and deposits, Susan, Materials Characterization Vol 57, 2006*

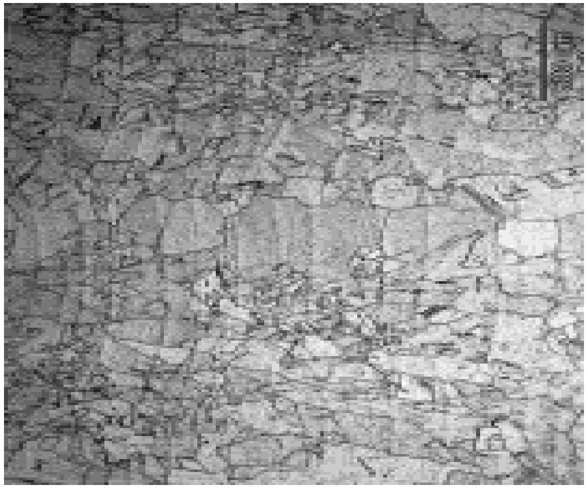
# Build Strategy

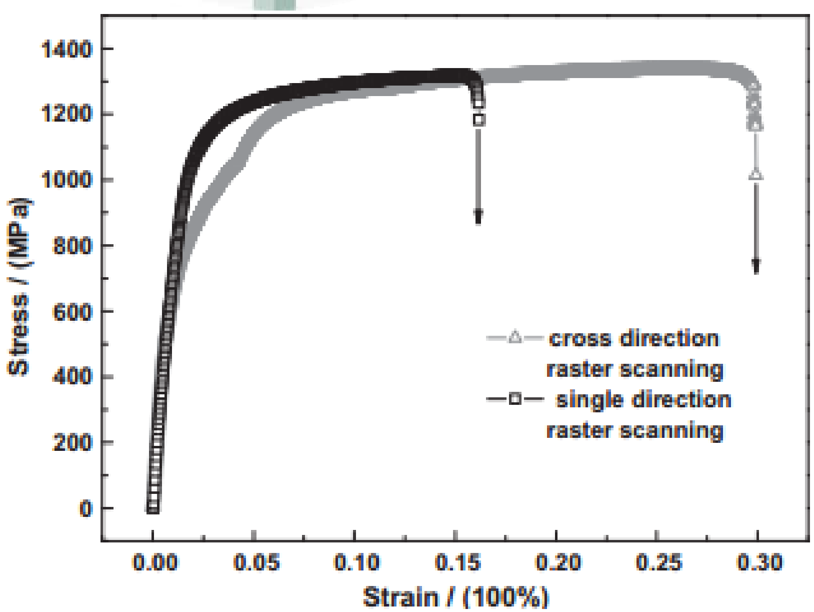
## Effect of Deposition Direction on Microstructure

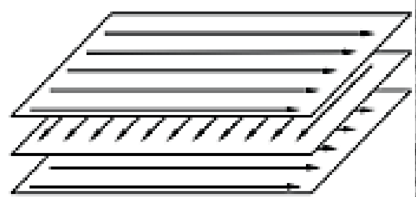




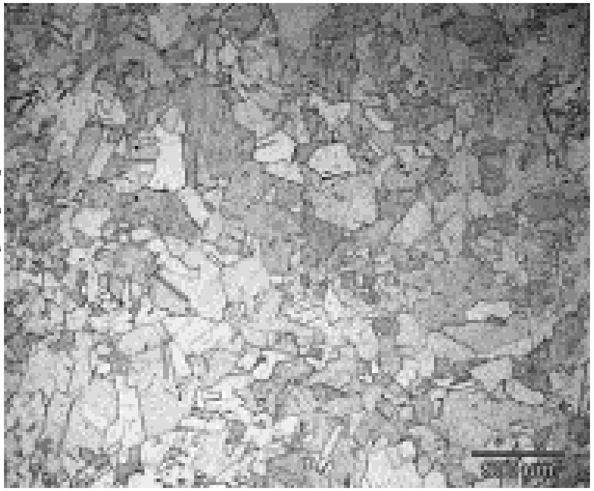
**Single Direction Scanning**





**Cross Direction Scanning**



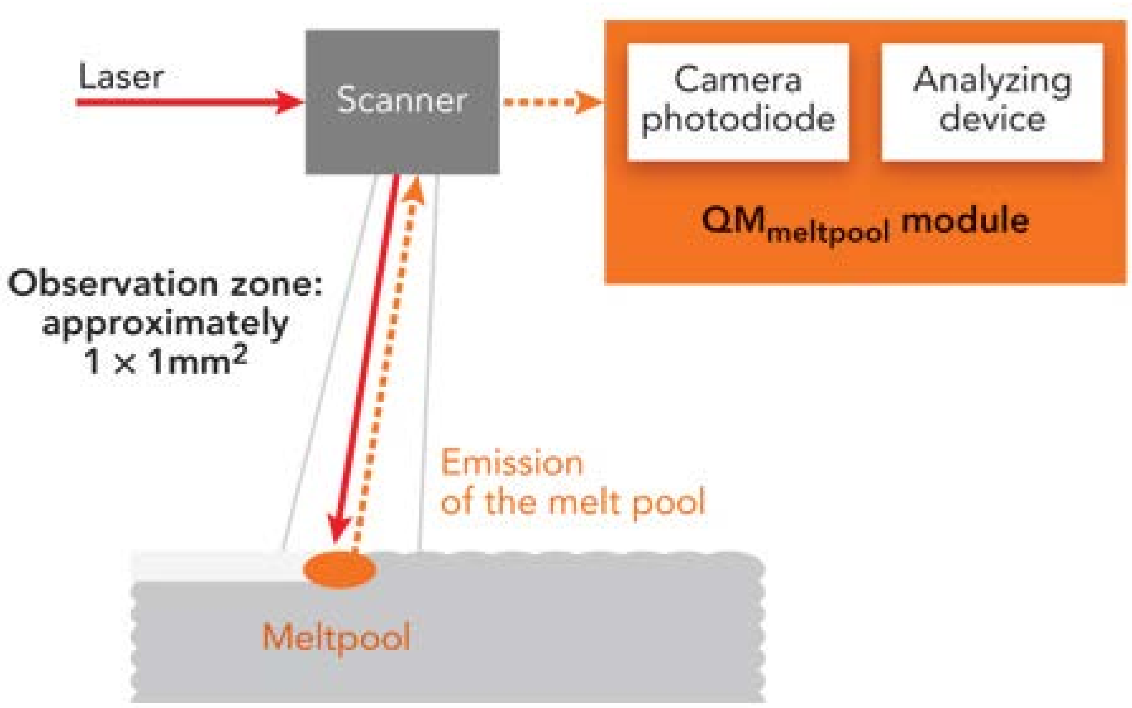
*The effect of laser scanning path on microstructures and mechanical properties of laser solid formed nickel-base superalloy Inconel 718, Liu, Journal of Alloys and Compounds, 2011*

# Outline

- Overview of DED and Electrospinning
- Process Parameters and Their Influences
- Sensing and Characterization Methods
- Process Control
- Research Needs

**Approaches**

- Imaging
    - Infrared (IR) and visible-wavelength cameras
- Emission detection
    - Variations of optical pyrometry or spectroscopy




C. Dunsky, Process monitoring in laser additive manufacturing, Industrial Laser Solutions for Manufacturing, September 12, 2014.

# Powder Delivery Rate Sensing

## Methods

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

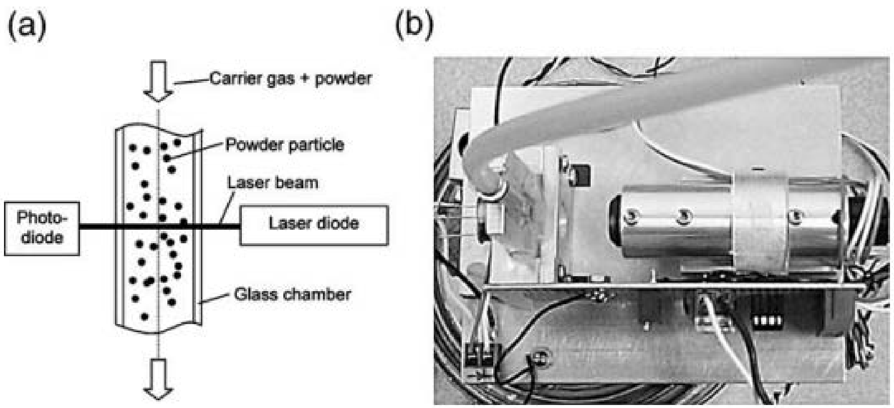



Fig. 1. Powder delivery rate sensor. (a) Schematic of the powder delivery rate sensor. (b) Setup of the powder delivery rate sensor.

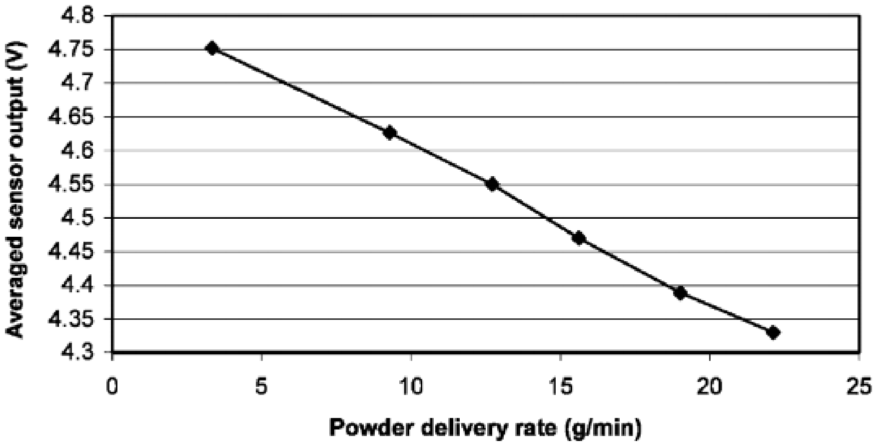
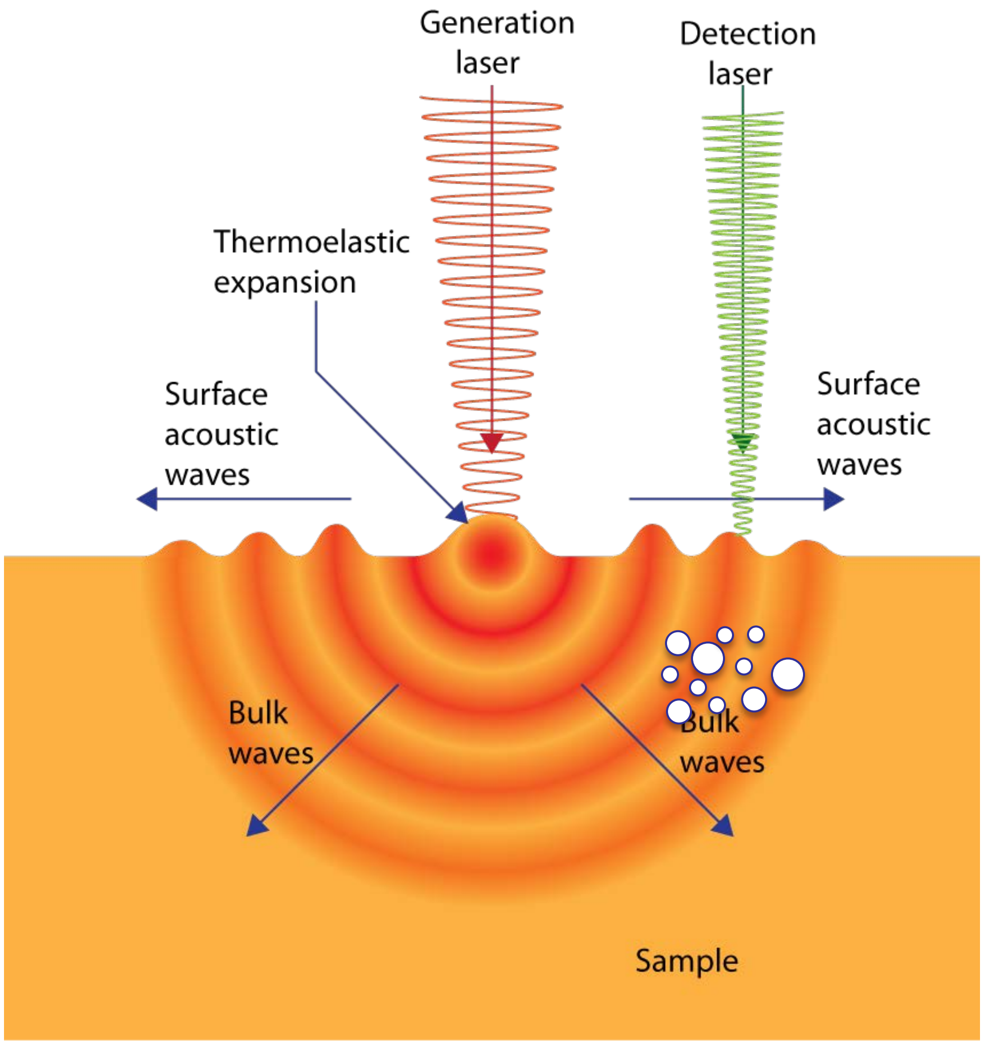



Fig. 2. Output performance of the powder delivery rate sensor.

Hu, D., & Kovacevic, R. (2003). Sensing, modeling and control for laser-based additive manufacturing. *International Journal of Machine Tools and Manufacture*, *43*(1), 51–60.

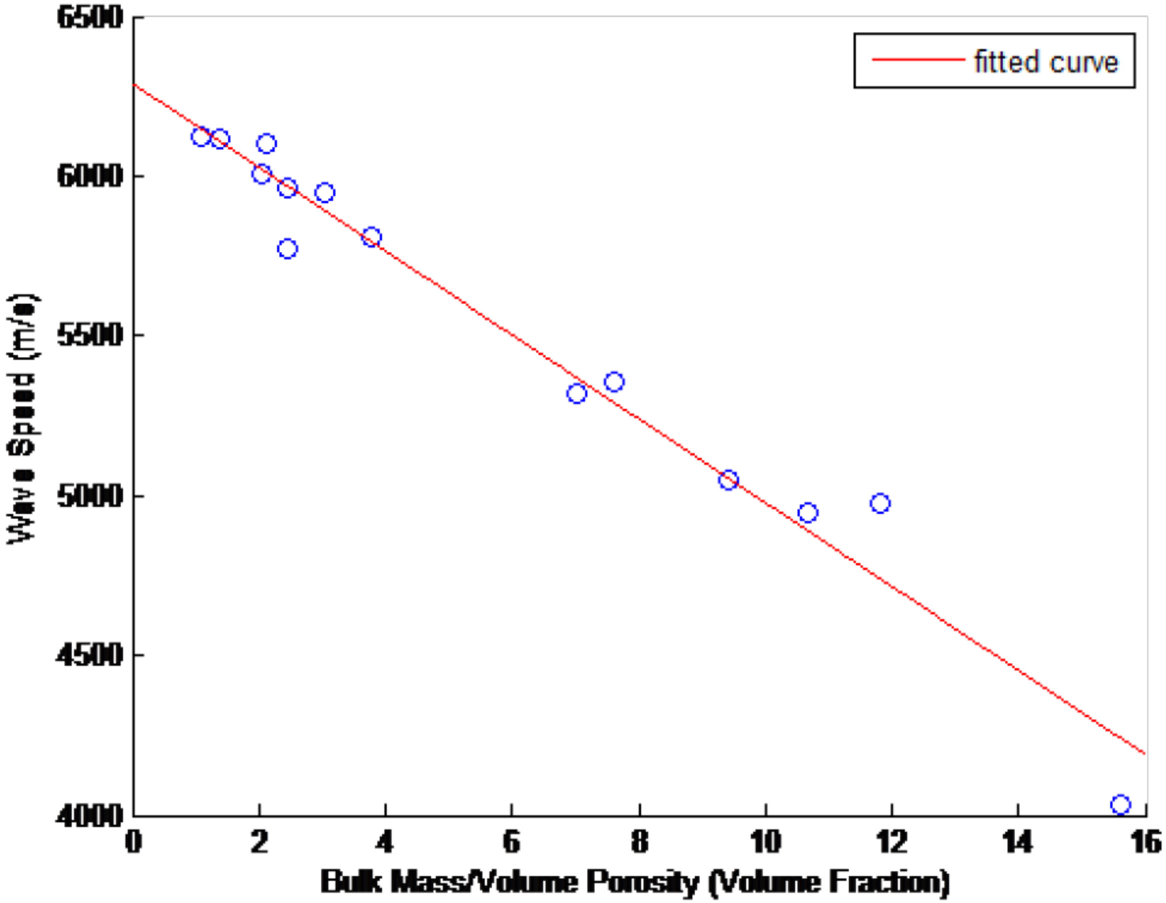
# Laser Ultrasonics




Balogun and Liou, Northwestern

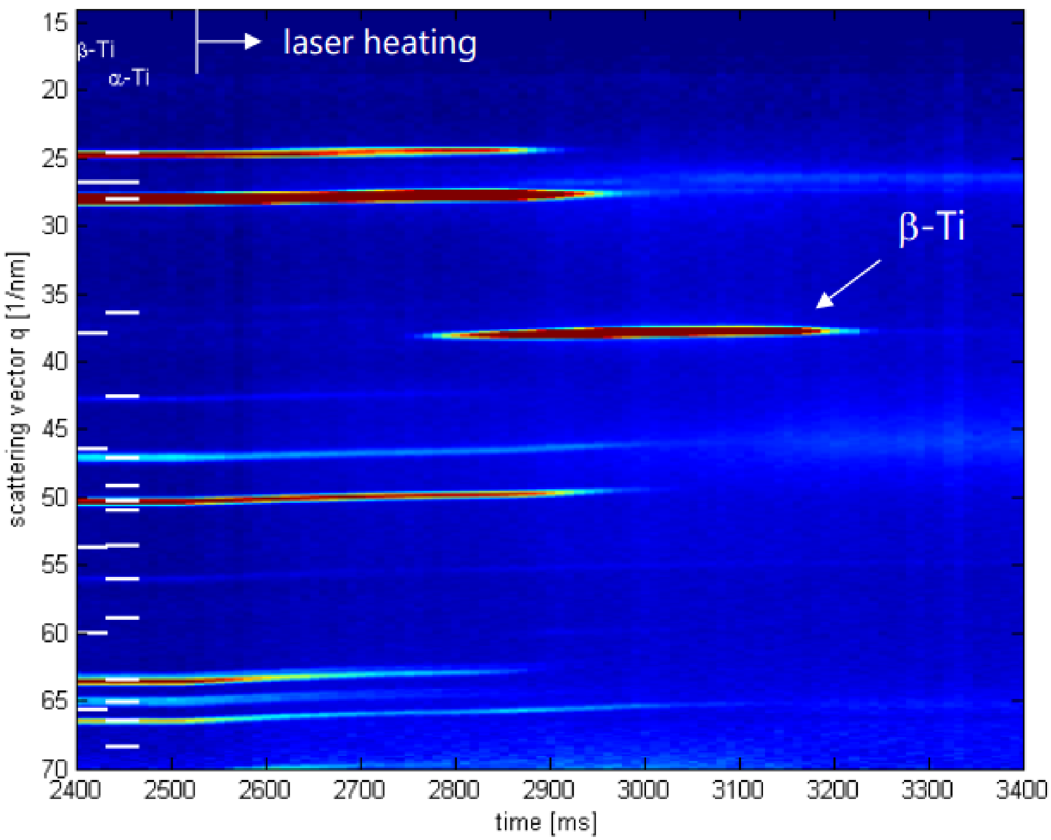
# Porosity Detection

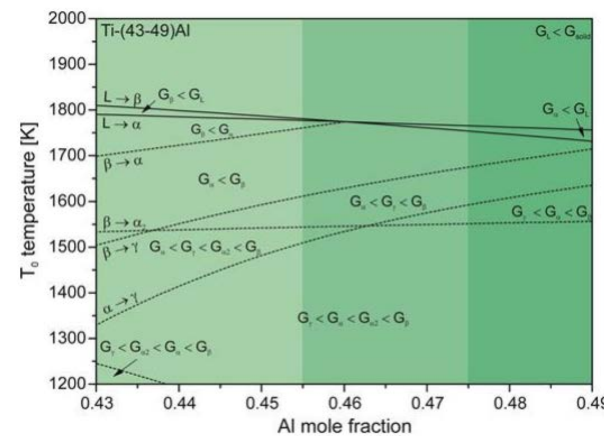
Bulk Ultrasonic Wave Speed Variation with Porosity in LENS® Manufactured CoCr Sample




J.A. Slotwinski, E.J. Garboczi, and K.M. Hebenstreit, "Porosity Measurements and Analysis for Metal Additive Manufacturing Process Control," Jornal of Research of the NIST **119**, pp. 494-528, (2014).

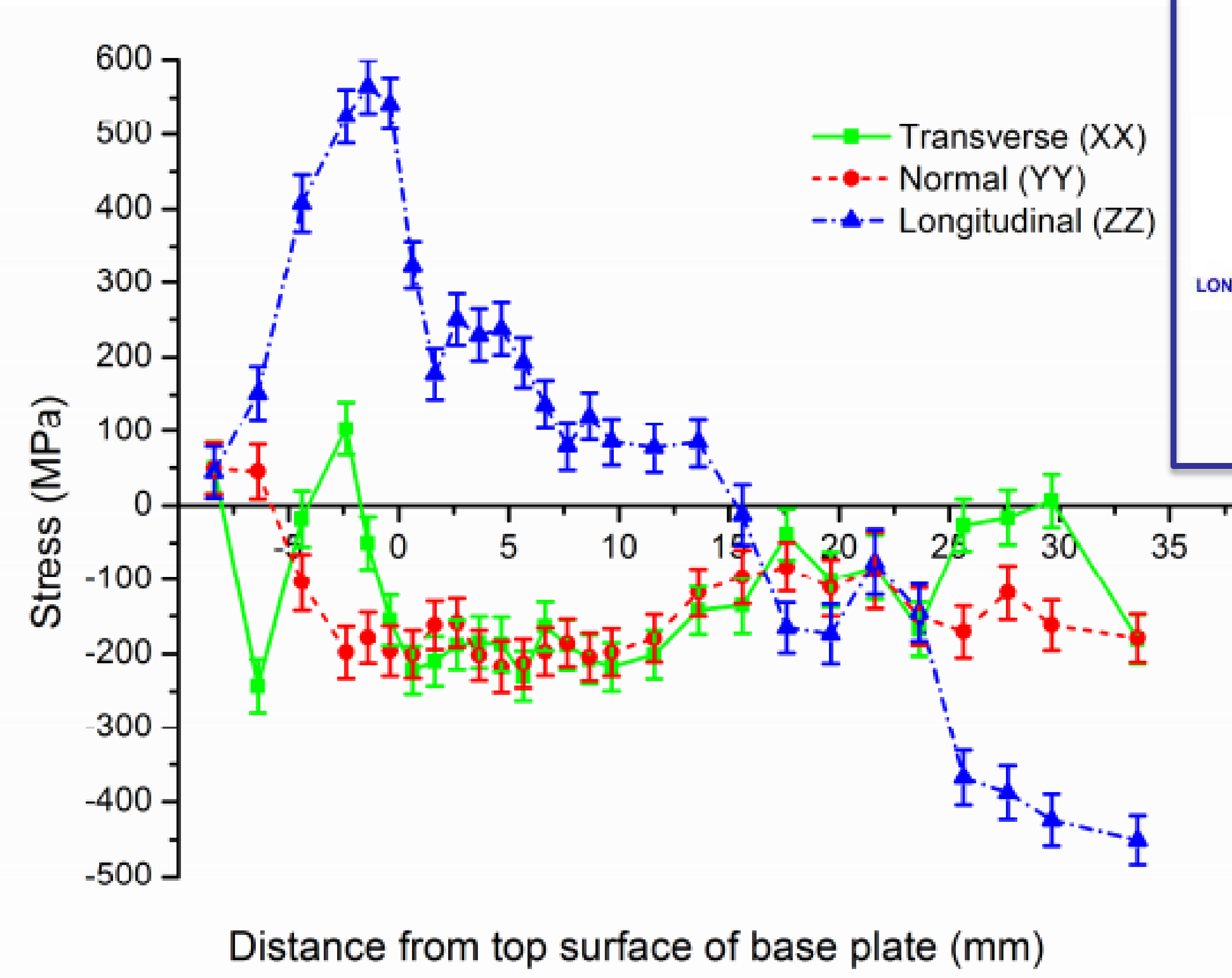
## In-situ X-ray diffraction (XRD) on rapidly heated and cooled Ti alloys

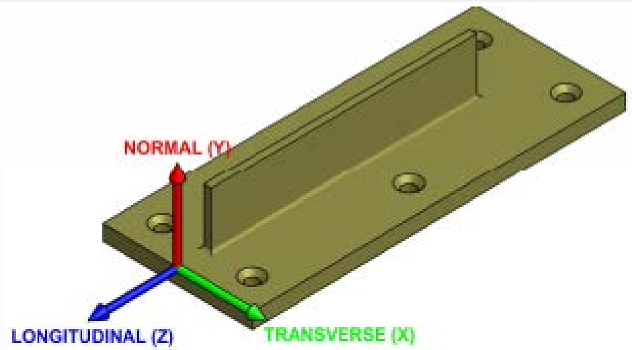


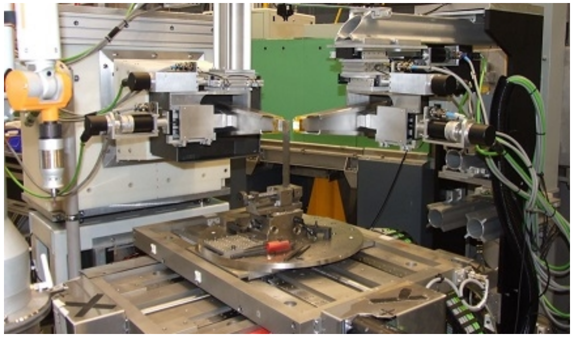

*Leinenbach, C., LANL Workshop, Santa Fe, 20/21.07.2015*

# Stress Measurement



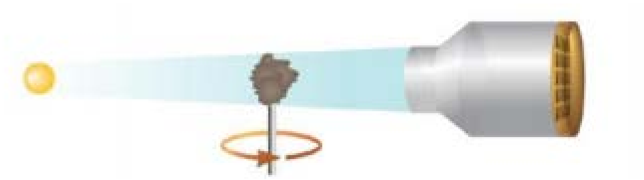

**Thin-walled component built on base plate**

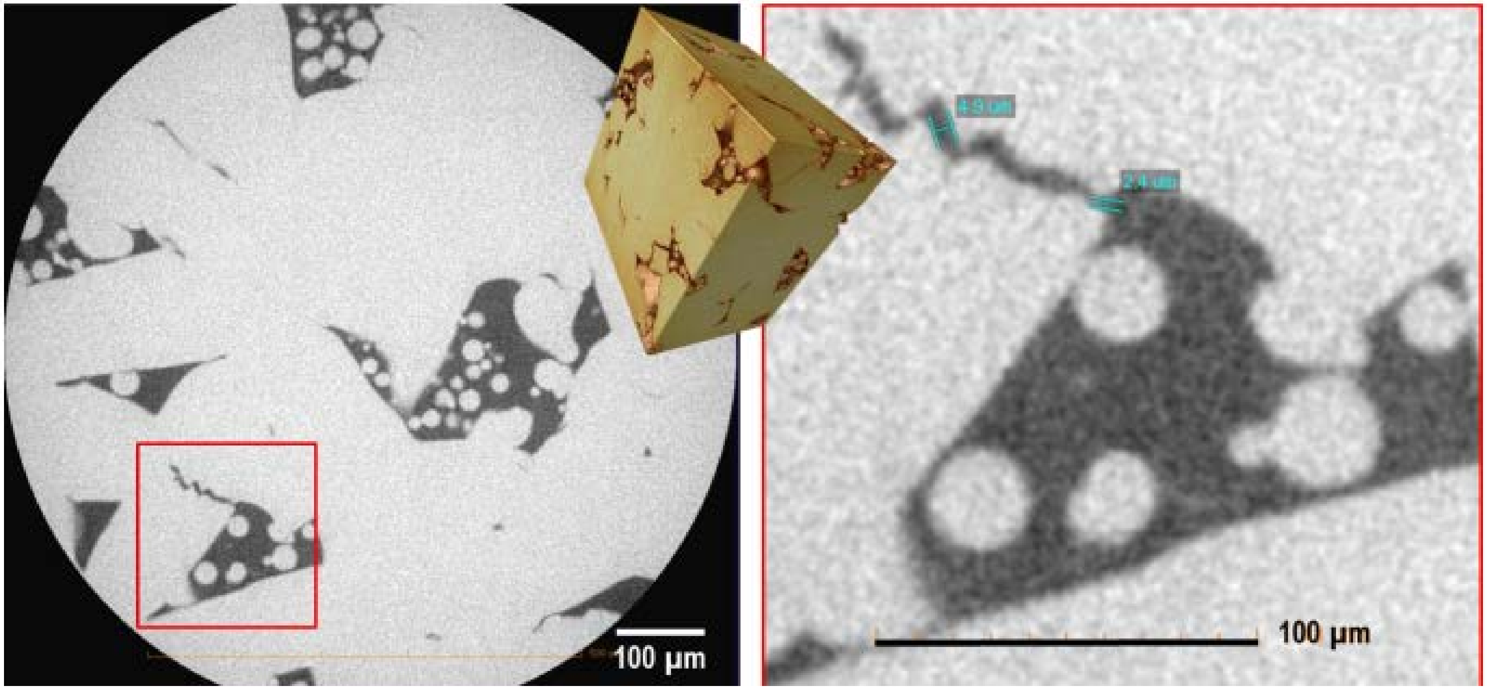


**KOWARI strain scanner using neutron diffraction**

*Hoye, N., et al. (2014). Measurement of residual stresses in titanium, aerospace components formed via additive manufacturing.* Material Science Forum.

# Novel submicron X-ray microscopy for sub-surface imaging and reveals 3D microstruture






Lavery, L. (2015). Recent advancements in 3D X-ray microscopes for additive manufacturing. Microscopy Society of America.

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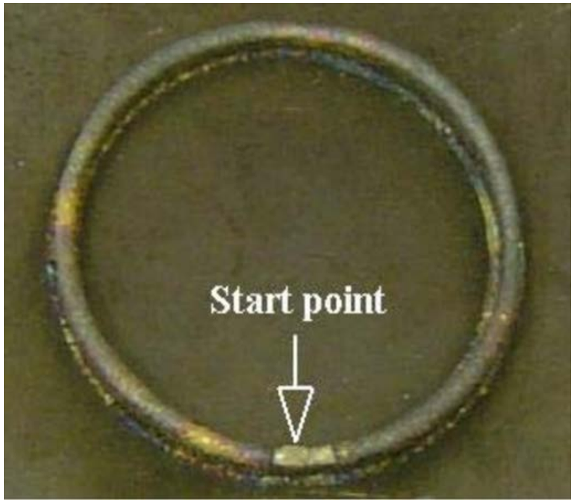
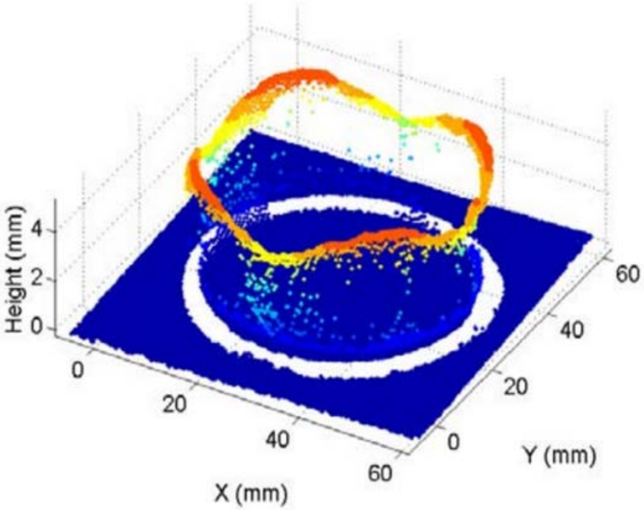
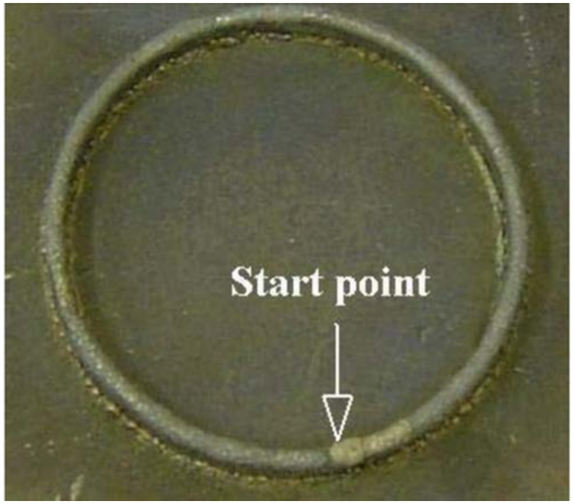
# Powder Flow Control

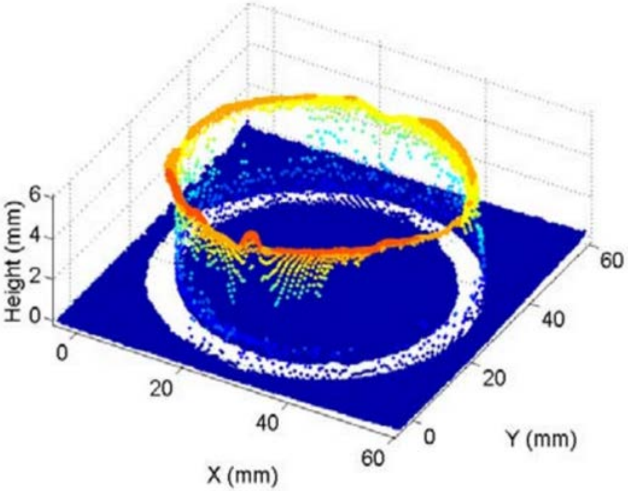
**Without Control**



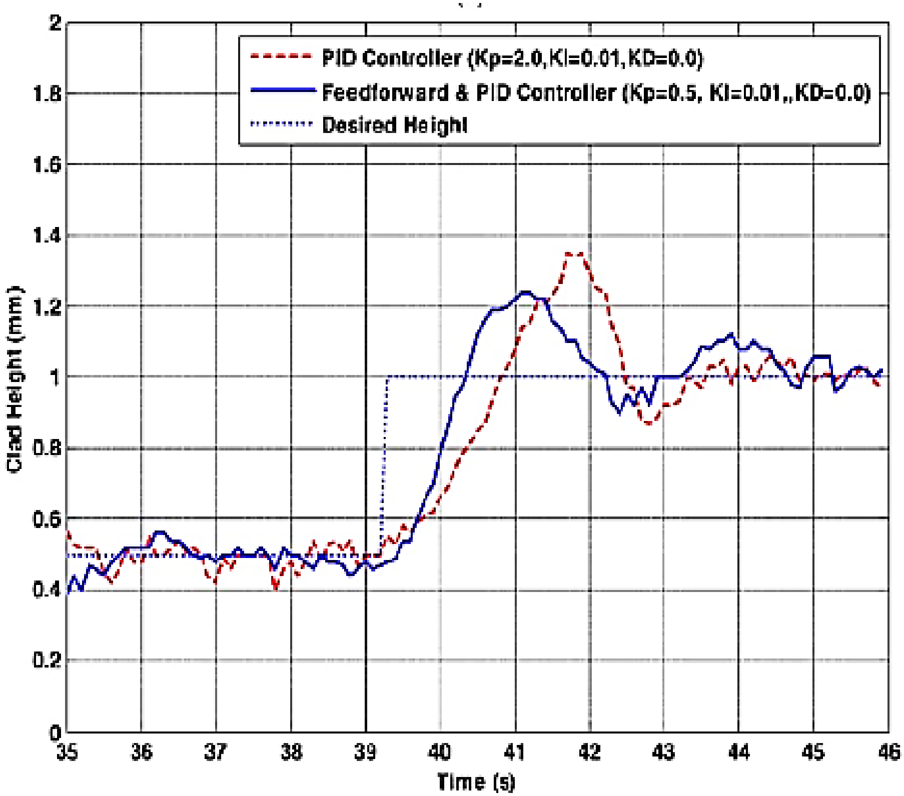

**With Control**

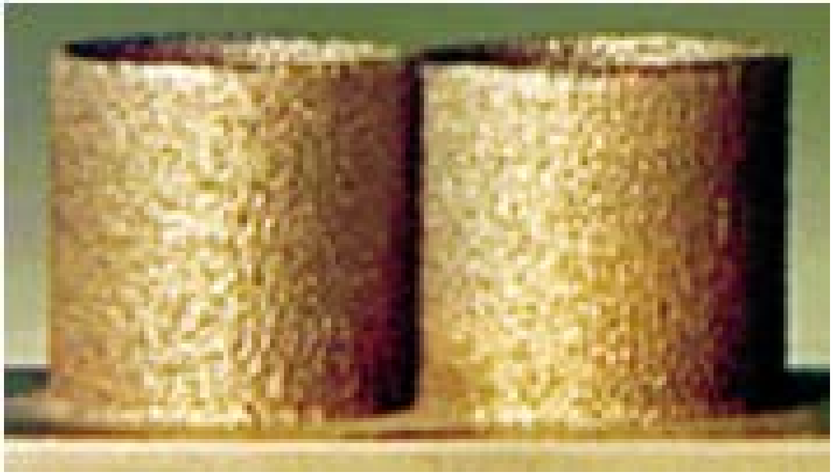


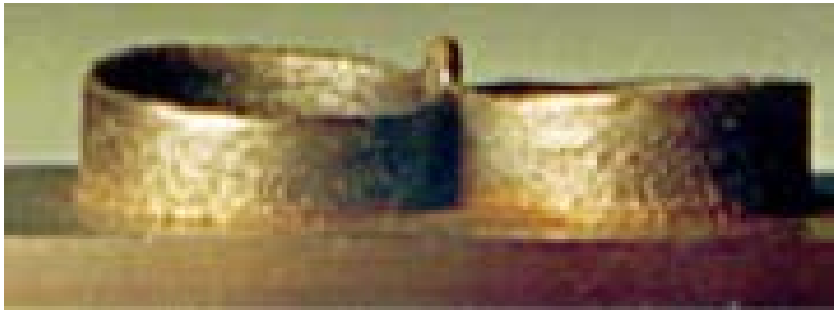

*Variable Powder Flow Rate Control in Laser Metal Deposition Processes, Tang, J. Manuf. Sci. Eng 130(4), 2008*

# Layer Height Control



With Control

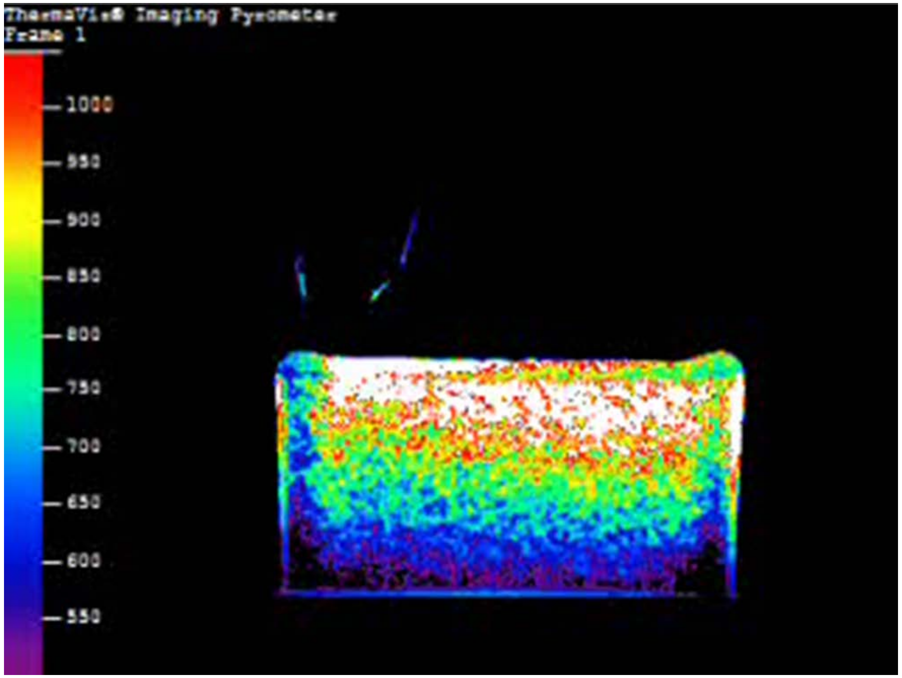


Without Control

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

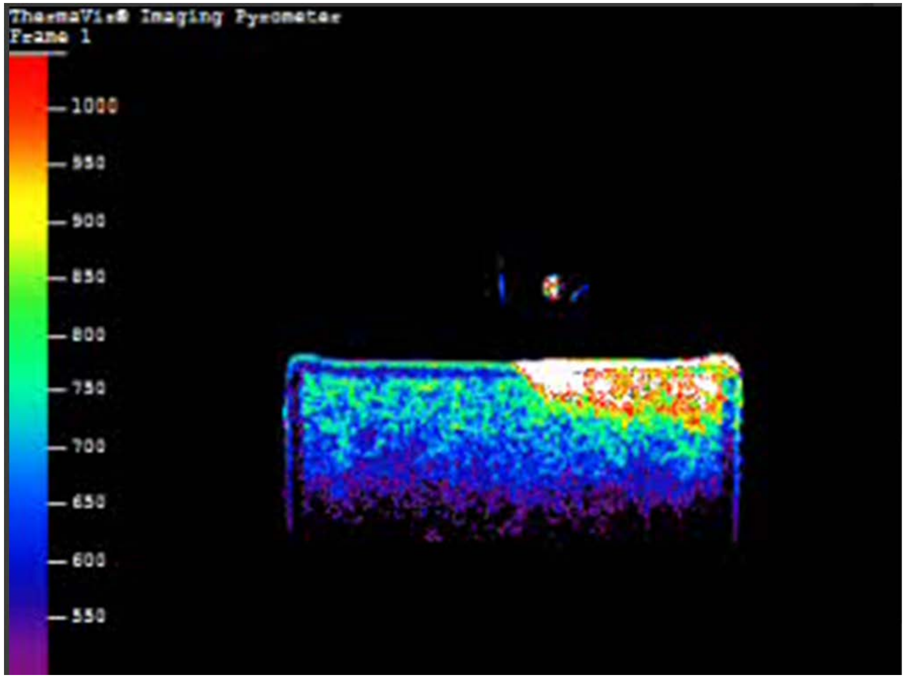
# Dwell Time Control

## Without Control




Deposit experiences increased heating during build

## With Control




Deposit experiences stable heating at reduced levels

*Stratonics Therma Viz*

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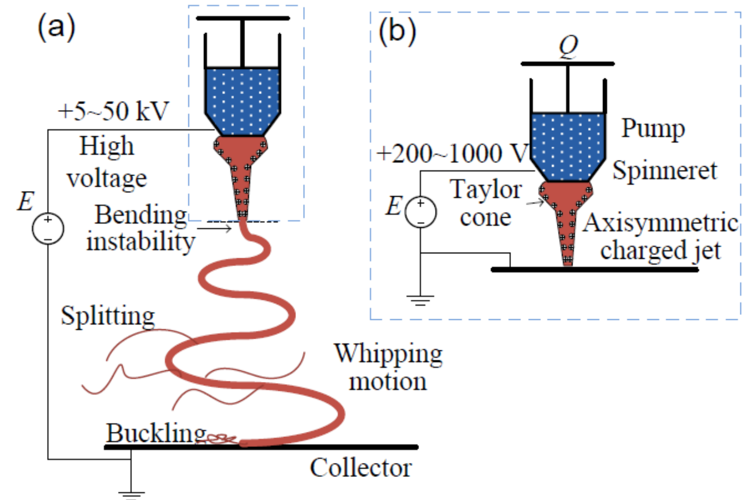
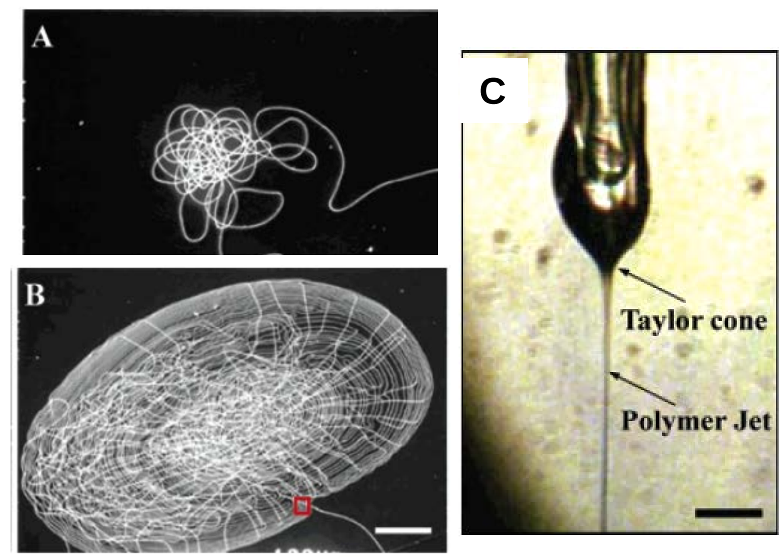
# Electrospinning

- 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.



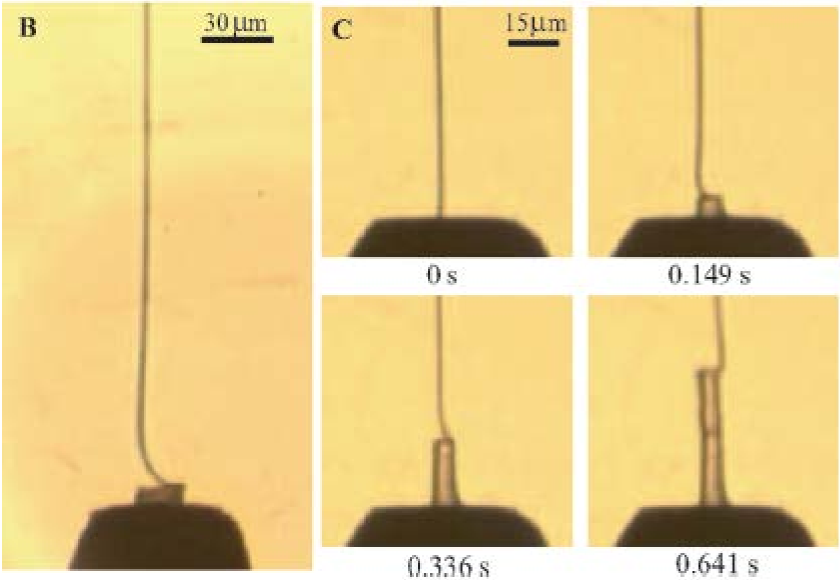




(A) Deposition of single fiber, scale bar: 100 µm (B) structure deposition, scale bar: 100 µm (C) Microscopic image of deposition process , scale bar: 25 µm

Sun, Daoheng, et al. "Near-field electrospinning." *Nano letters* 6.4 (2006): 839-842.

# Process Parameters

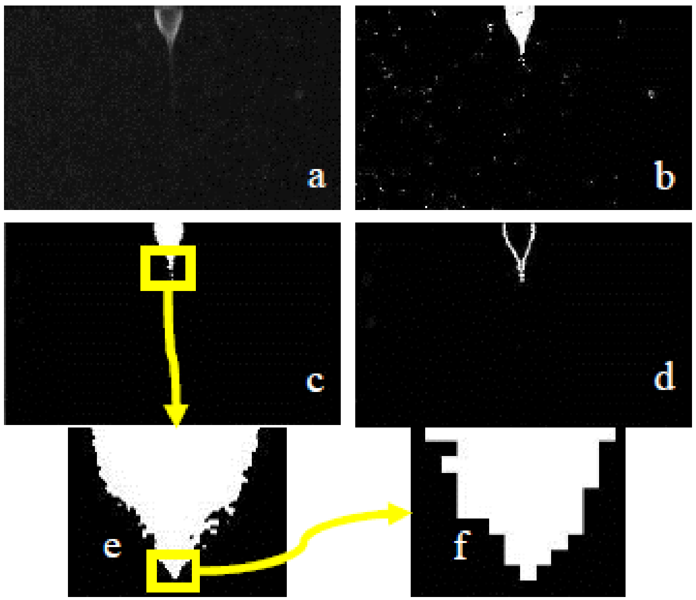
- **Process parameters:** electric field strength, flow rate, deposition speed, and evaporation rate.
- On line **diagnostic requires** high magnification and high temporal resolution of deposition process over large areas.
  - Fiber diameters range from ~ 5 nm to tens of microns.
  - Collector speeds up to 100s of millimeters per second
  - Areas of tens of centimeters.
- **Monitoring of fiber** in flight: diameter, speed, orientation



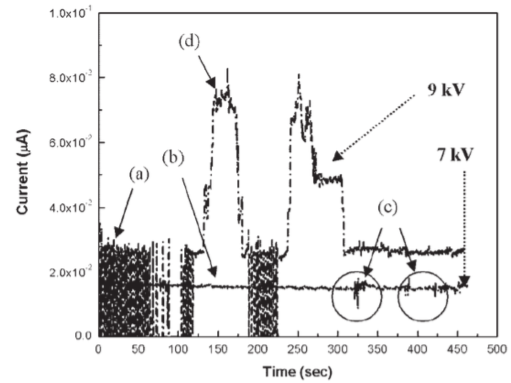

Kim, Ho-Young, et al. "Nanopottery: coiling of electrospun polymer nanofibers."*Nano letters* 10.6 (2010): 2138-2140.
Huang, Zheng-Ming, et al. "A review on polymer nanofibers by electrospinning and their applications in nanocomposites." *Composites science and technology*63.15 (2003): 2223-2253.

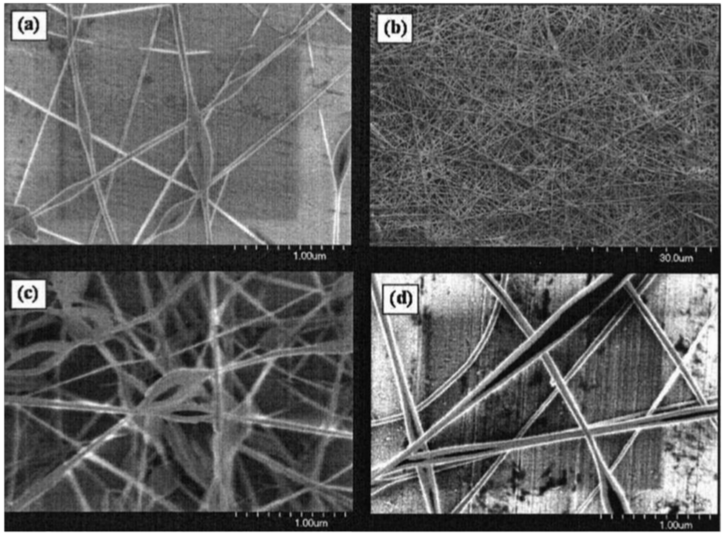
# Sensing and Control

- 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.

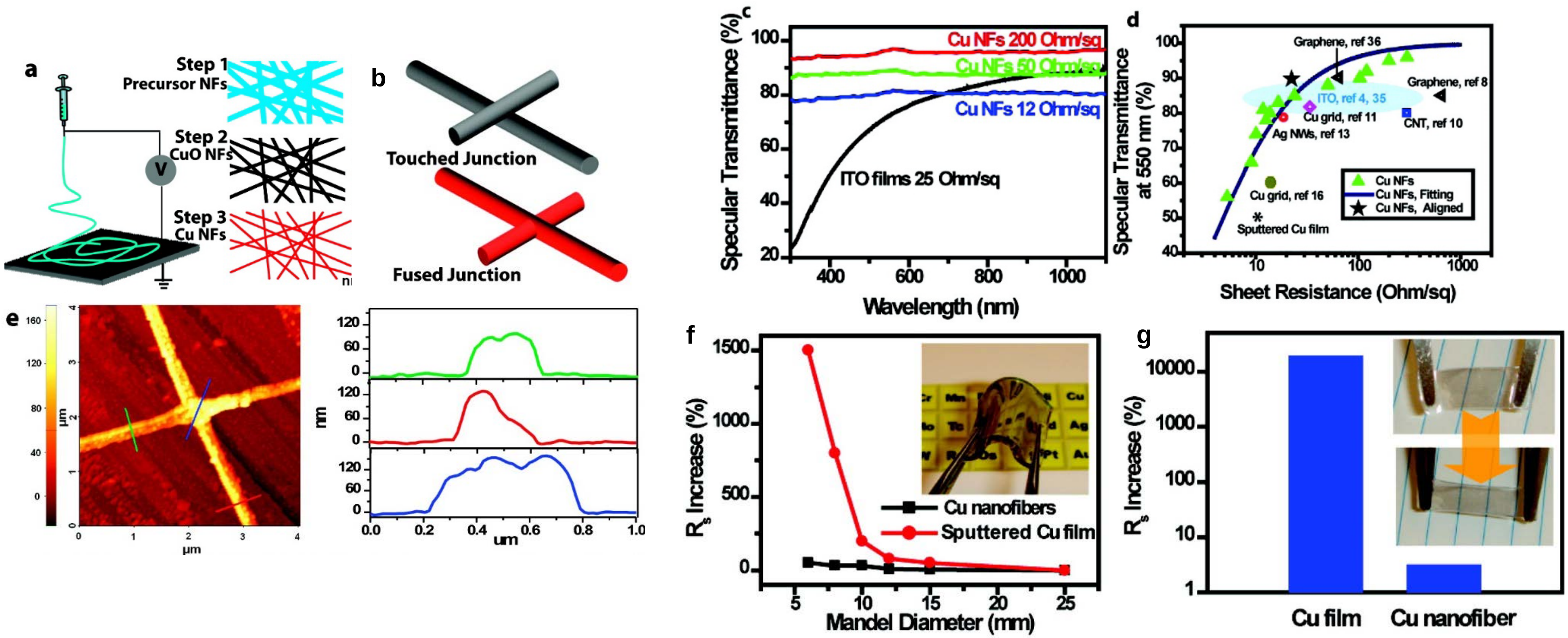



Relation between electric current and fiber morphology

Liu, Da Li, et al. "Algorithm research of pattern recognition for process control of electrospinning." *Advanced Materials Research*. Vol. 314. 2011.
Samatham, Ravikant, and Kwang J. Kim. "Electric current as a control variable in the electrospinning process." *Polymer engineering and science* 46.7 (2006): 954.

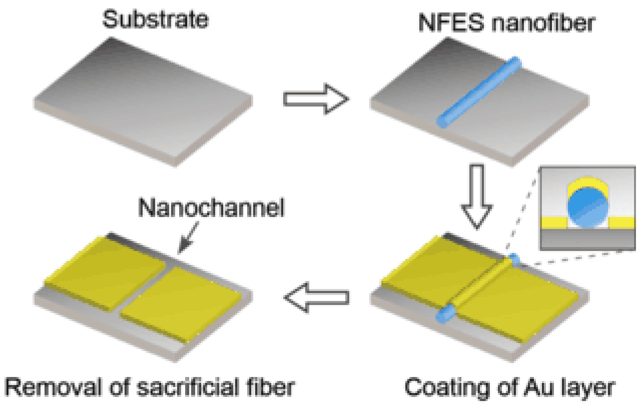
# Applications



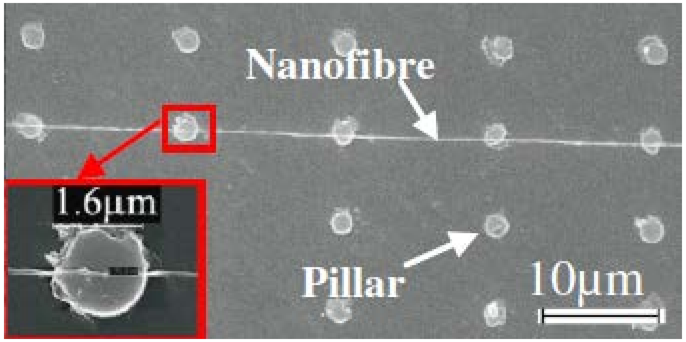

- Production of copper nanofiber webs via two-step pyrolysis of PVA and copper acetate webs deposited by electrospinning.
- High fiber density leads to resistance reduction
- High transparency and conductivity.

Wu, Hui, Liangbing Hu, Michael W. Rowell, Desheng Kong, Judy J. Cha, James R. McDonough, Jia Zhu, Yuan Yang, Michael D. McGehee, and Yi Cui. "Electrospun metal nanofiber webs as high-performance transparent electrode." *Nano letters* 10, no. 10 (2010): 4242-4248.

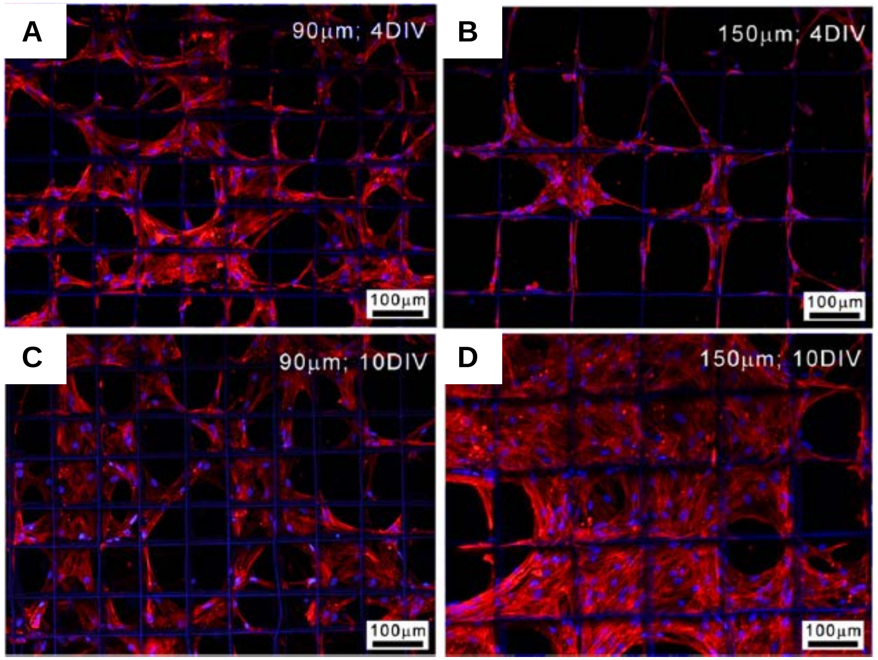
# Applications




Printing of nano and microchannels



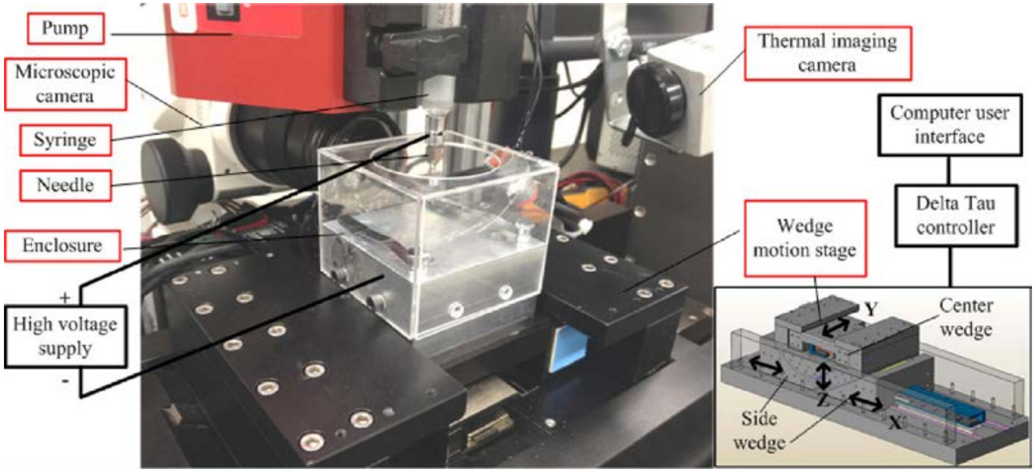

Deposition of nanofibers on patterned silicon collector



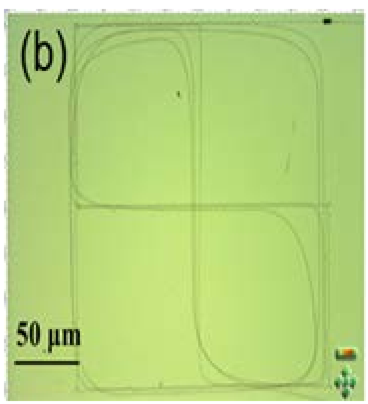

Cell Scaffolds with excellent spacing control printed via near field melt electrospinning

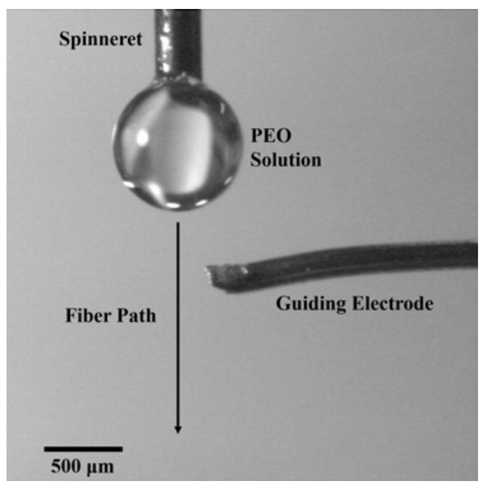
Wang, Xiang, et al. "Fabrication of nanochannels via near-field electrospinning."*Applied Physics A* 108.4 (2012): 825-828.
Zheng, Gaofeng, et al. "Precision deposition of a nanofibre by near-field electrospinning." *Journal Of Physics. D. Applied Physics* 43.41 (2010): 415501.
Hochleitner, Gernot, et al. "Additive manufacturing of scaffolds with sub-micron filaments via melt electrospinning writing." *Biofabrication* 7.3 (2015): 035002.

# Process Control

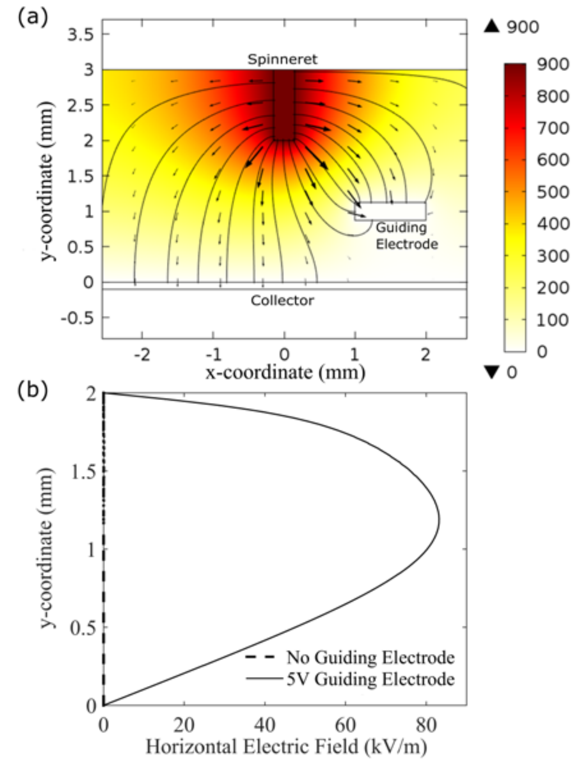



NFES Setup



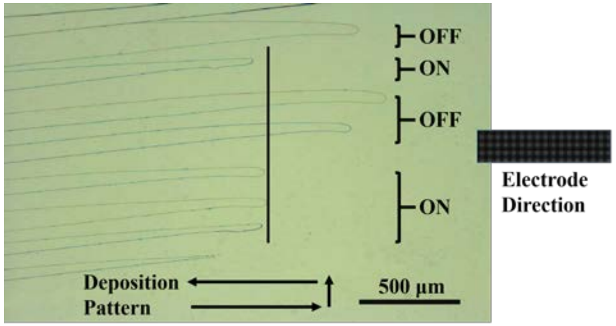

Guiding electrode as used



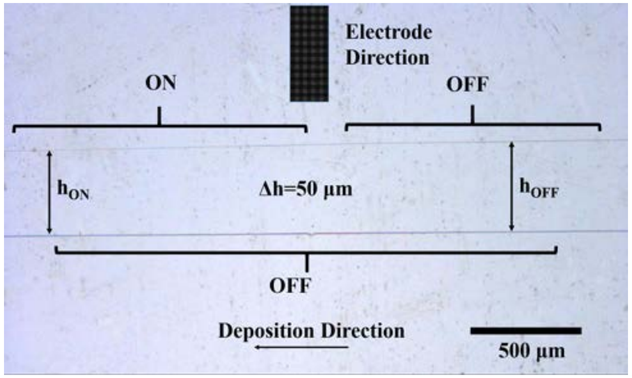

(a) Electric field simulation: electric potential contours, electric field streamlines, and electric field arrows. (b) Comparison of the horizontal component of the electric field along the central axis when the guiding electrode is not present and when a 5 V potential is applied to it

Martinez-Prieto, N., Abecassis, M., Xu, J., Guo, P., Cao, J., & Ehmann, K. F. (2015). Feasibility of Fiber-Deposition Control by Secondary Electric Fields in Near-Field Electrospinning. *Journal of Micro and Nano-Manufacturing*, *3*(4), 041005.

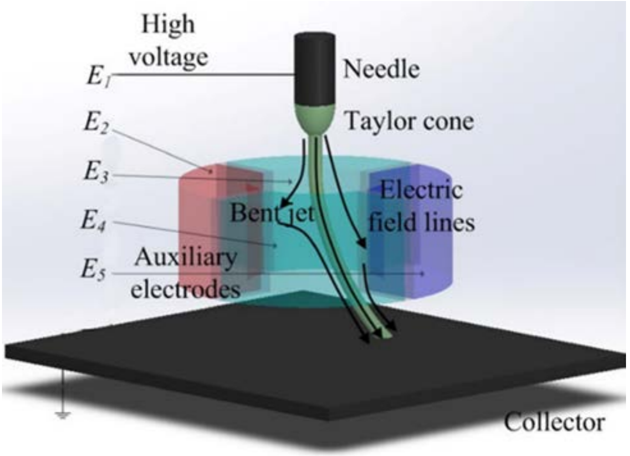
# Process Control



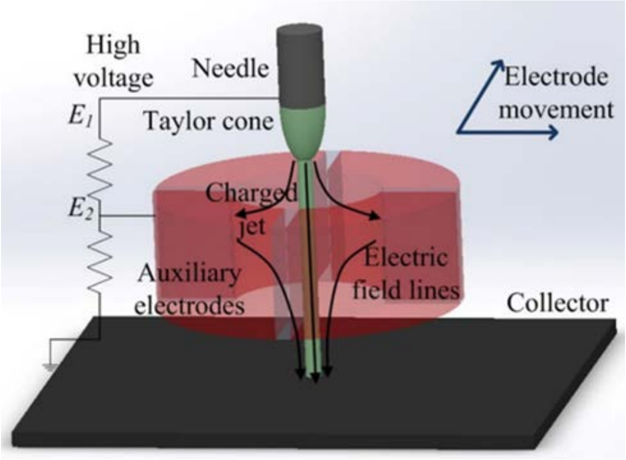

Results show increased repeatability in deposition when secondary electrode is used.




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




Proposed stationary electrode ring design with four independent potentials.

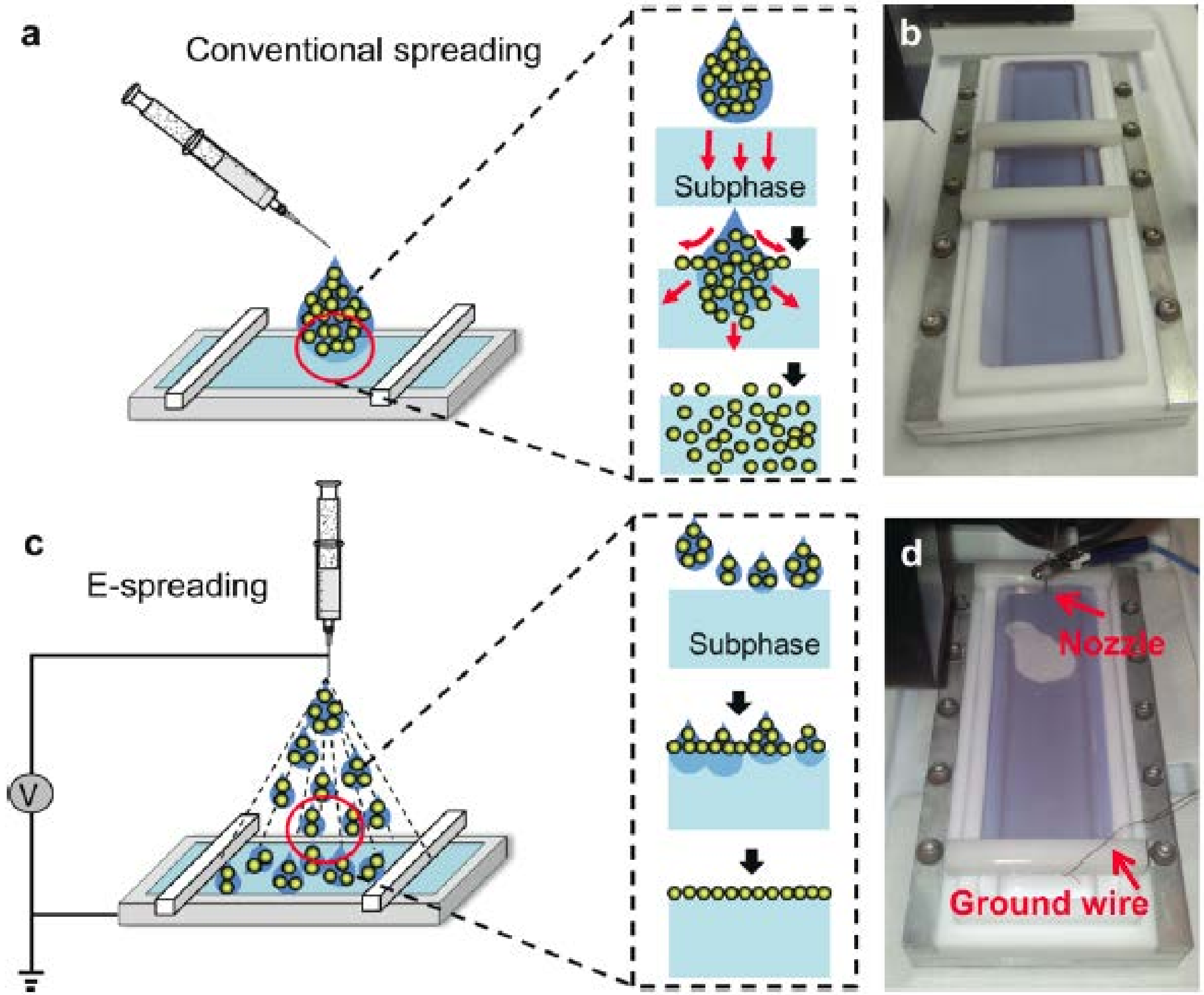



Proposed piezo actuated electrode ring design at a single potential.

Martinez-Prieto, N., Abecassis, M., Xu, J., Guo, P., Cao, J., & Ehmann, K. F. (2015). Feasibility of Fiber-Deposition Control by Secondary Electric Fields in Near-Field Electrospinning. *Journal of Micro and Nano-Manufacturing*, *3*(4), 041005.

# Electrospray assisted Langmuir-Blodgett assembly






Nie, H.L. *et al.*, *JACS*, **2015** 137,10683

# Outline

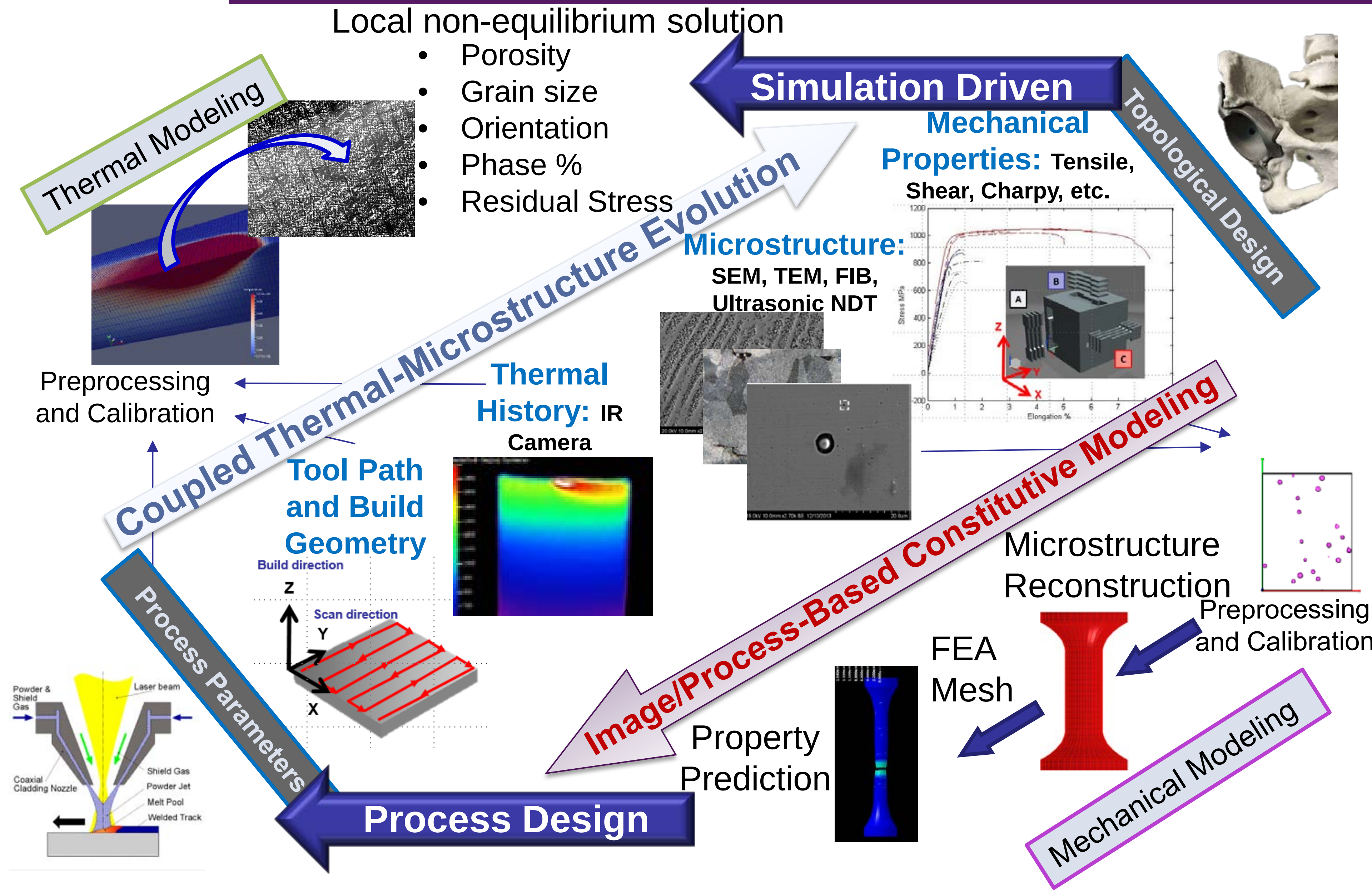
- **Overview of DED and Electrospinning**

- **Process Parameters and Their Influences**
- **Sensing and Characterization Methods**
- **Process Control**

- **Research Needs**

# 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?


Local non-equilibrium solution
• Porosity
• Grain size
• Orientation
• Phase %
• Residual Stress
Simulation Driven
Topological Design
Mechanical Properties: Tensile, Shear, Charpy, etc.
Microstructure: SEM, TEM, FIB, Ultrasonic NDT
Thermal Modeling
Coupled Thermal-Microstructure Evolution
Preprocessing and Calibration
Thermal History: IR Camera
Tool Path and Build Geometry
Build direction
Scan direction
Z
Y
X
Image/Process-Based Constitutive Modeling
Microstructure Reconstruction
Preprocessing and Calibration
FEA Mesh
Property Prediction
Mechanical Modeling
Process Parameters
Process Design
Powder & Shield Gas
Laser beam
Coaxial Cladding Nozzle
Shield Gas
Powder Jet
Melt Pool
Welded Track
Elongation %
Stress MPa

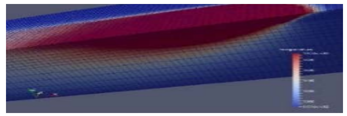
# Adaptive Bayesian Inference

## Identify key unknown parameters in the material model

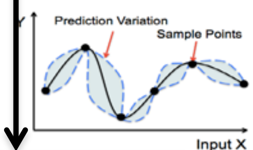
### Key Model Parameters

Processing Model
- Beam Power
- Scanning Speed
- Powder Feed Rate

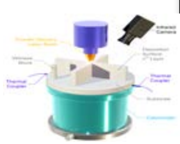
Thermal Model
- Thermal conductivity
- Cooling rate
- Thermal expansion coefficient



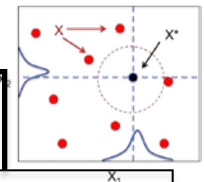
**Physics-based Models**



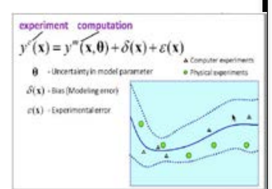

**Surrogate Models**



**Sensor Signals**



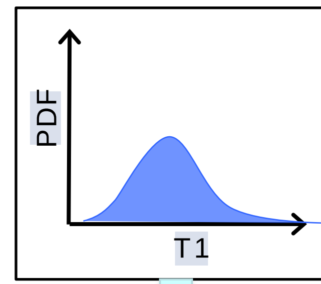

**Adaptive Sampling**

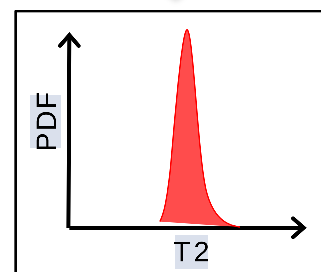


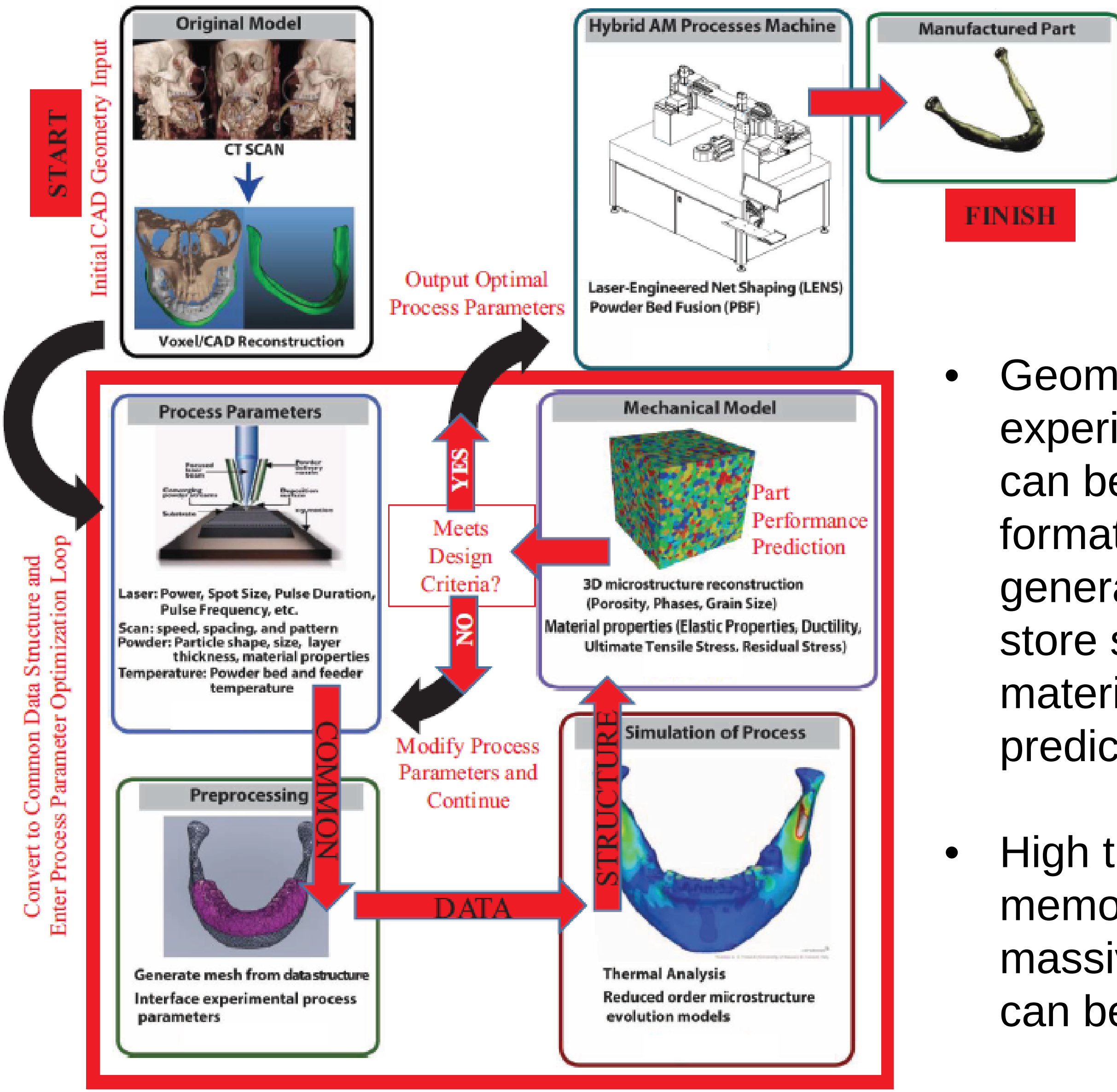

**Bayesian Inference**

### Parameters Updating

Posterior distribution






- Geometric and experimental information can be saved in a compact format which is used to the generate simulation mesh, store simulation results and material performance prediction.
- High throughput and memory bandwidth of massively parallel GPUs can be leveraged.

# 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?

* 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 | CONCENTRATED | DISTRIBUTED + CONCENTRATED |
|---|---|---|
| 1800 AD<br>Self-reliance | 2000 AD<br>Reliance on others | 2100 AD |

## CURRENT FORCES NOW AT WORK

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

→ Rapid Flexible Manufacturing

# Acknowledgment

**Support from NIST, NSF, DOD and DMG MORI**

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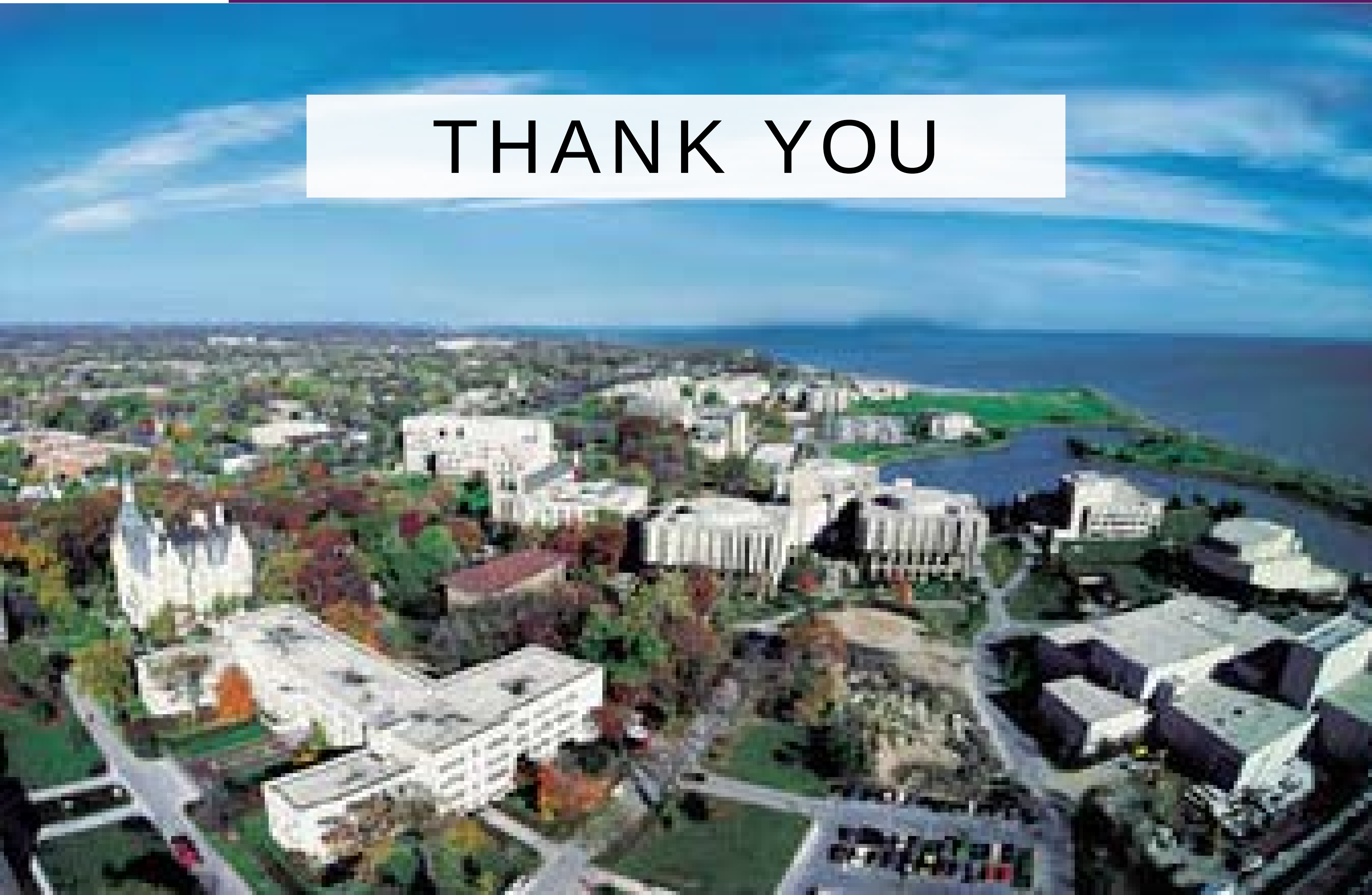
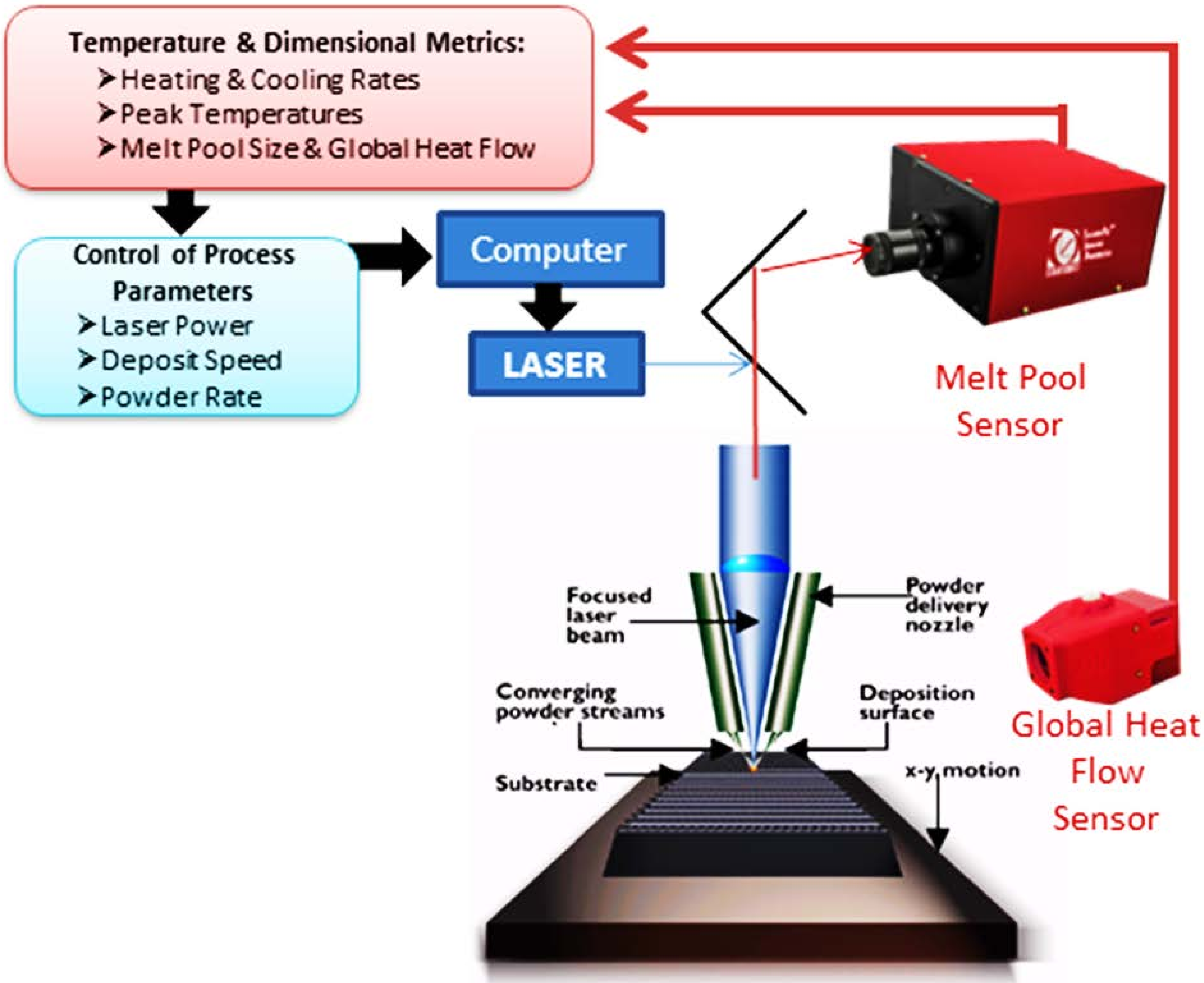
Drs. Zequn Wang, Joseph Santner

# THANK YOU



# Stratonics Therma Viz System




Stratonics Therma Viz