Advanced Qualification of Additive Manufacturing Materials Workshop

Temperature Simulations and Measurements for Process Qualification in Powder-Bed Electron Beam Additive Manufacturing

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Disclaimer and Note

- **The materials presented and opinions expressed in this seminar were solely from the presenter himself. They do not represent the viewpoints of The University of Alabama, nor the Advanced Manufacturing National Program Office.**
- **The materials presented in this seminar are mainly from the following articles.**
  - Cheng, B., S. Price, J. Lydon, K. Cooper and K. Chou, "**On Process Temperature in Powder-Bed Electron Beam Additive Manufacturing: Model Development and Experimental Validation**," *Journal of Manufacturing Science and Engineering*, Vol. 136, No. 6, pp. 061018 (1-12), 2014.
  - Price, S., B. Cheng, J. Lydon, K. Cooper and K. Chou, "**On Process Temperature in Powder-Bed Electron Beam Additive Manufacturing: Process Parameter Effects**," *Journal of Manufacturing Science and Engineering*, Vol. 136, No. 6, pp. 061019 (1-10), 2014.
  - Gong, X., J. Lydon, K. Cooper, and K. Chou, "**Beam Speed Effects on Ti-6Al-4V Microstructures in Electron Beam Additive Manufacturing**," *Journal of Materials Research*, Vol. 29, No. 17, pp. 1951-1959, 2014.
  - Gong, X., J. Lydon, K. Cooper, and K. Chou, "**Characterization of Ti-6Al-4V Powder in Electron-Beam-Melting Additive Manufacturing**," *International Journal of Powder Metallurgy*, Vol. 51, No. 1, pp. 1-10, 2015.

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Quality Control in AM Material and Process

Feedstock

Δ_1

Process

Δ_2

EBAM Process Video

Part

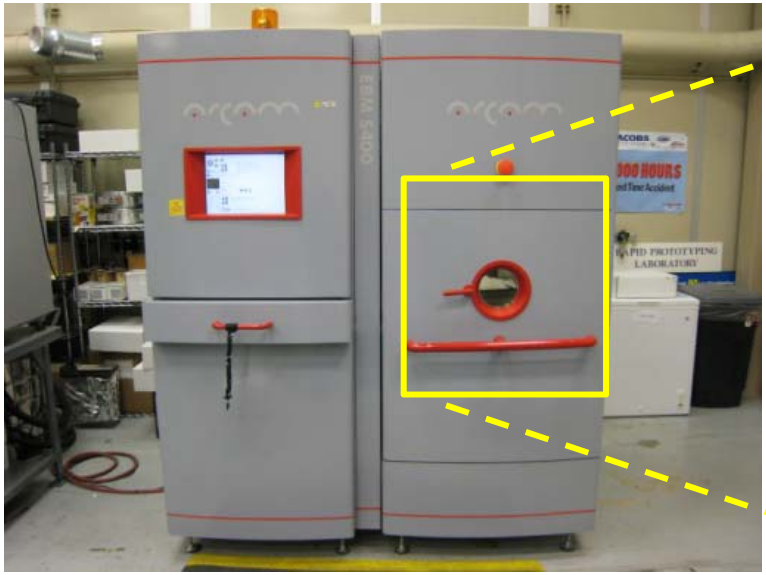
Δ_f

GE Aviation

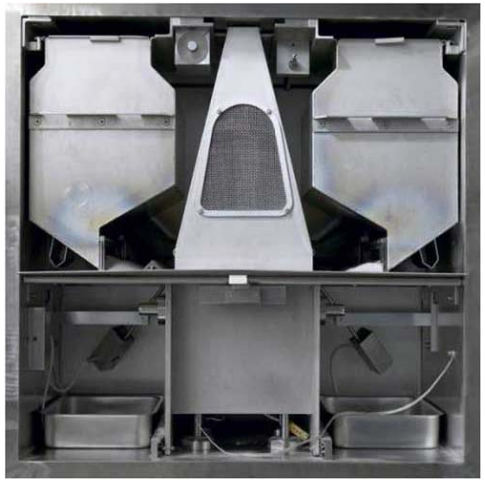
$$\Delta_f = Fn\ (\Delta_1, \Delta_2, \text{etc.})$$

EBAM System Characteristics

EBAM machine
(example, old model)



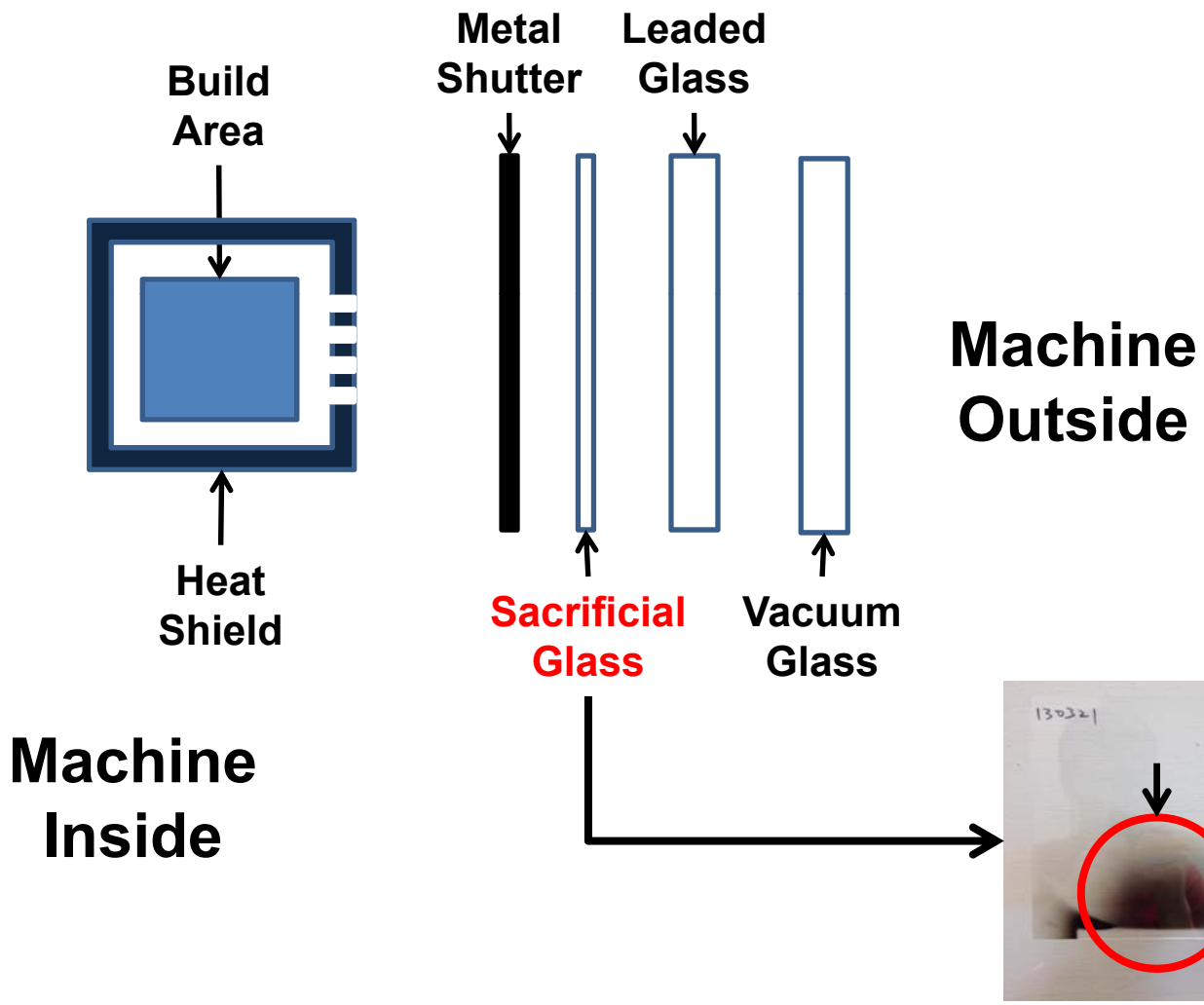
Build chamber



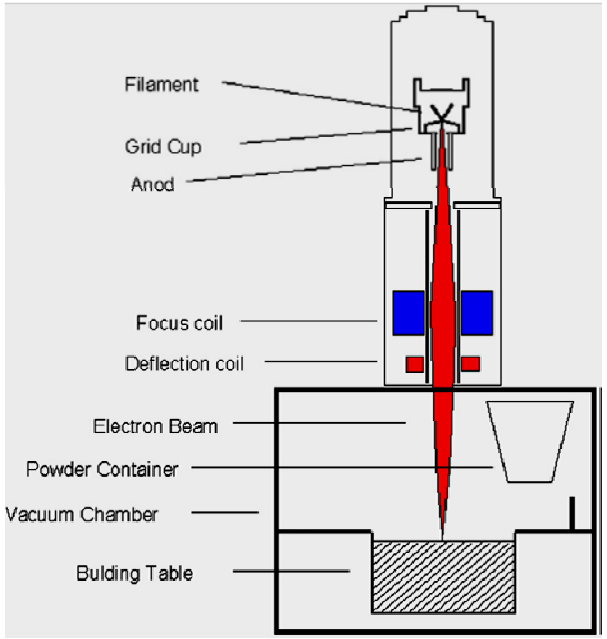
High power
60 keV electron gun
No moving part

Leaded glass
High strength glass
Heat shield
Sensor access limitation

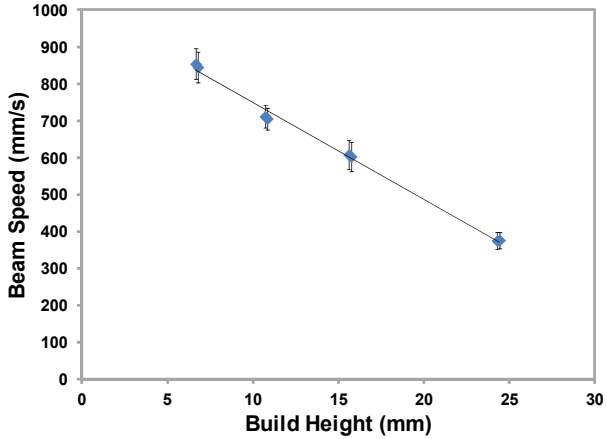
EBAM Viewport Window

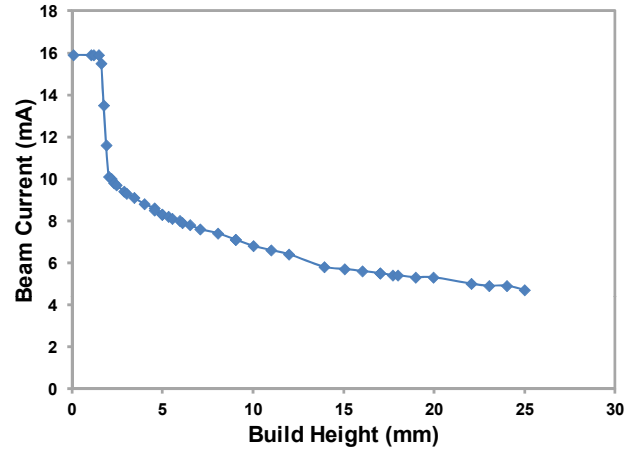


EBAM Process Characteristics

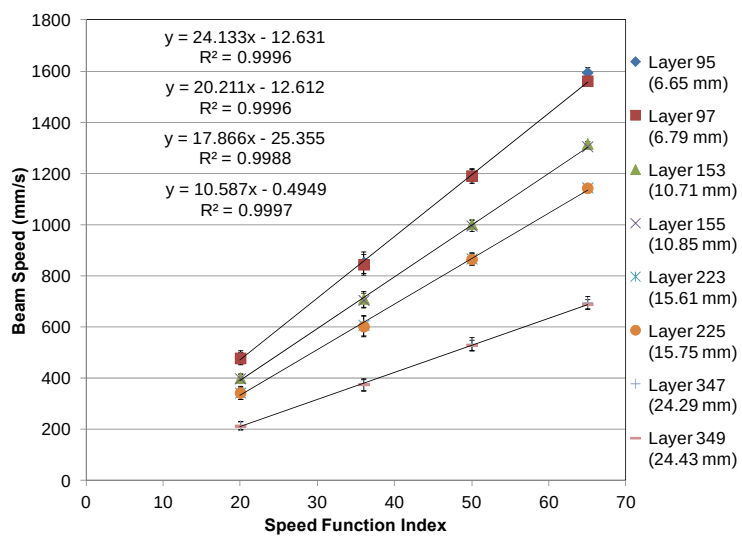


Speed Function (SF)





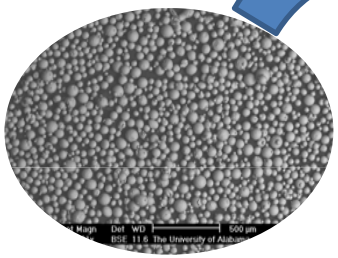
Beam Speed = function (SF, height)



- Vacuum (little He)
- Pre-heating, sintering
- Warm process (> ~650 ˚C)
- High scanning speed
- Process parameters change through the build
- Metalizing film
- Slow post-process cooling

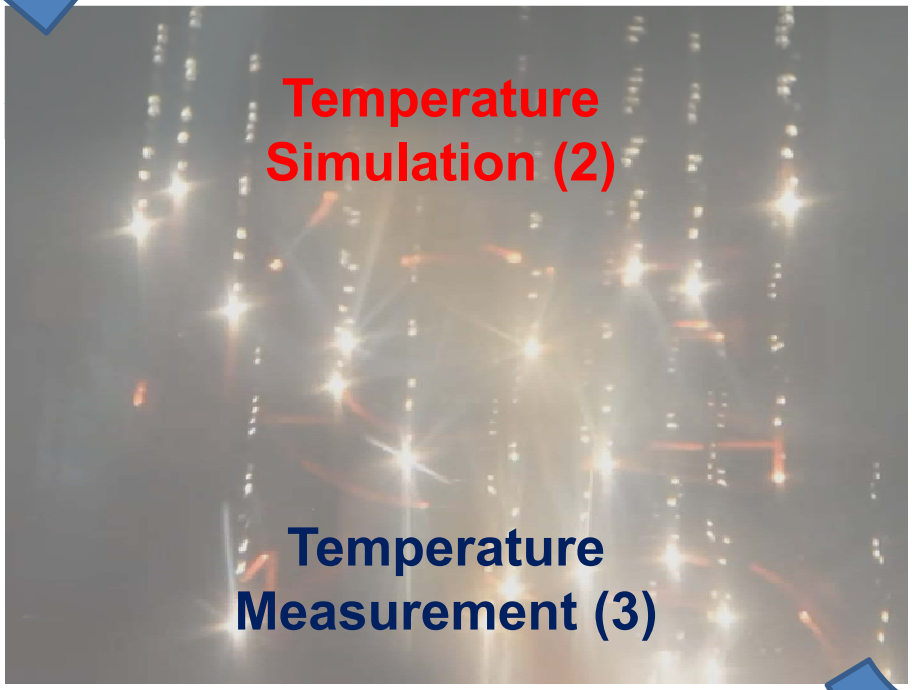
EBAM Process/Material Studies

Process Physics

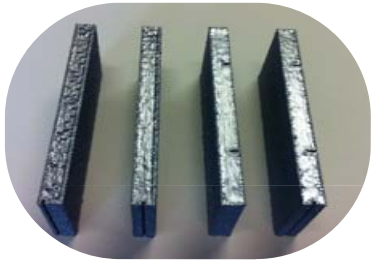


Powder-Bed (1)

Ti-6Al-4V



AM Part (4)

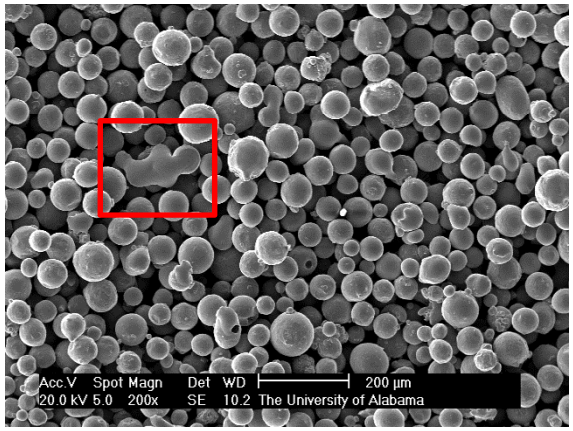


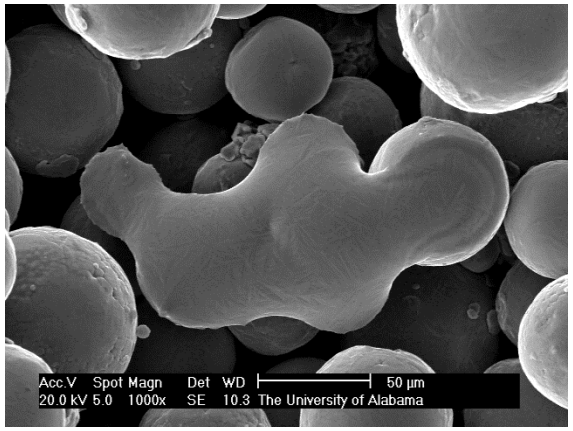
(1) Feedstock Characterization

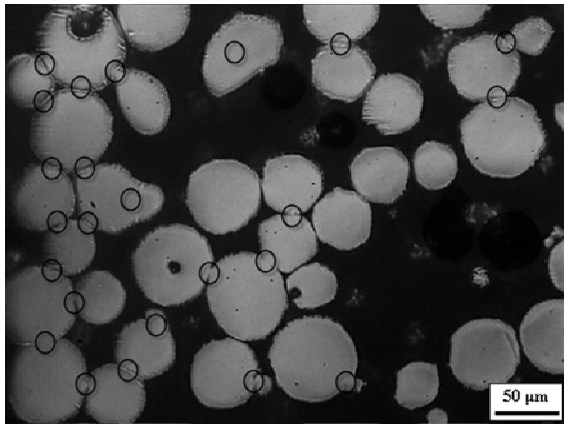
- √ **Powder-Bed Particles, Porosity**
  - **Metallography, Micro-CT**
- √ **Thermal Conductivity**
  - **Hot-Disk Thermal Analyzer**

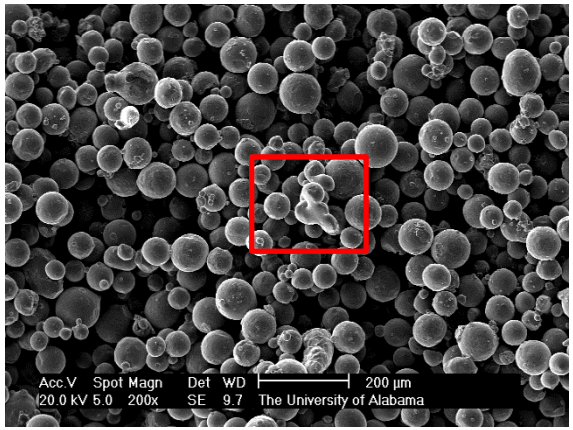
Preheated Powder

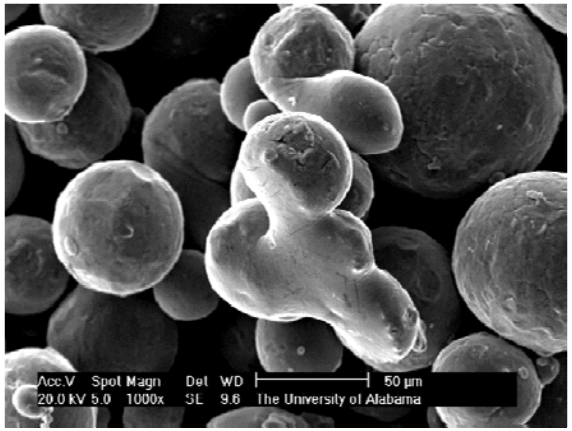
Z-plane

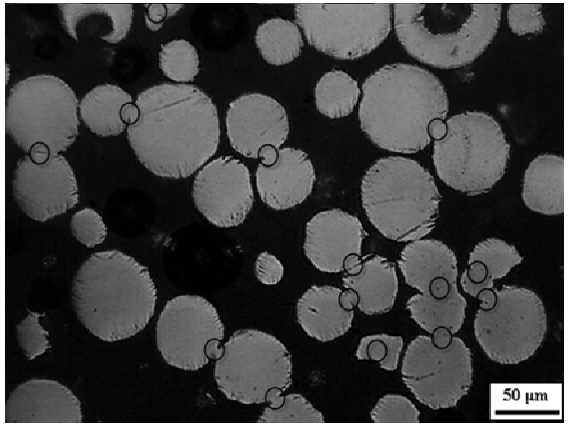








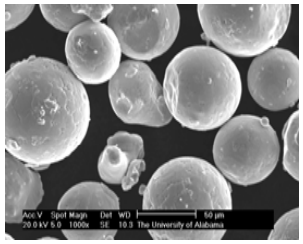




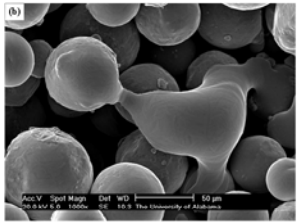
X-plane

Porosity Study - Micro-CT

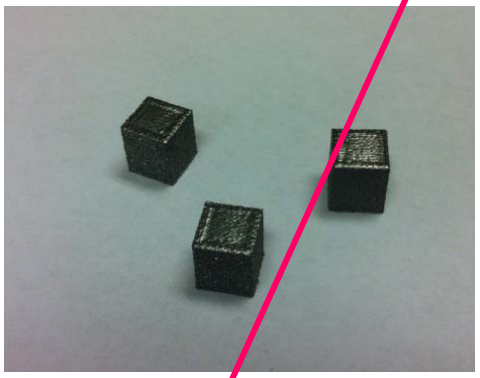
- 10 mm Ti-6Al-4V Cube (hollow)
- Skyscan 1172 Micro-CT
- Size/Porosity Distribution
  ~ 2 µm resolution

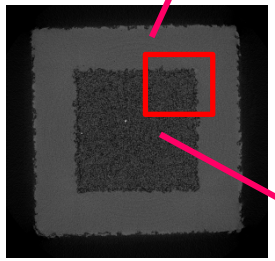


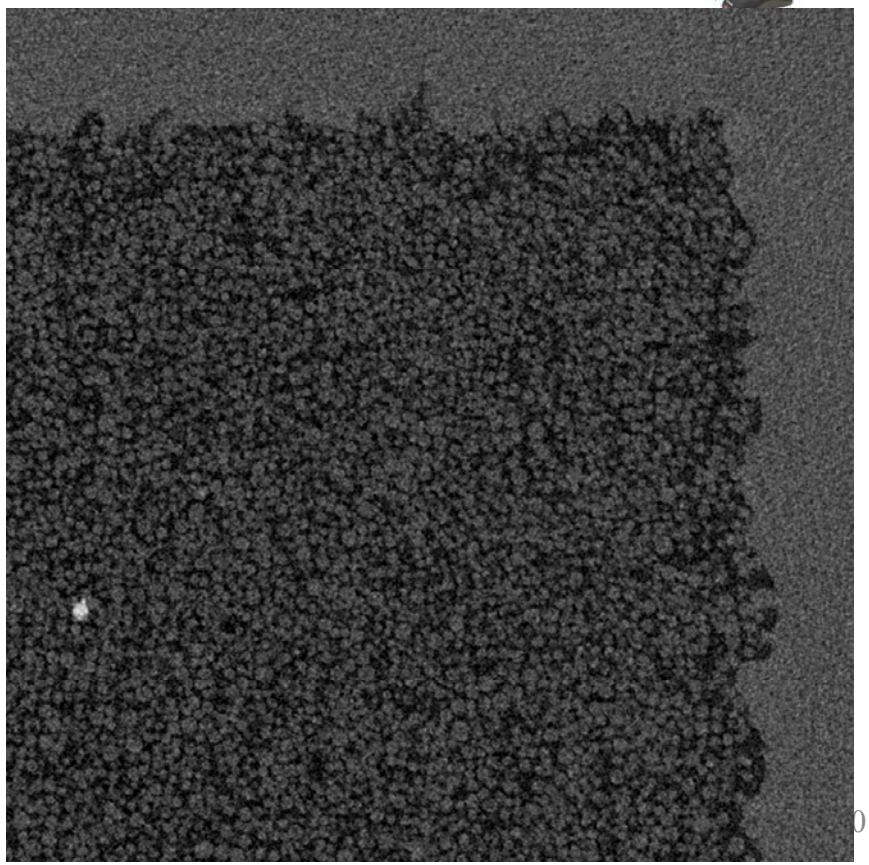
Loose powders



Sintered powders

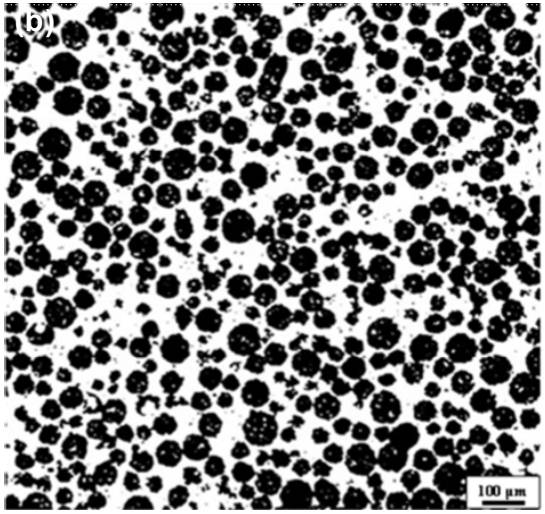


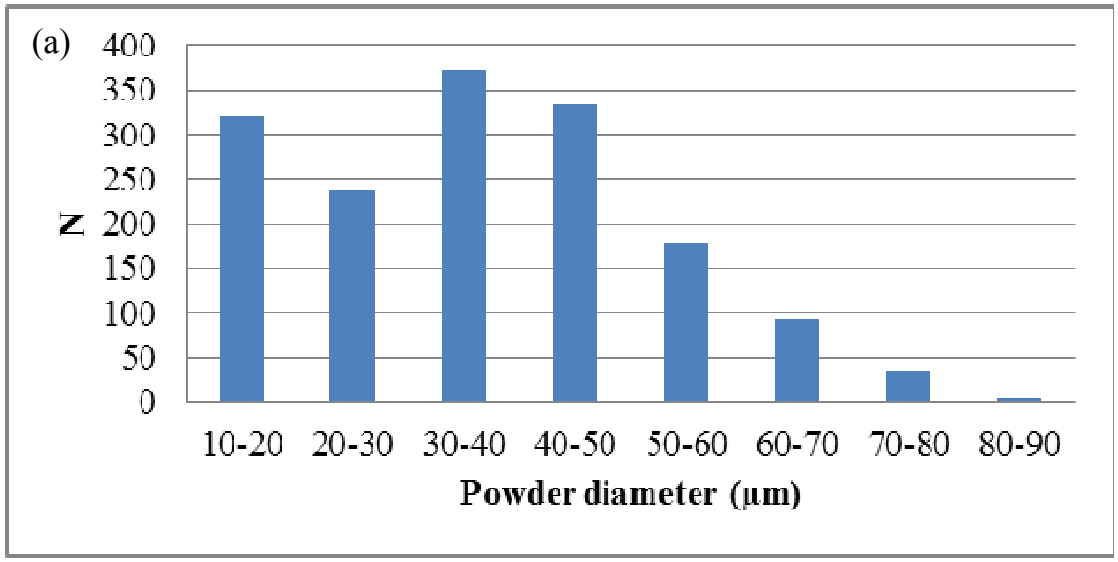




Porosity and Powder Size

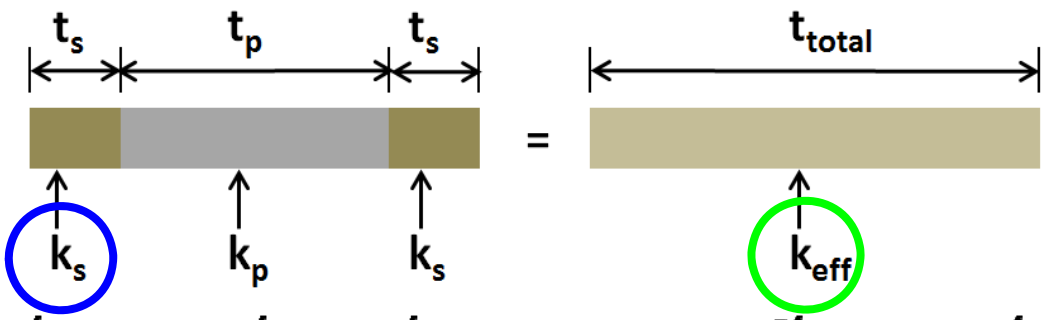
- **Powder-Bed Porosity, ~ 50%**
- **Particle Size Distribution**
  Major: ~ 30 to 50 μm



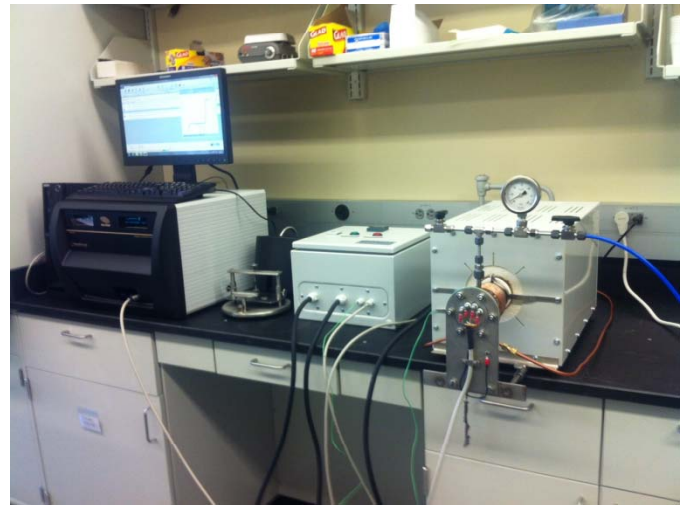


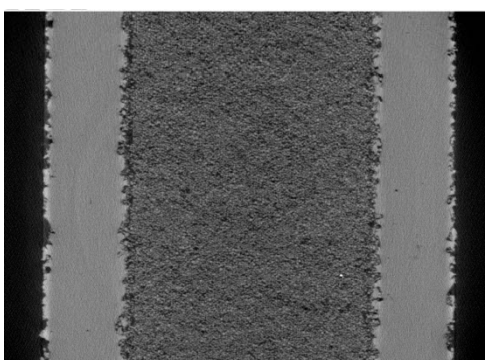
Powder Thermal Conductivity

- **TPS2500 S Thermal Analyzer (Hot Disk)**
  - **Solid and Hollow samples**



$$\frac{t_{total}}{k_{eff}} = 2\left(\frac{t_s}{k_s}\right) + \left(\frac{t_p}{k_p}\right) \rightarrow k_p = t_p\left[\frac{t_{total}}{k_{eff}} - 2\left(\frac{t_s}{k_s}\right)\right]^{-1}$$



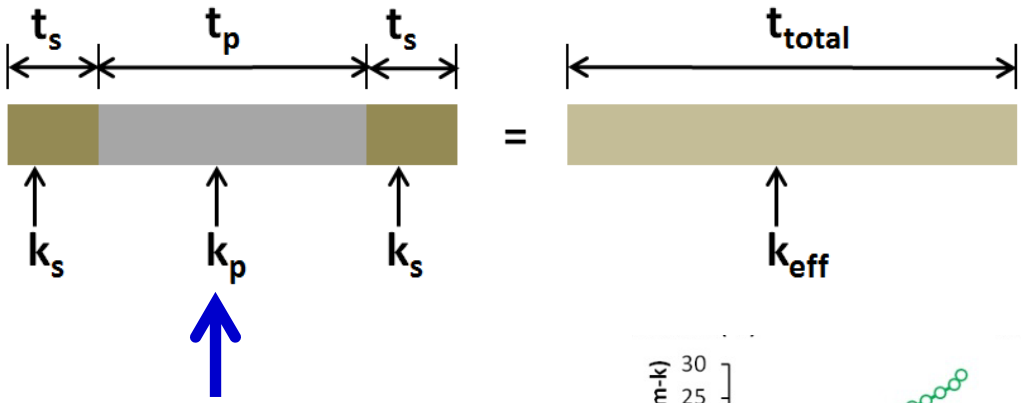


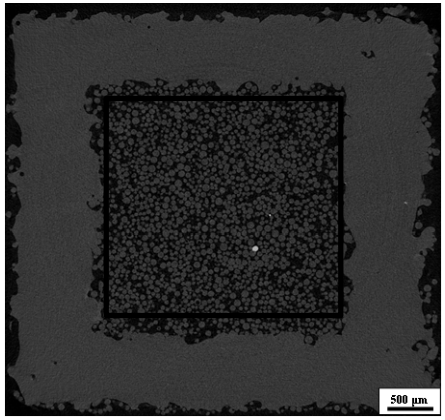
Solid vs. Hollow

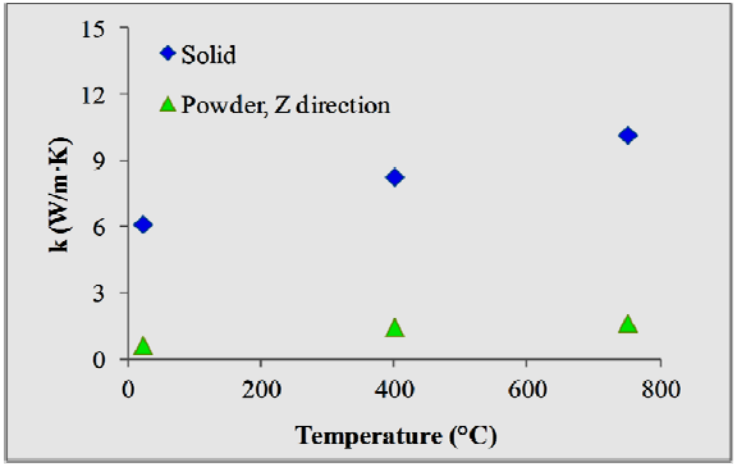
Hollow sample with shell removed (1 side)

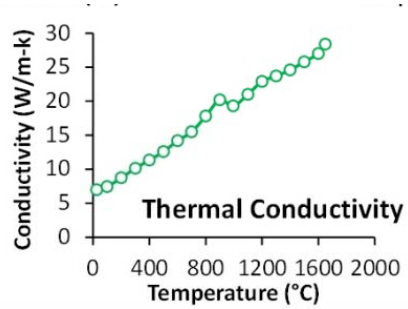
Powder Thermal Conductivity

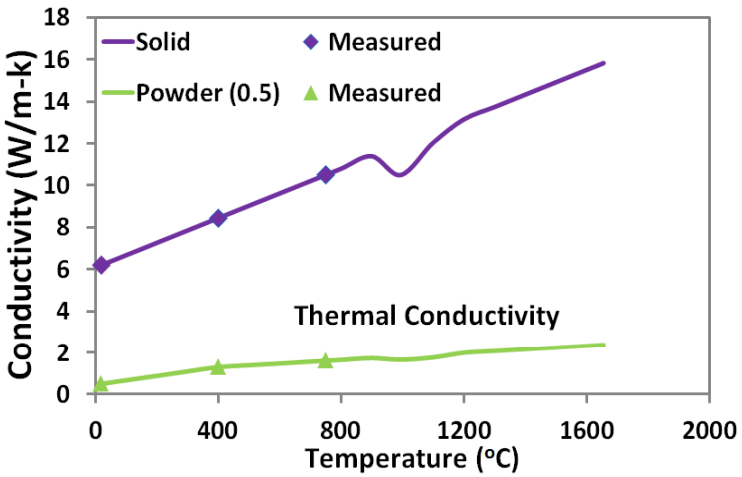
- **Sintered Powder Specimens**











(2) Temperature Simulation
- Finite Element Modeling

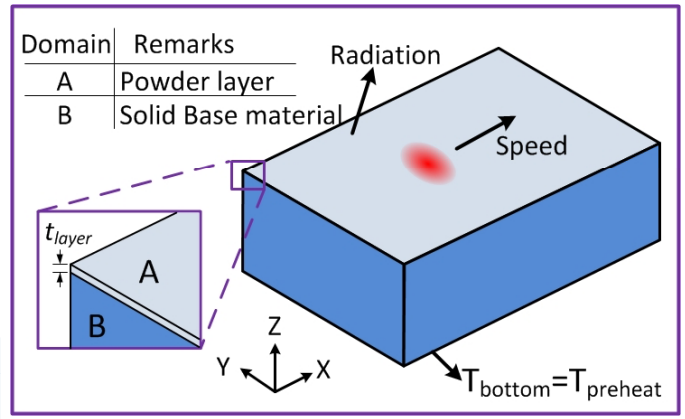
- ☑ Heat Transfer
- ☑ Heat Source
- ☑ Material/Powder Properties
- ☑ Latent Heat of Fusion

Governing Equations

Heat Transfer

$$\nabla(k\nabla T)+\dot{Q}=\frac{\partial(\rho c_p\cdot T)}{\partial t}+v_s\frac{\partial(\rho c_p\cdot T)}{\partial x}$$

T - Temperature
$\dot{Q}_{(x,y,z)}$ - Absorbed heat flux
c - Specific heat capacity
ρ - Density
λ - Thermal conductivity
v_s - Constant speed of the moving heat source



Latent Heat of Fusion

$$\Delta H(T)=\int c\,dT+L_f f$$

$$f=\begin{cases}0 & T<T_S,\\ \dfrac{T-T_S}{T_L-T_S} & T_S\le T\le T_L,\\ 1 & T>T_L\end{cases}$$

ΔH_f - latent heat of fusion
T_l - liquidus temperature
T_s - solidus temperature
f_s - solid fraction

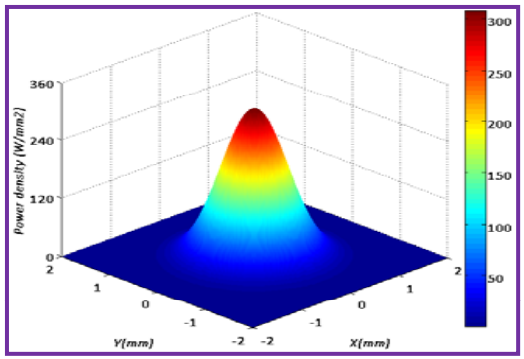
Assumptions:

- **Heat Conduction**
- **Negligible molten flow within molten pool**
- **Radiation considered as boundary condition**
- **Uniform temperature as the part initial temperature**

Heat Source Equations

Intensity distribution: a conical source:

- **Horizontal – Gaussian distribution**
- **Vertical – Decaying with increasing of penetration depth**



$$\dot{Q}_{(x,y,z)} = \eta \times \frac{H_s \times I_z}{S}$$

$$I_z = \frac{1}{0.75}\left(-2.25\left(\frac{z}{S}\right)^2 + 1.5\left(\frac{z}{S}\right) + 0.75\right)$$

$$H_s = \frac{2UI_b}{\pi\Phi_E^2}\exp\left\{-\frac{2\left[(x-x_s)^2 + (y-y_s)^2\right]}{\Phi_E^2}\right\}$$

η - electron beam efficiency coefficient

U - voltage

I_b - current

S - penetration depth

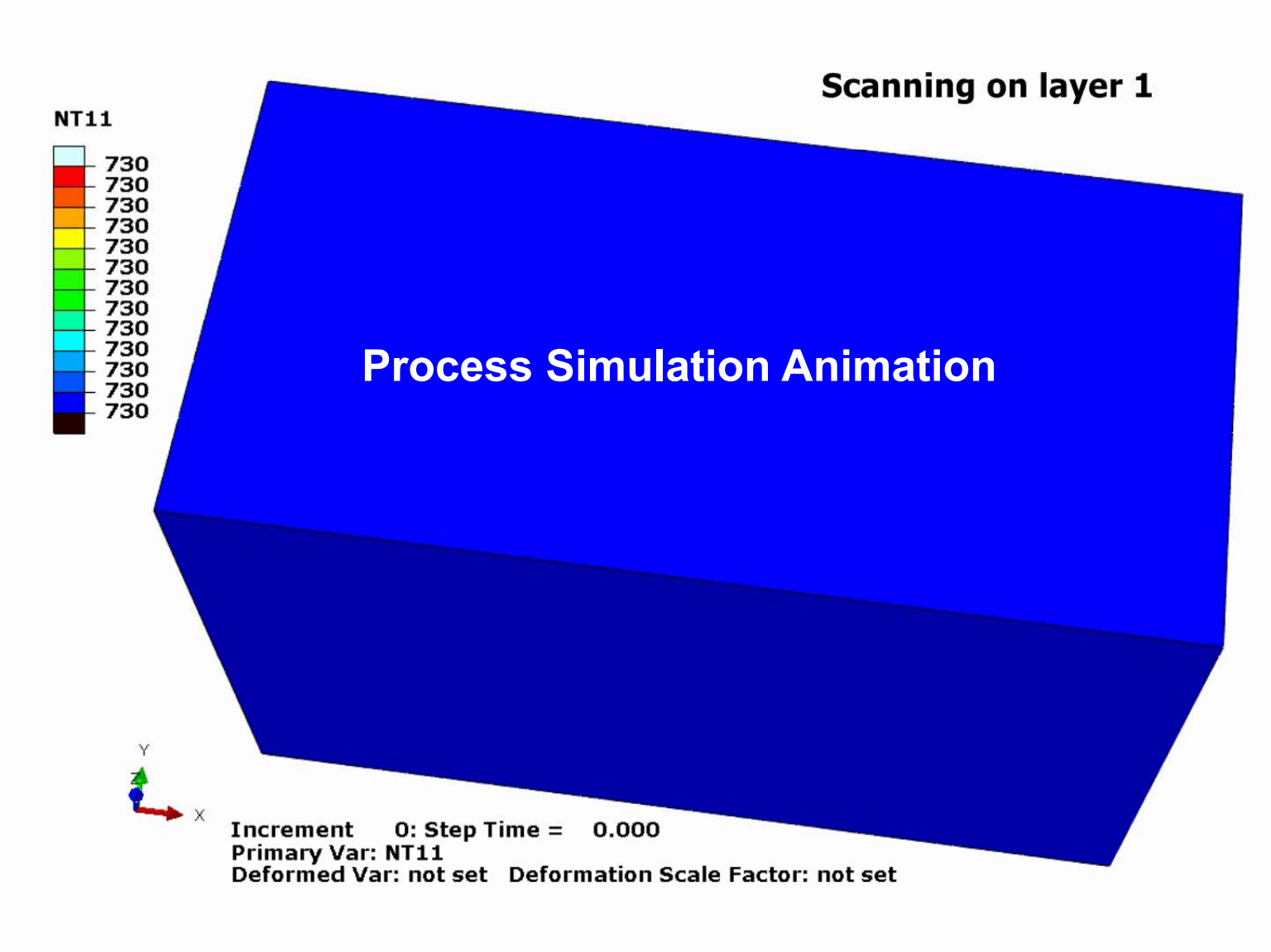
Φ_E - beam diameter

x_S, y_S - horizontal position of heat source center

H_s - Gaussian heat source, Cline and Anthony

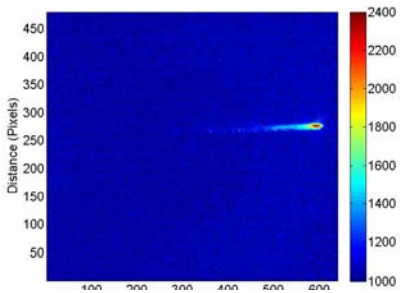
I_z - penetration function, Zäh and Lutzmann

Simulation Example

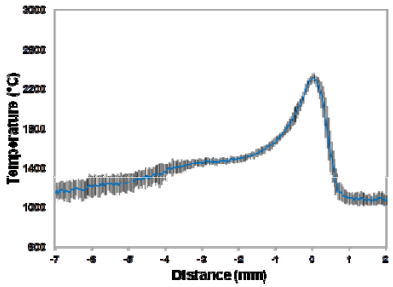


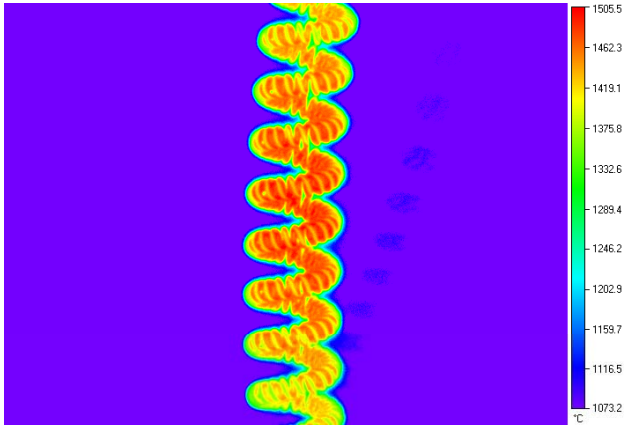
(3) Temperature Measurements - Near IR Thermography

- ☑ Spectral Range
- ☑ Build Area View Access
- ☑ Resolutions (Spatial/Temporal)
- ☑ Emissivity
- ☑ Transmission Loss



EBAM Temperature Measurements



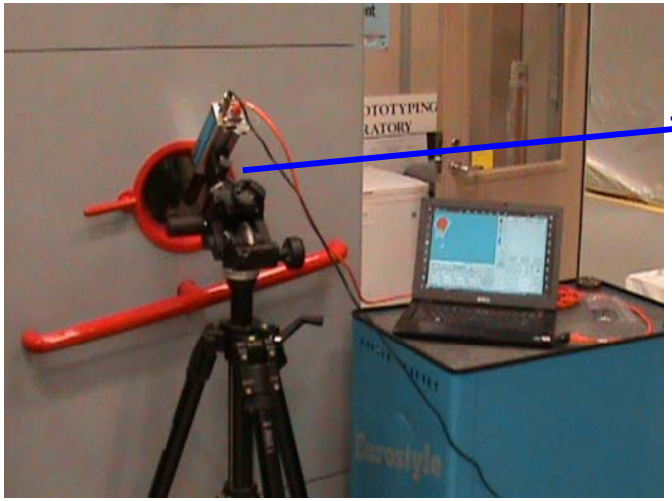


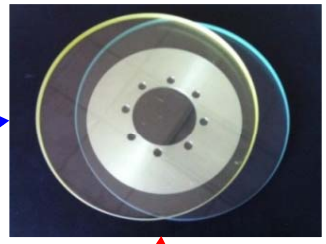
Near Infrared Thermal Imager

- LumaSense MCS640
- Spectral Range: 780 – 1080 nm
- 640 by 480 FPA (Amorphous Si based)
- Temperature Range: 600 to 3000 ˚C (3 domains)
- Frame Rate: Max. 60 Hz
- Lens: ~ 500 mm Focal Distance
- View Area: 32 mm by 24 mm
- Spatial Resolution: ~ 50 µm

Challenges:
Emissivity and Transmission

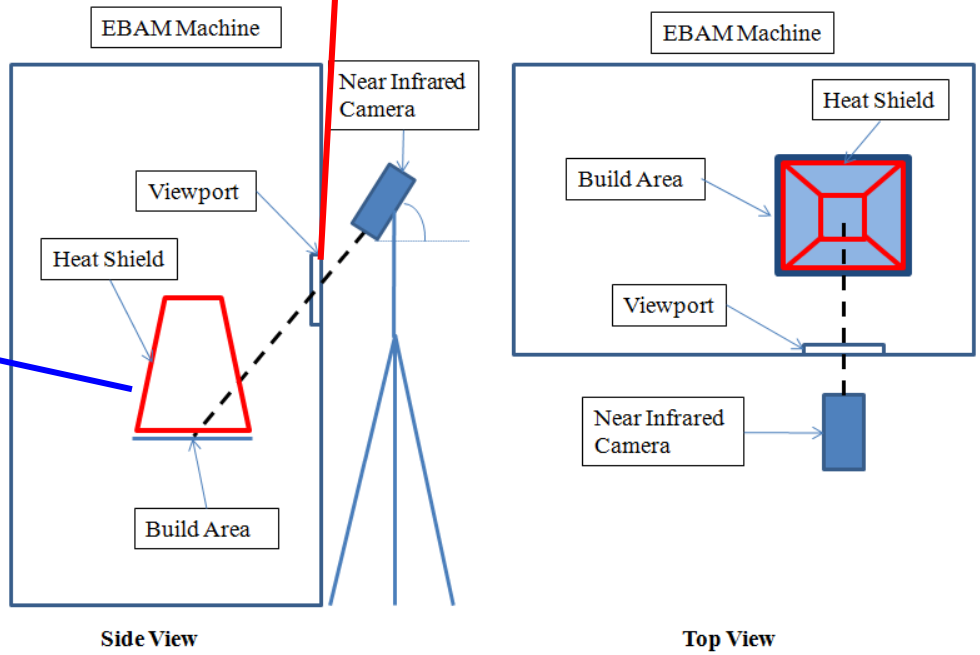
Measurement Setup



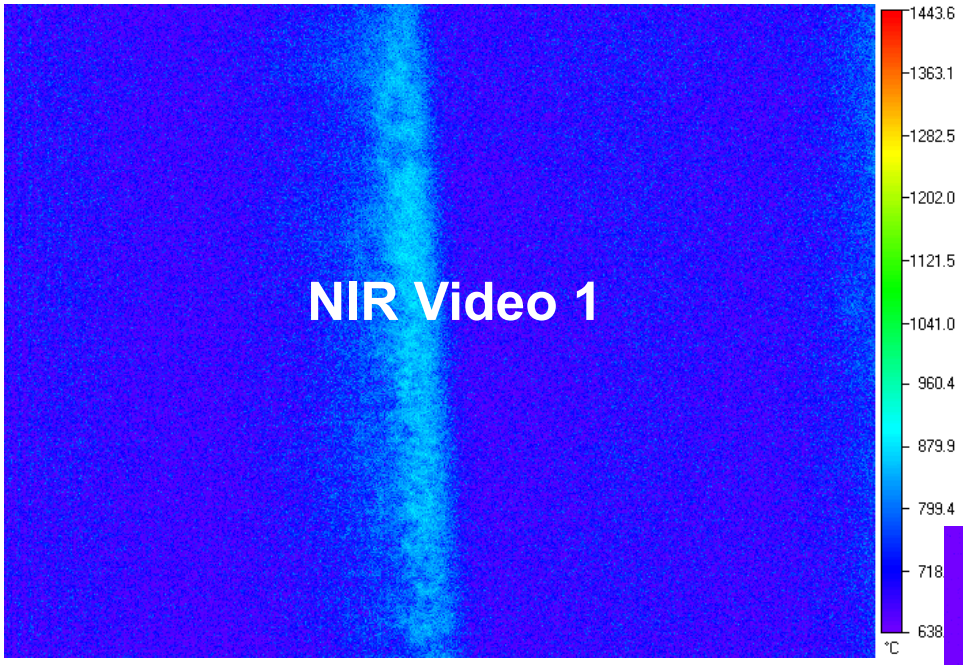


Emissivity (Single Setting, Estimated)
Transmission (Calibrated, 3 Ranges, with Glasses)

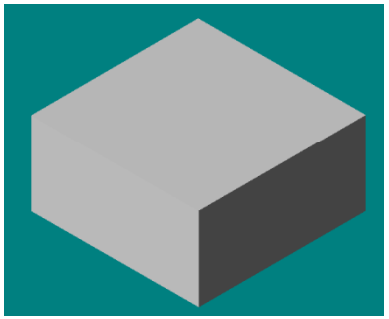
Heat shield



NIR Video Examples

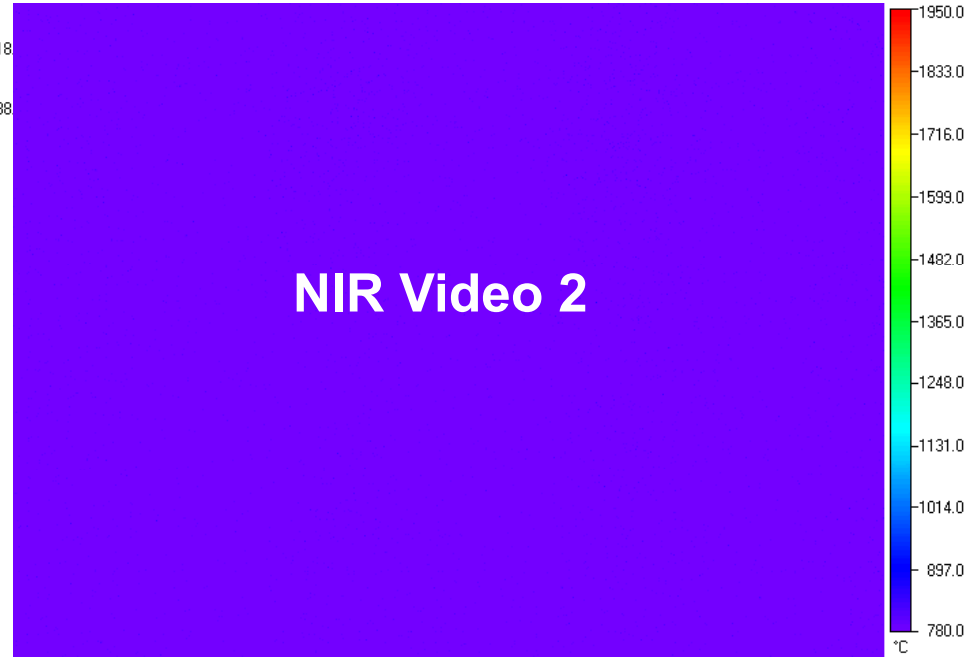


Medium Temperature Range

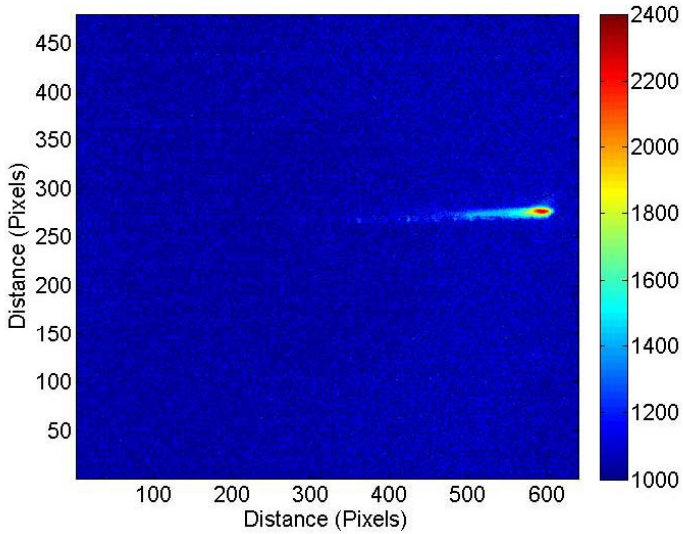


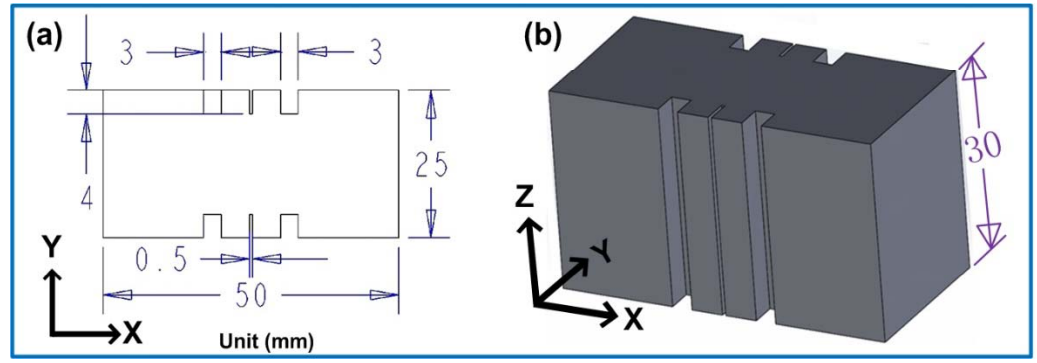
Build model:
25. 4 mm square block

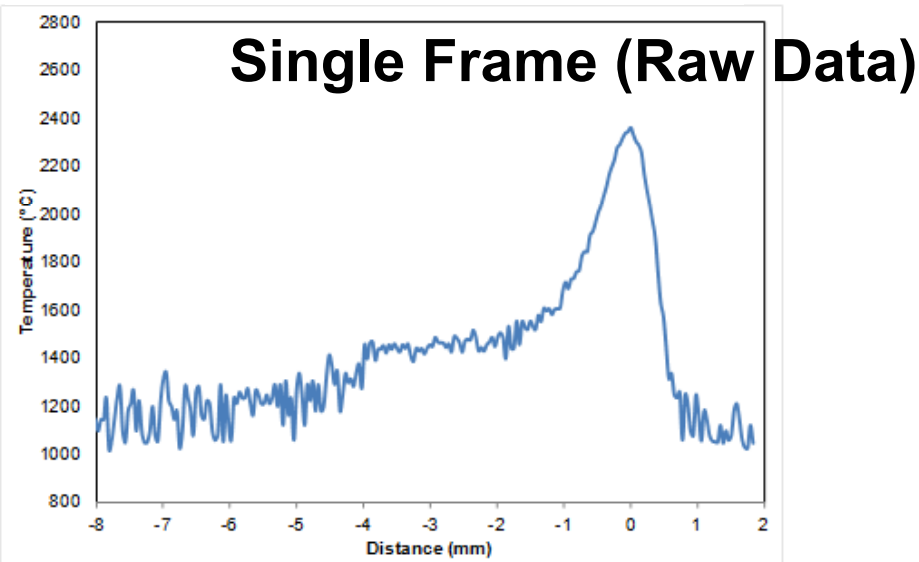
High Temperature Range

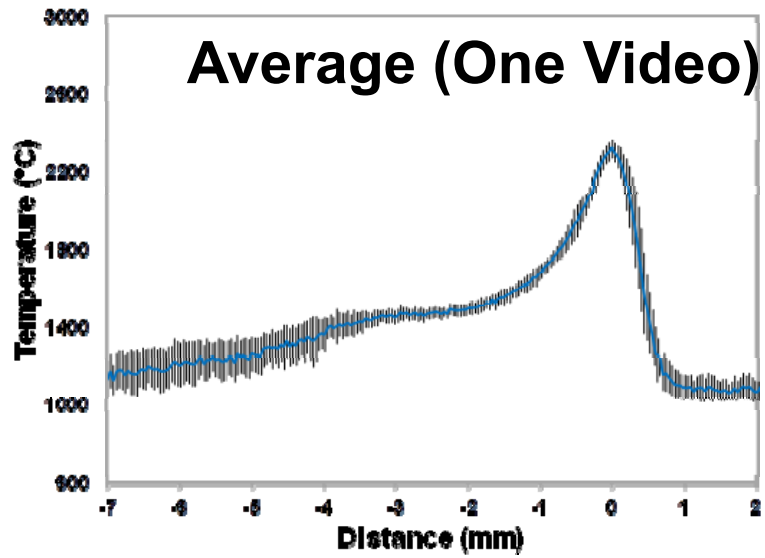


Temperature Profile Analysis (Hatch Melt)







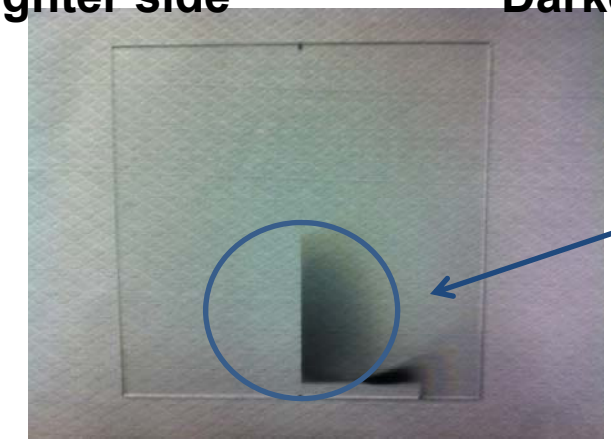


Transmission Loss Study

Lighter side

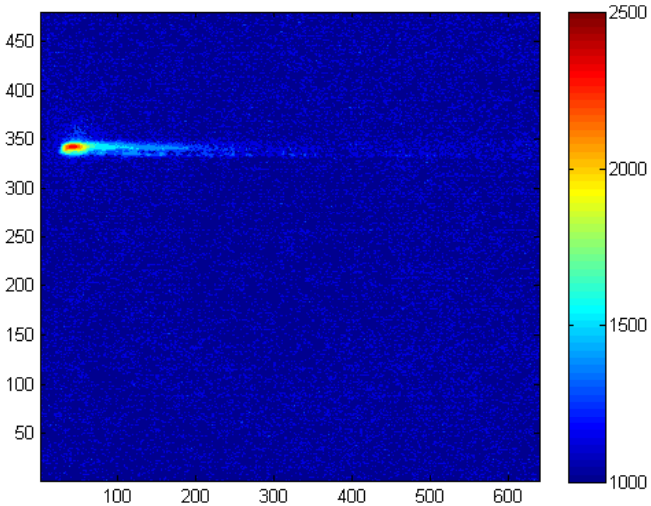
Darker side

Controlled Exposure

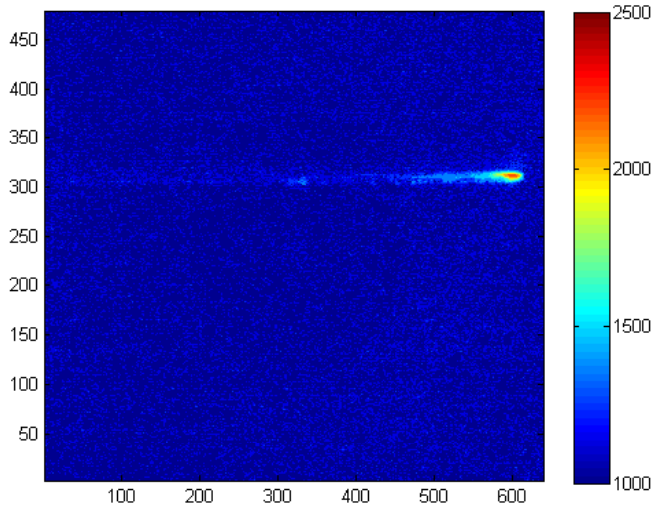


Viewing Area

Sacrificial glass with two levels of metallization.



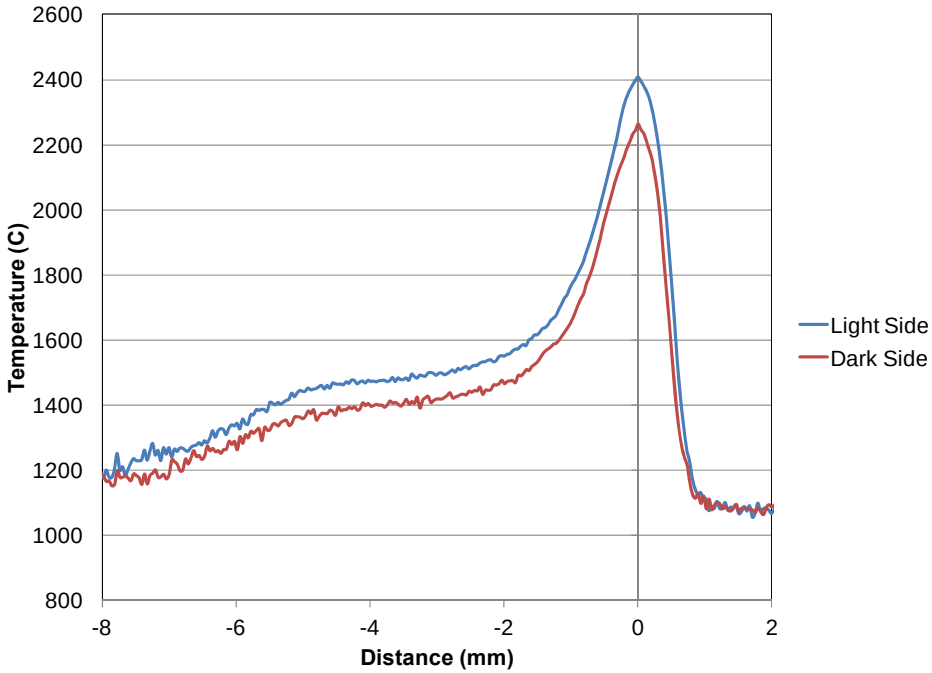
Thermal image on lighter side



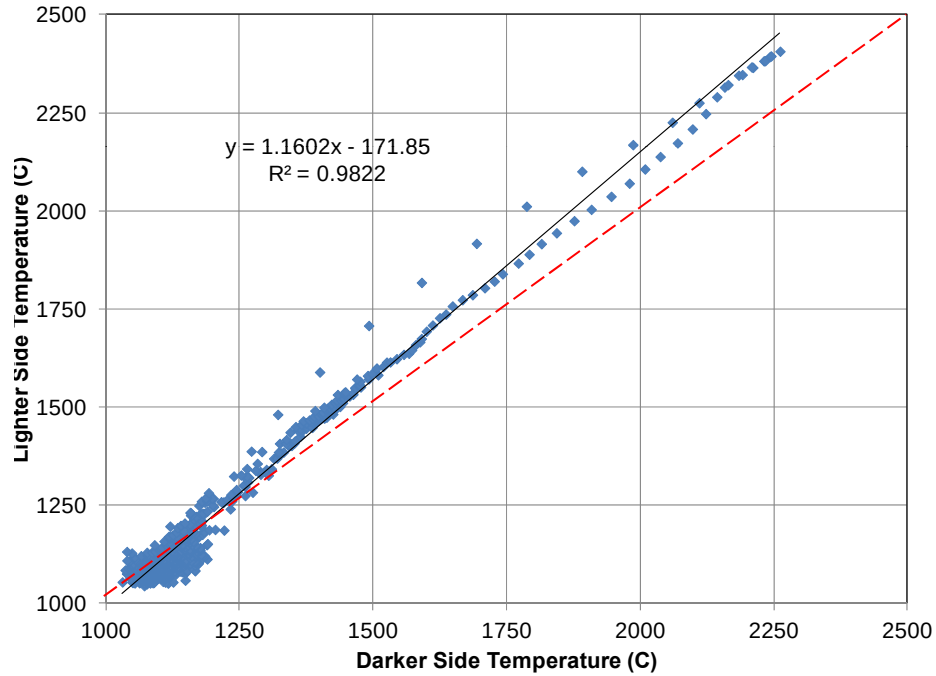
Thermal image on darker side

Controlled Exposure Experiment

Temperature Profiles Observed Through Different Levels of Metallization



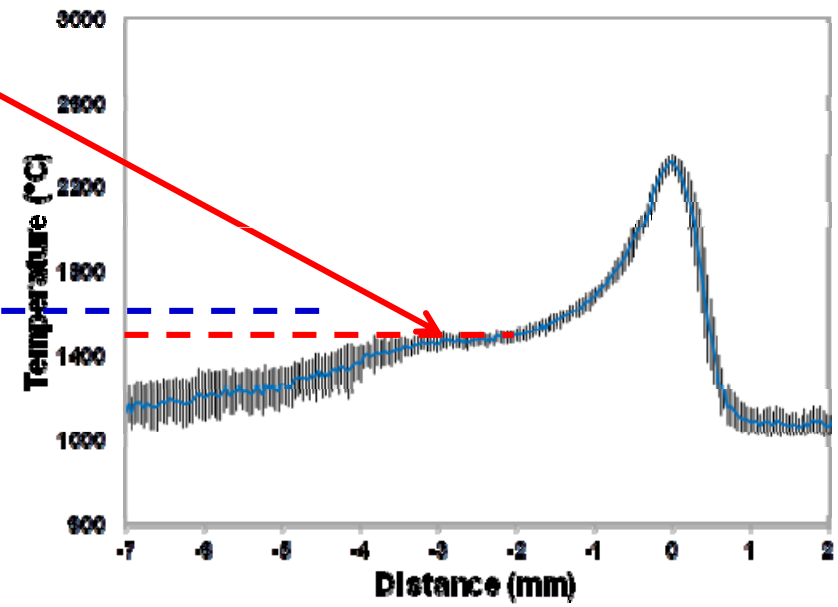
Average Temperature Profiles (6.37 mm Build Height)



Relationship Between Temperatures Observed Through Different Levels of Metallization

Molten State Emissivity Estimate

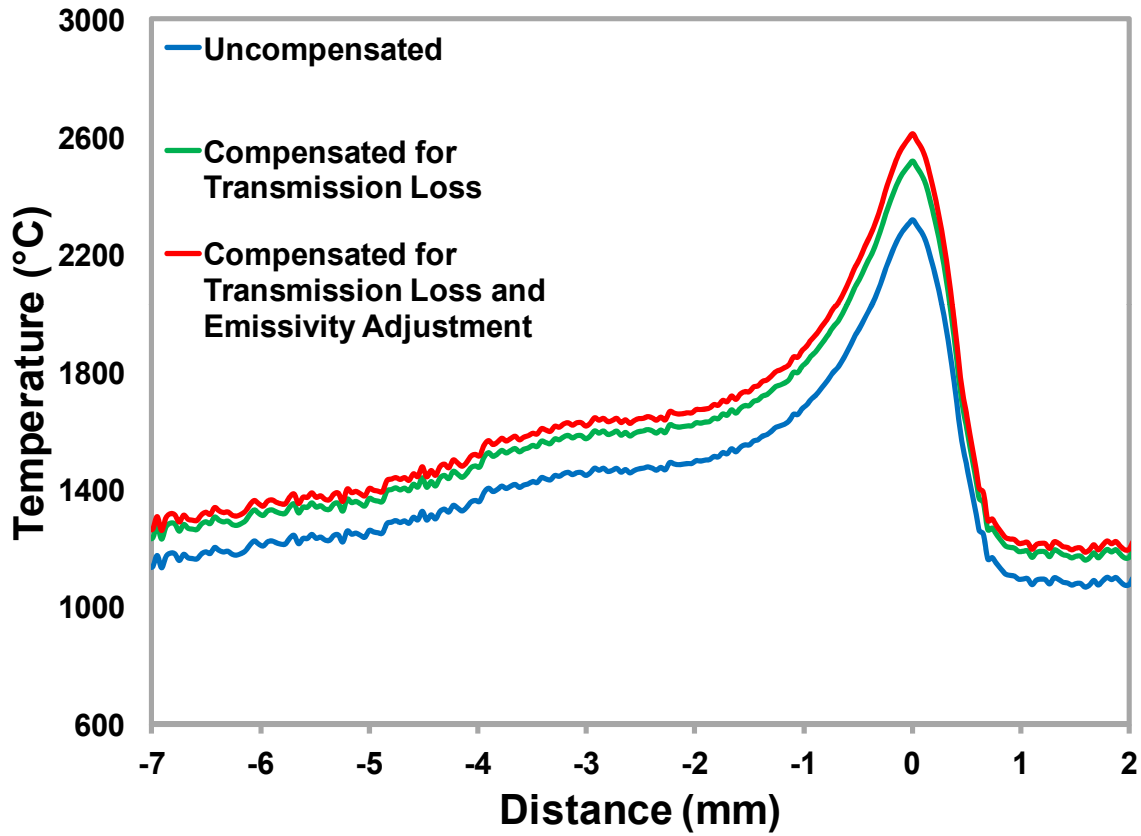
1. Identify Measured Liquidus Temperature
2. Solve for Apparent Liquidus Temperature, (function of measured liquidus temperature, assumed emissivity, etc.)
3. Solve for True Emissivity, (function of True Liquidus Temperature, Apparent Liquidus Temperature, etc.)



Estimate T_m measured → Estimate T_{app} (ε=1), with T_m measured → Estimate ε_{true} with true T_m, T_{app} → ε_{true} value

Estimated molten pool ε: ~0.28

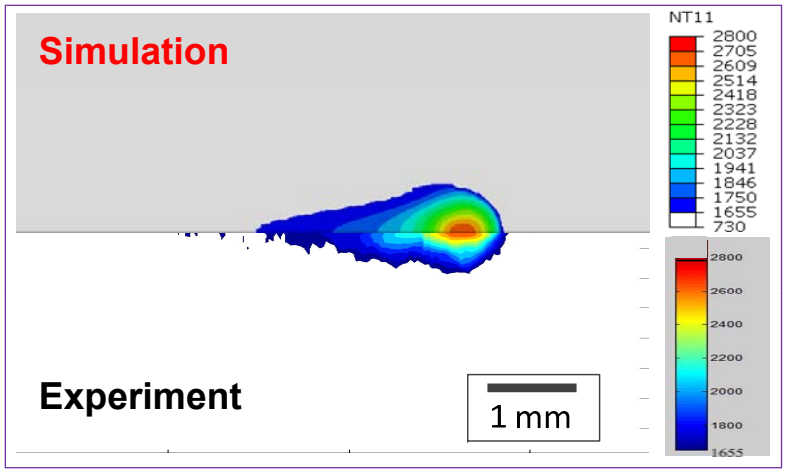
Temperature Profile Compensation

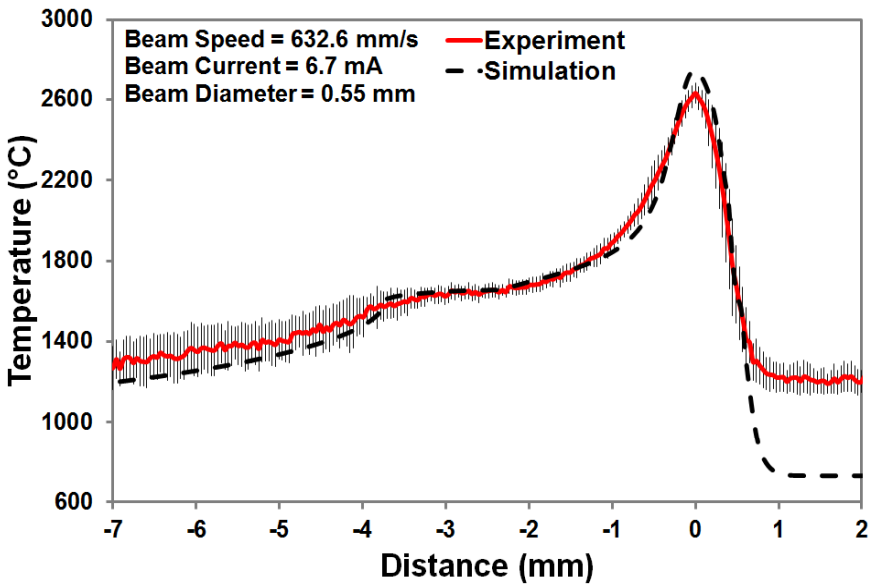


Average Temperature Profile (6.37 mm Build Height)

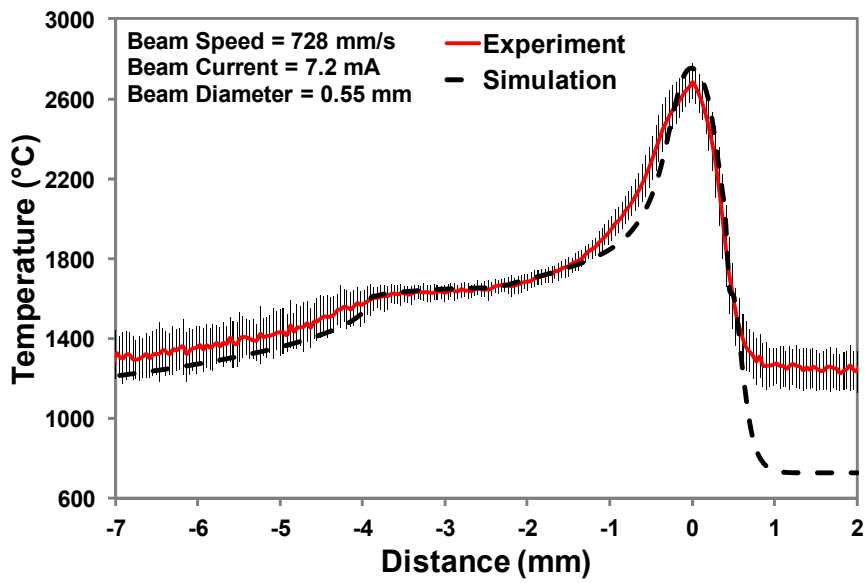
Simulation vs. Experiment

Set 1 Build height = 26.53 mm



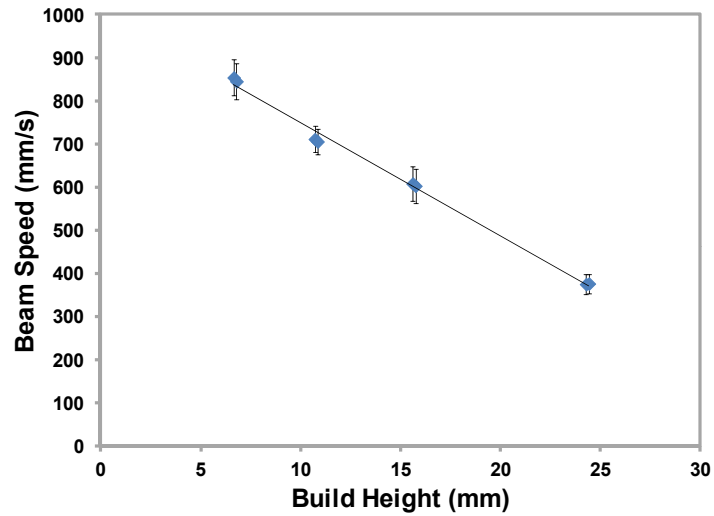


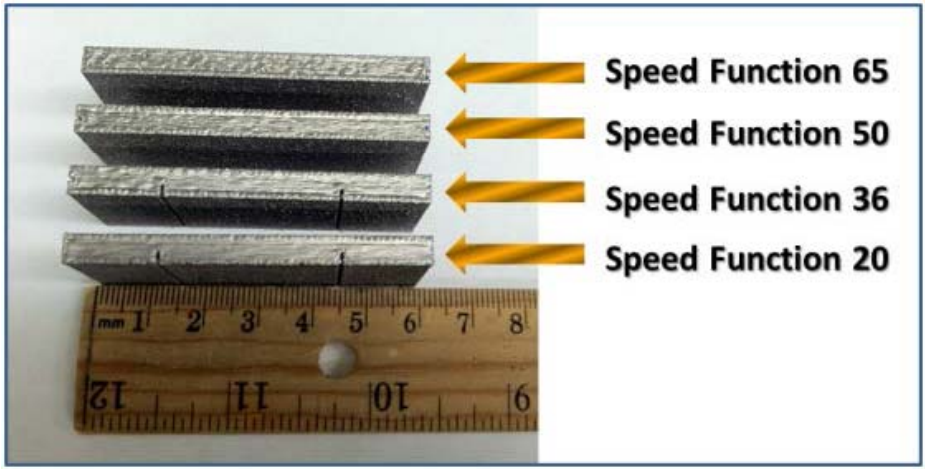
Set 2 Build height = 16.87 mm

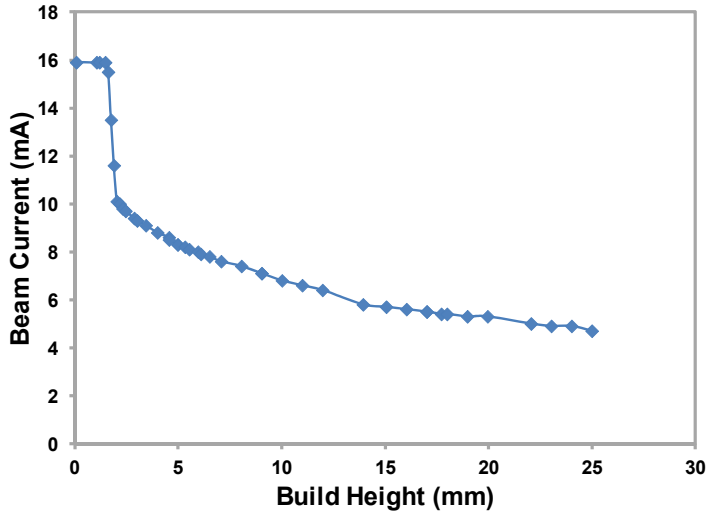


Process Parameter Effect

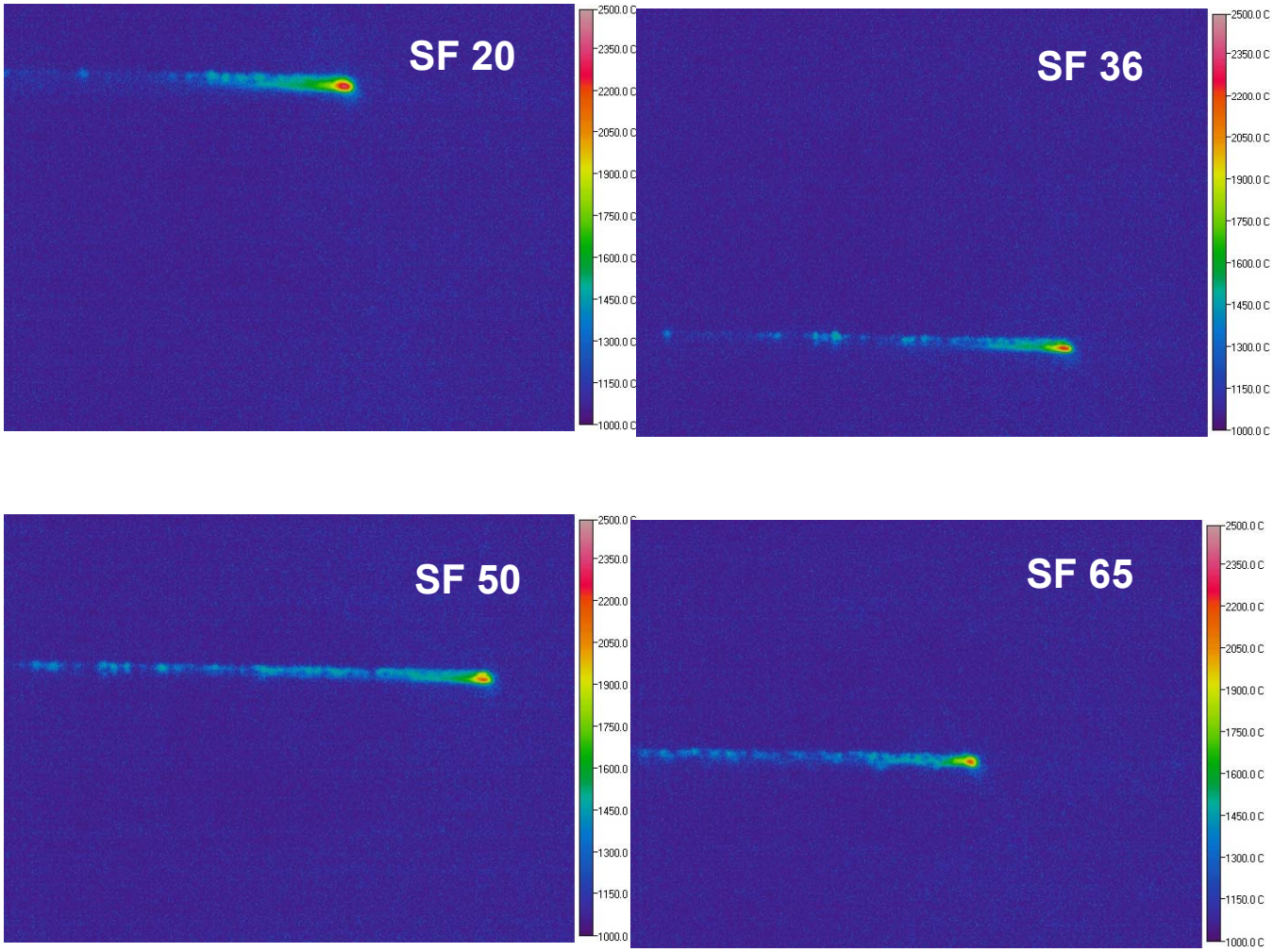
- Speed Function (SF) Index
  - System Setting
- Beam Speed, Current
- Tested Range
  - SF20 – SF65





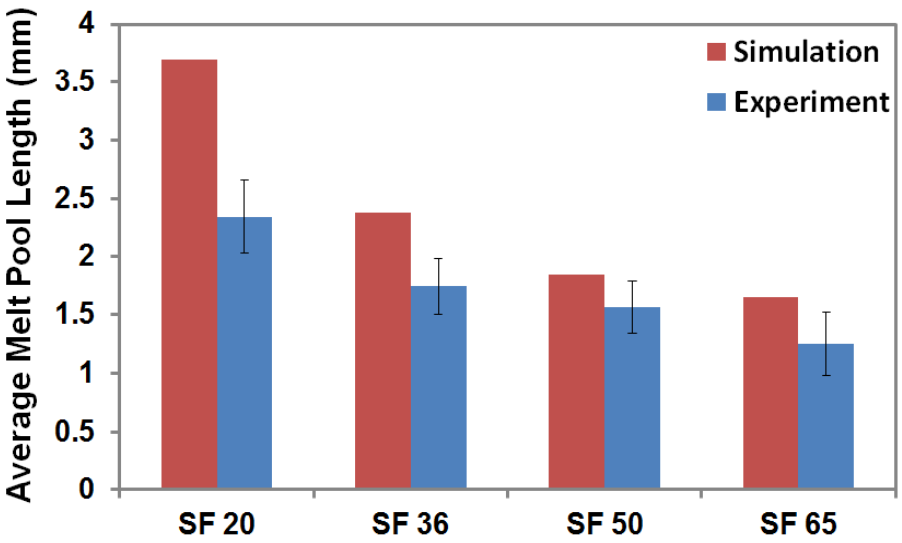


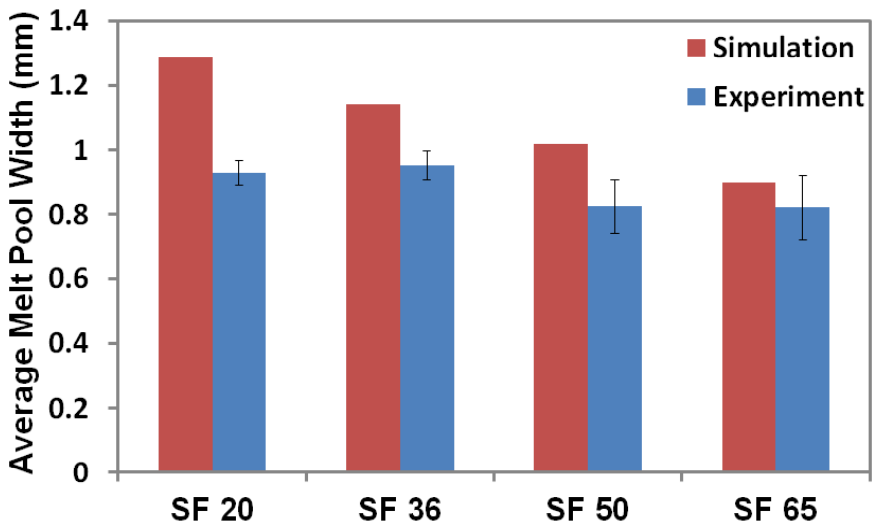
NIR Images – Different SF Indices

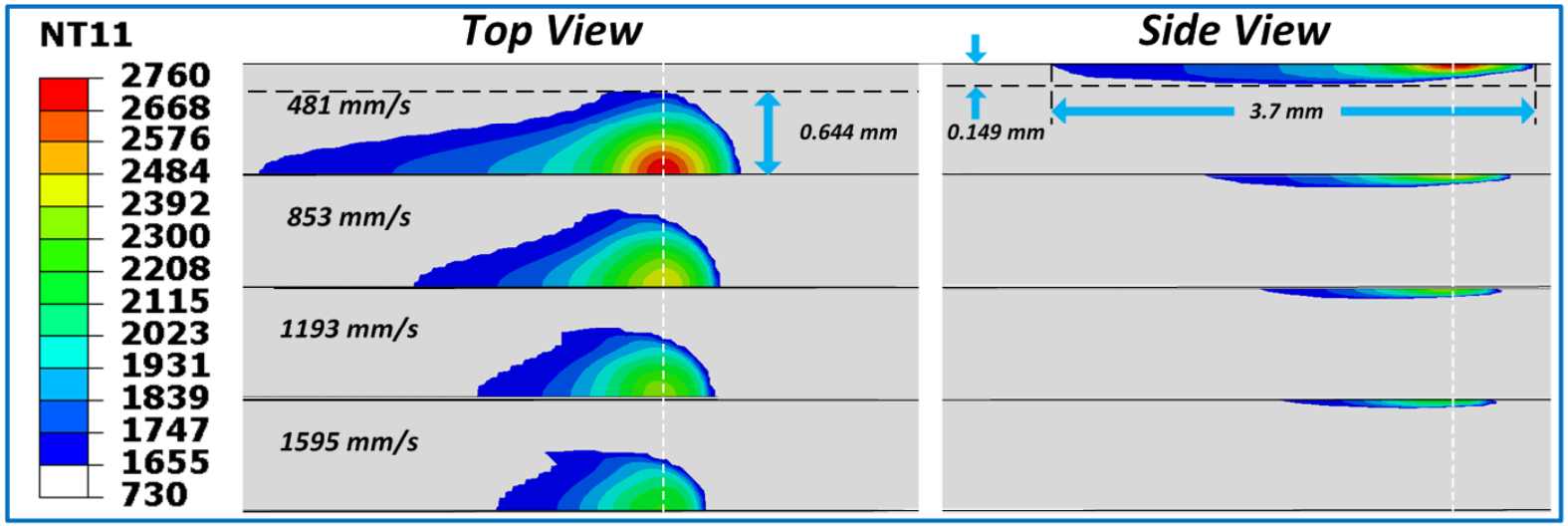


Melt Pool Size Comparisons

7.7 mA current, 0.65 mm diameter, 6.65 mm build height

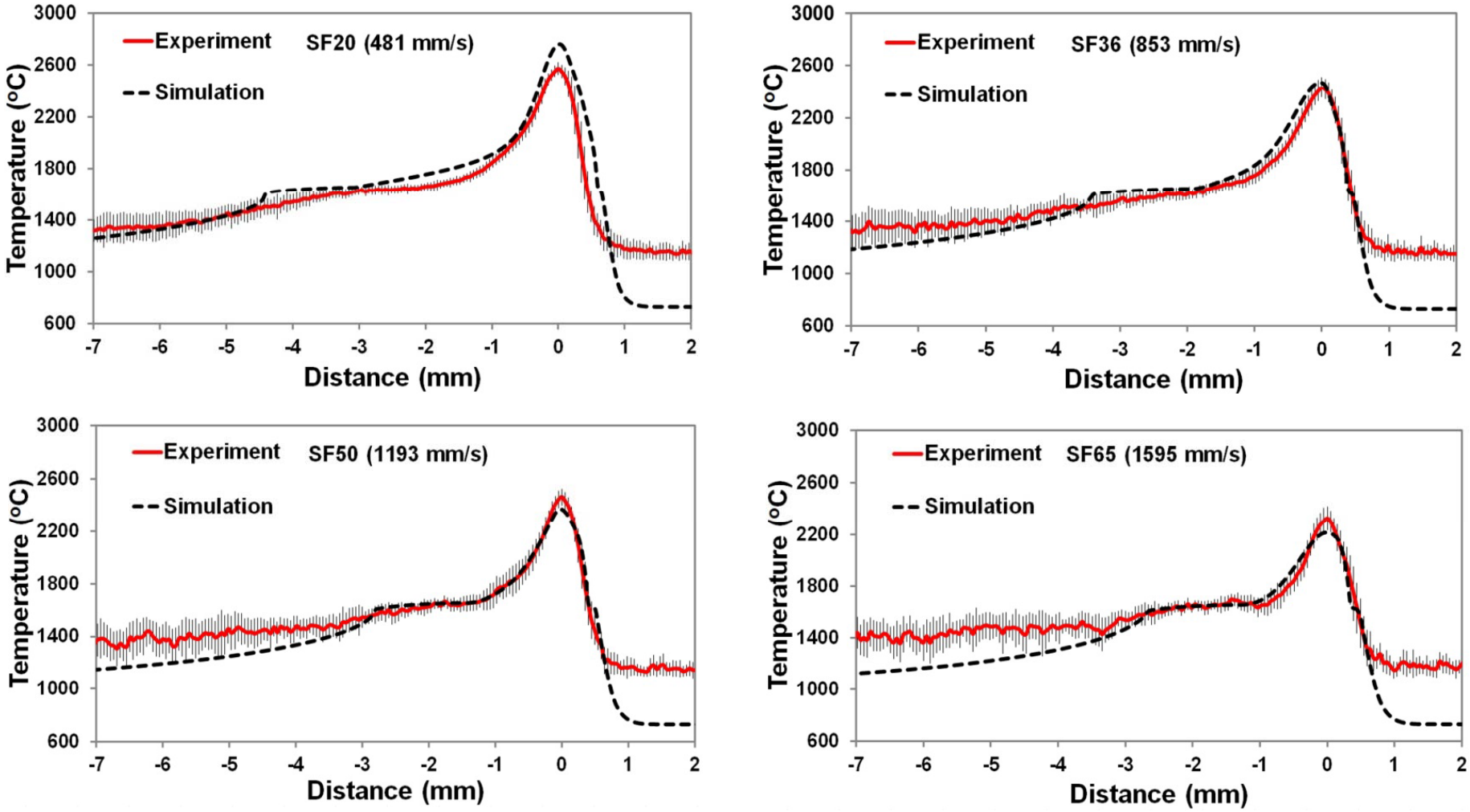






Temperature Analysis
Beam Speed Effect

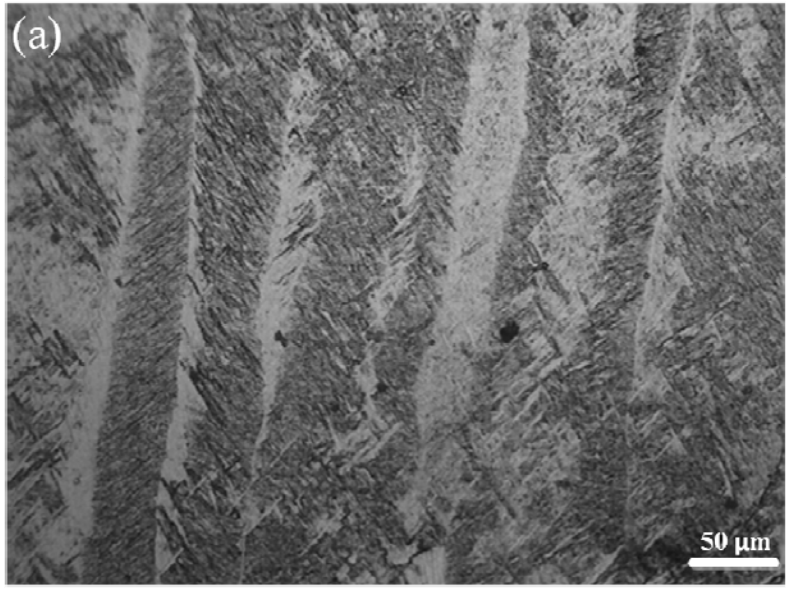
7.7 mA current, 0.65 mm diameter, 6.65 mm build height



(4) Part Characterization

- ☑ Microstructures (Phases, Grain Sizes)
- ☑ Mechanical Properties (E, H, YS, UTS)

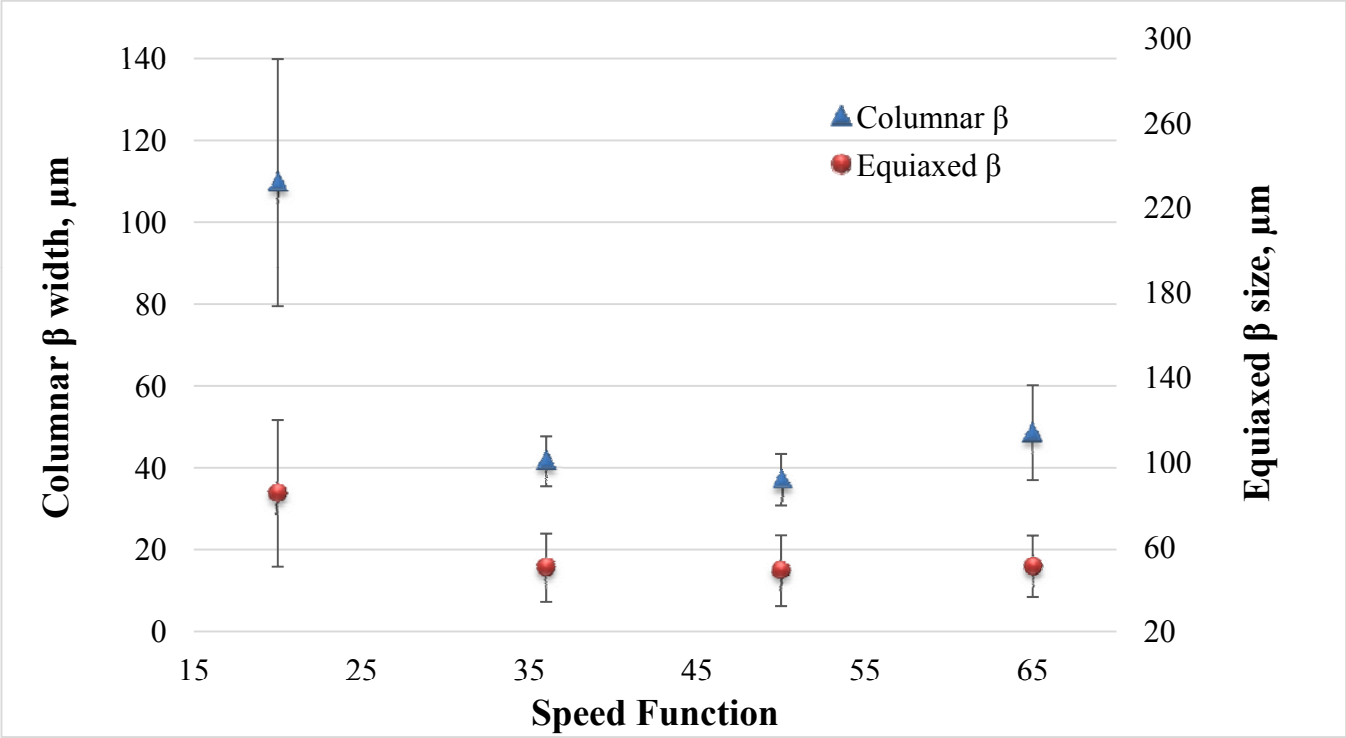
EBAM Ti-6Al-4V Microstructure



Side surface (X-plane)

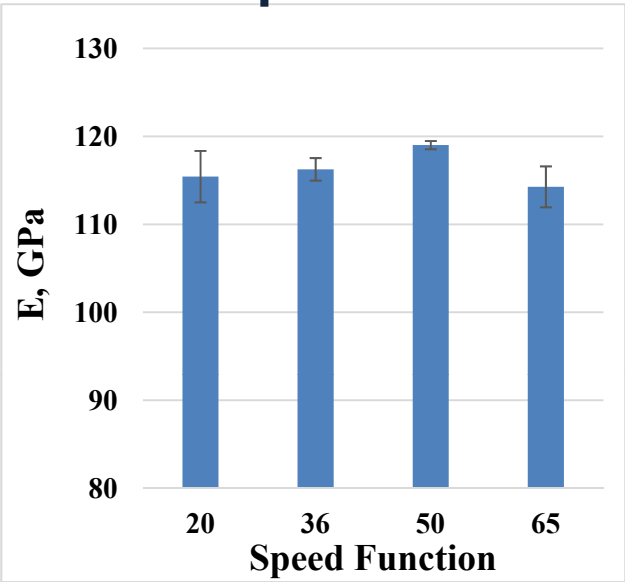
Scanning surface (Z-plane)

Process Parameter Effects

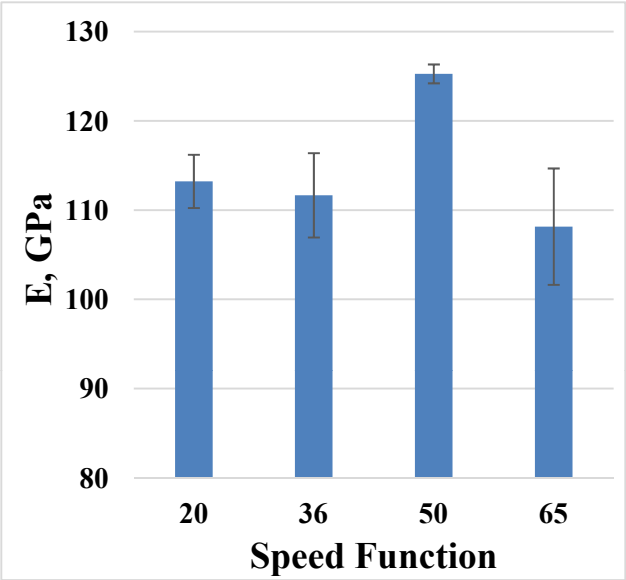


Mechanical Property (Nanoindentation)

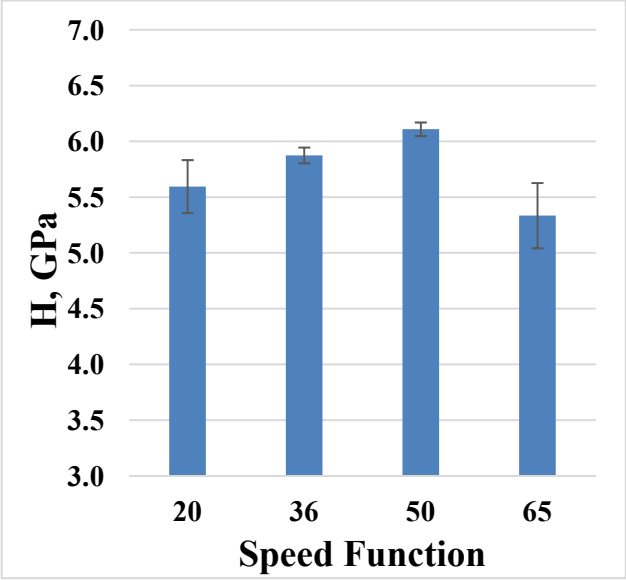
Z-plane

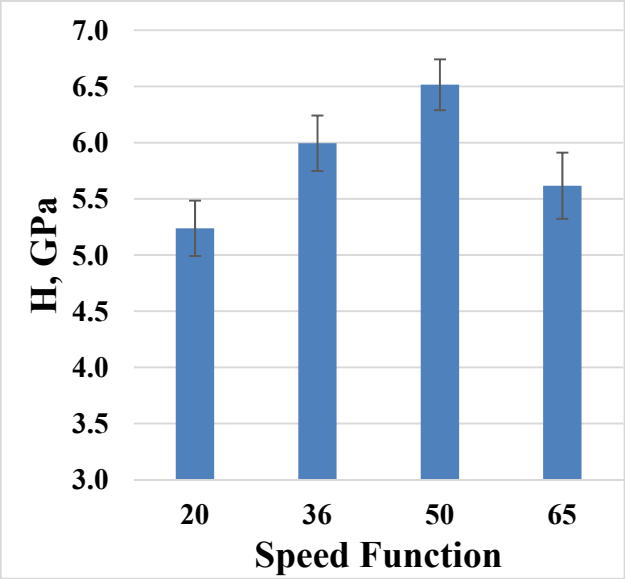


X-plane



Young's modulus

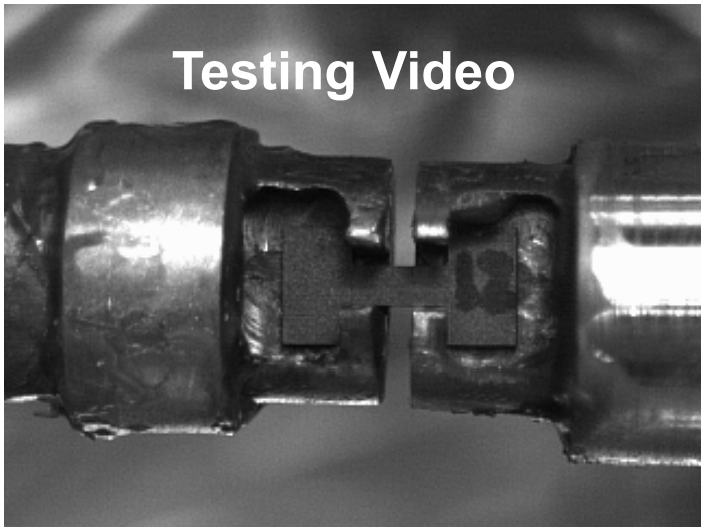


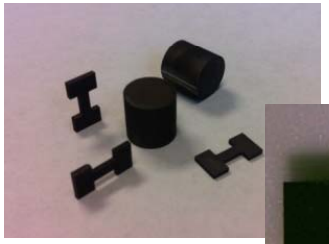


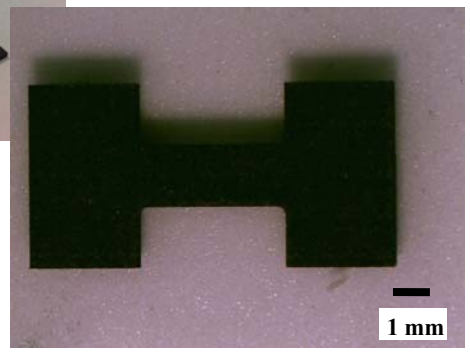
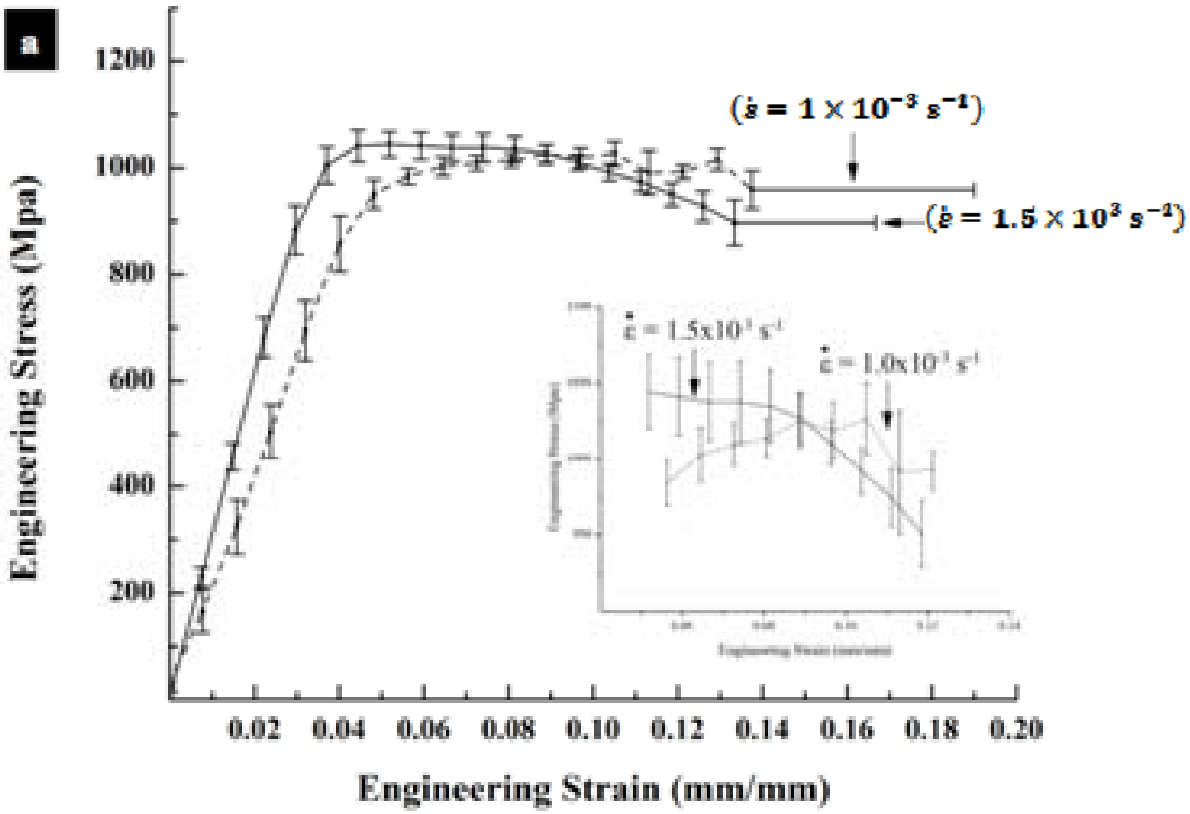
Hardness

Split-Hopkinson Bar Testing (P. Allison)

- Uniaxial Tensile, Quasi-static and Dynamic
- Mechanical Behavior







YS: ~975 MPa, UTS: ~1030 MPa