TFAWS Passive Thermal Paper Session

Development of High-Temperature Lightweight Radiator Panels with 3-D Printed Titanium Loop Heat Pipes

Parth Agrawal[1], Ashley Paz y Puente[1], Dinc Erdeniz[1], Ying Sun[1], Sandeep Hatte[2], Calin Tarau[2], Braden Stevens[3], Chinmaya Joshi[3], Han Hu[3]

[1]University of Cincinnati, 2600 Clifton Ave, Cincinnati, OH 45221
[2]Advanced Cooling Technologies, 1046 New Holland Ave., Lancaster, PA 17601
[3]University of Arkansas, Fayetteville, AR 72701

Presented By

Parth Agrawal, Chinmaya Joshi

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Presentation Agenda

- **Project Overview and Innovative Aspects**
- **Additive Manufacturing of Ti Wicks**
  - Printing of Ti-6Al-4V Wicks
  - Printing of CP-Ti Wicks
- **Spectrally Selective Radiator Coatings**
- **Ti-encapsulated Pyrolytic Graphite Radiator Fins**
- **Conclusions**
- **References**

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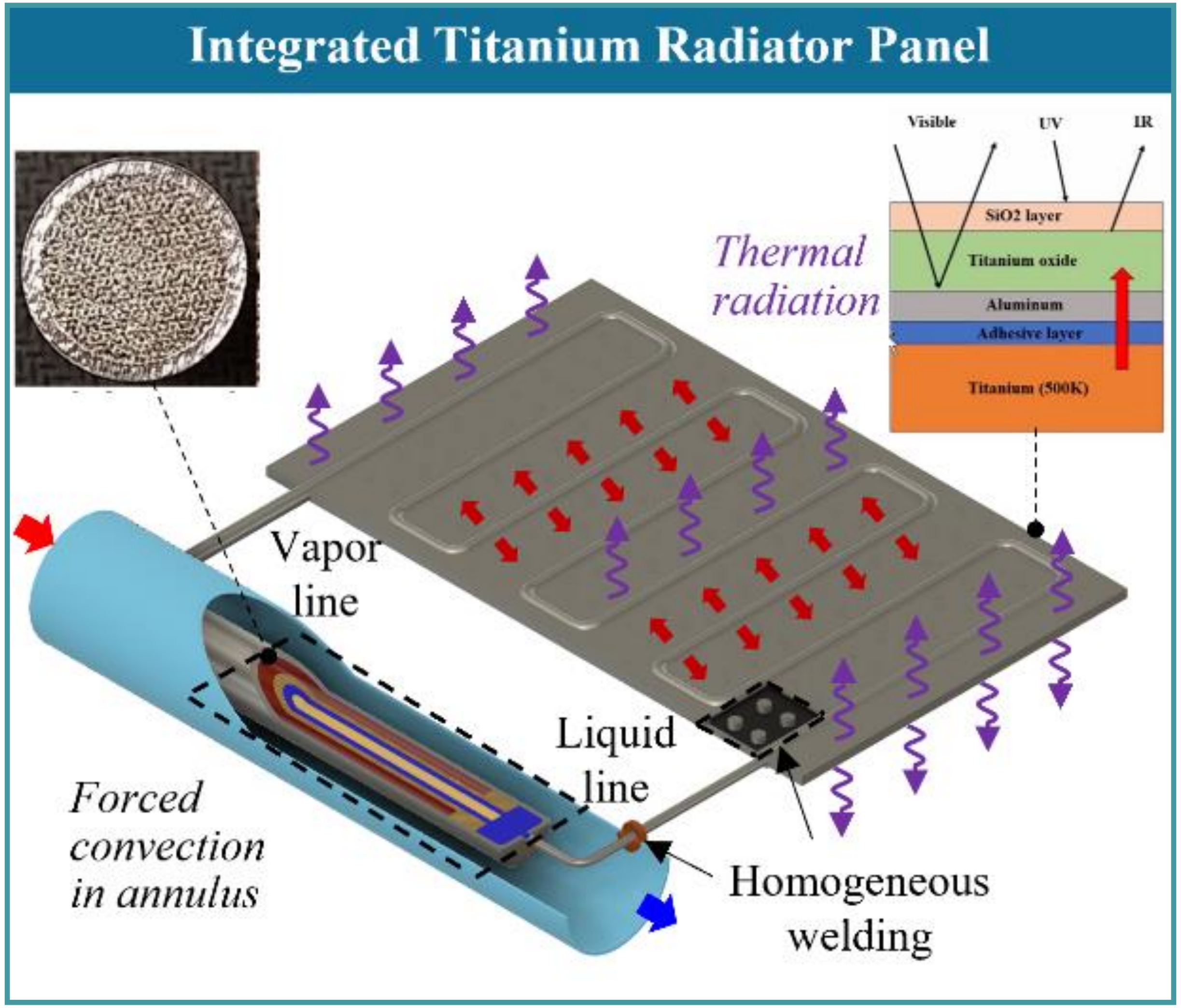
Project Overview

The project aims to develop and demonstrate a *high-temperature, light-weight spacecraft radiator with additively manufactured titanium loop-heat pipes (LHPs) and Ti-encapsulated pyrolytic graphite fins* to simultaneously improve thermal performance and mechanical robustness for sustainable heat dissipation of nuclear propulsion systems.



Innovative Aspects

Advantages of Additively Manufactured LHP Radiators:

- Operates reliably over long distances;
- Enables simple and flexible designs with single, connected structures that minimize joints
- Minimizes interfacial thermal resistances and mismatch in the coefficient of thermal expansion (CTE)
- Reduces manufacturing cost
- Achieves best aerial density and thermal performance with highly conductive, lightweight pyrolytic graphite core
- Can be tested under gravity

LHPs can see potential use in future manned Mars missions.

Innovative Claims

Innovations:

- 3D-printed titanium loop heat pipe
- Titanium-encapsulated pyrolytic graphite fin with spectrally selective coating
- Homogeneous welding
- Annular heat exchanger

Metrics:

- Power density ~ 3,000 W/cm^2
- Aerial density ~ 2.0 kg/m^2
- In-plane k ~ 1,750 W/m-K
- Out-of-plane k ~ 18 W/m-K

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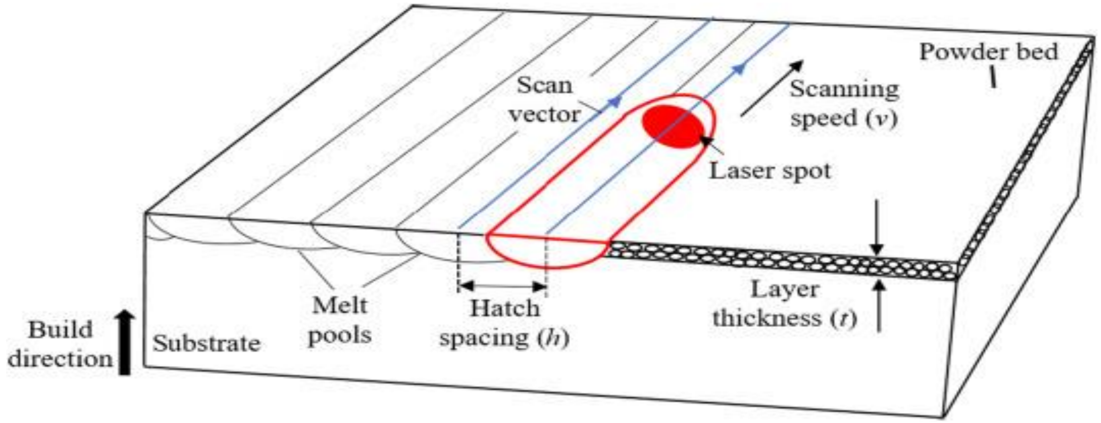
Additive Manufacturing of Ti Wicks

Laser Powder Bed Fusion (L-PBF)



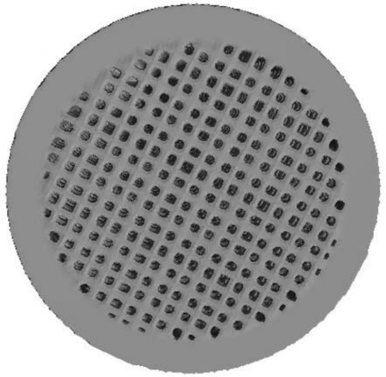
P- Laser Power
v - Scan Speed
h - Hatch Spacing
t - Layer Thickness
S - Laser Spot Size

Volumetric Energy Density (*VED*)

$$VED = \frac{P}{vht}$$

Challenge –

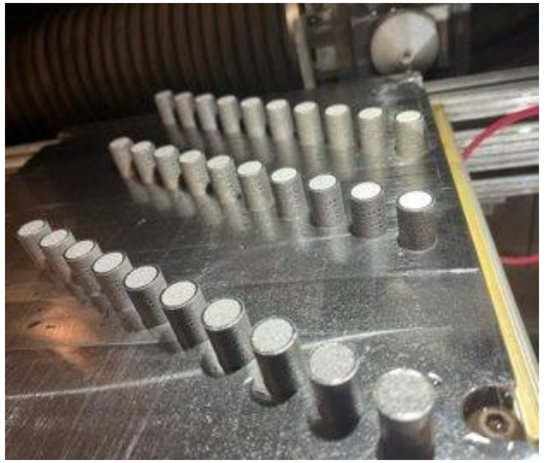
- Smaller strut and pore sizes are limited by machine parameters (Laser Spot Size ~ 100 µm) during controlled printing.
- *New approach is needed for smaller features.*



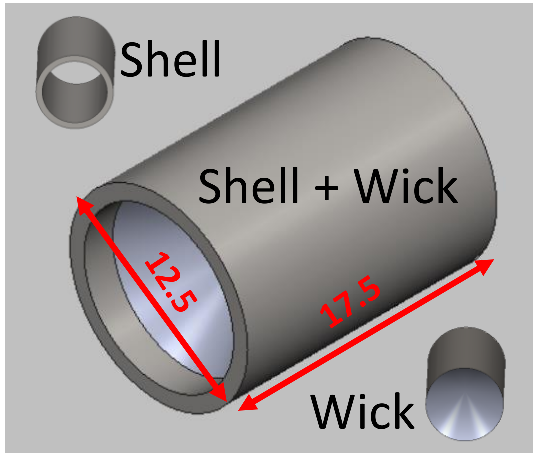
Strut Size ~ 130 µm
Pore Size ~ 100 µm

Printing of Ti-6Al-4V Wicks

Technical Data for Printer	
Laser Power	200 W
Build Volume	250 x 250 x 215 mm
Layer thickness	20 µm or 40 µm
Scan Speed	Up to 7.0 m/s
Focus Diameter	100 µm



Printed Wicks on Build Plate



Specimen Geometry

Close up of Wick Structures

Varied Hatch Spacing (*h*)
Constant *VED* = 10 J/mm^3

Power (W)	Scan Speed (mm/s)	Hatch Spacing (µm)
50	500	250
75	750	250
100	1000	250
100	1250	200
125	1500	208
125	1750	179
150	1750	214
150	2000	188
175	2000	219
175	2250	194

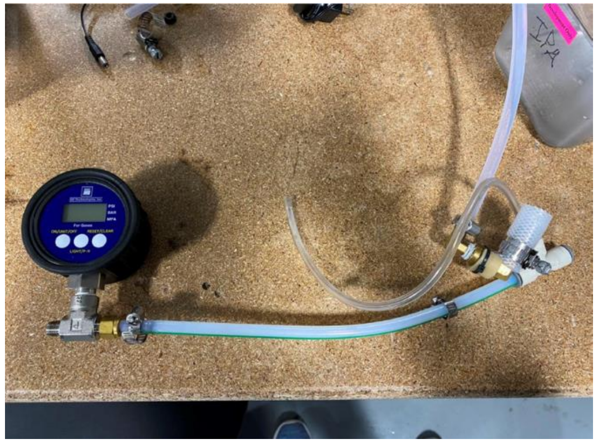
$$VED = \frac{P}{vht}$$

P – Laser Power
v – Scan Speed
h – Hatch Spacing
t – Layer Thickness

Varied *VED*
Constant *h* = 300 µm

VED	Power (W)	Scan Speed (mm/s)
10	50	417
10	75	625
10	100	833
10	125	1042
10	150	1250
15	50	278
15	75	417
15	100	556
15	125	694
15	150	833
20	50	208
20	75	313
20	100	417
20	125	521
20	150	625
25	50	167
25	75	250
25	100	333
25	125	417
25	150	500

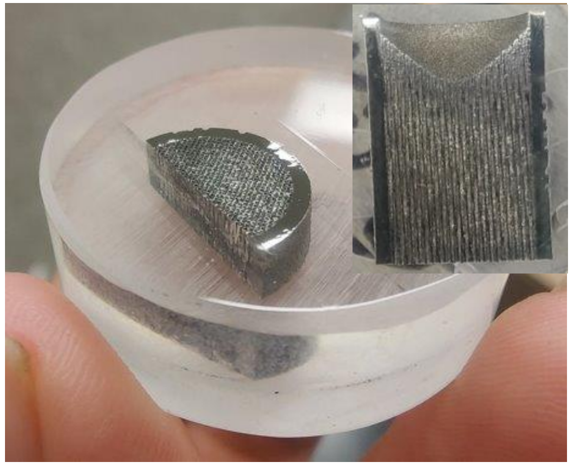
Wick Characterization



1. Bubble Test
- Max pore radius

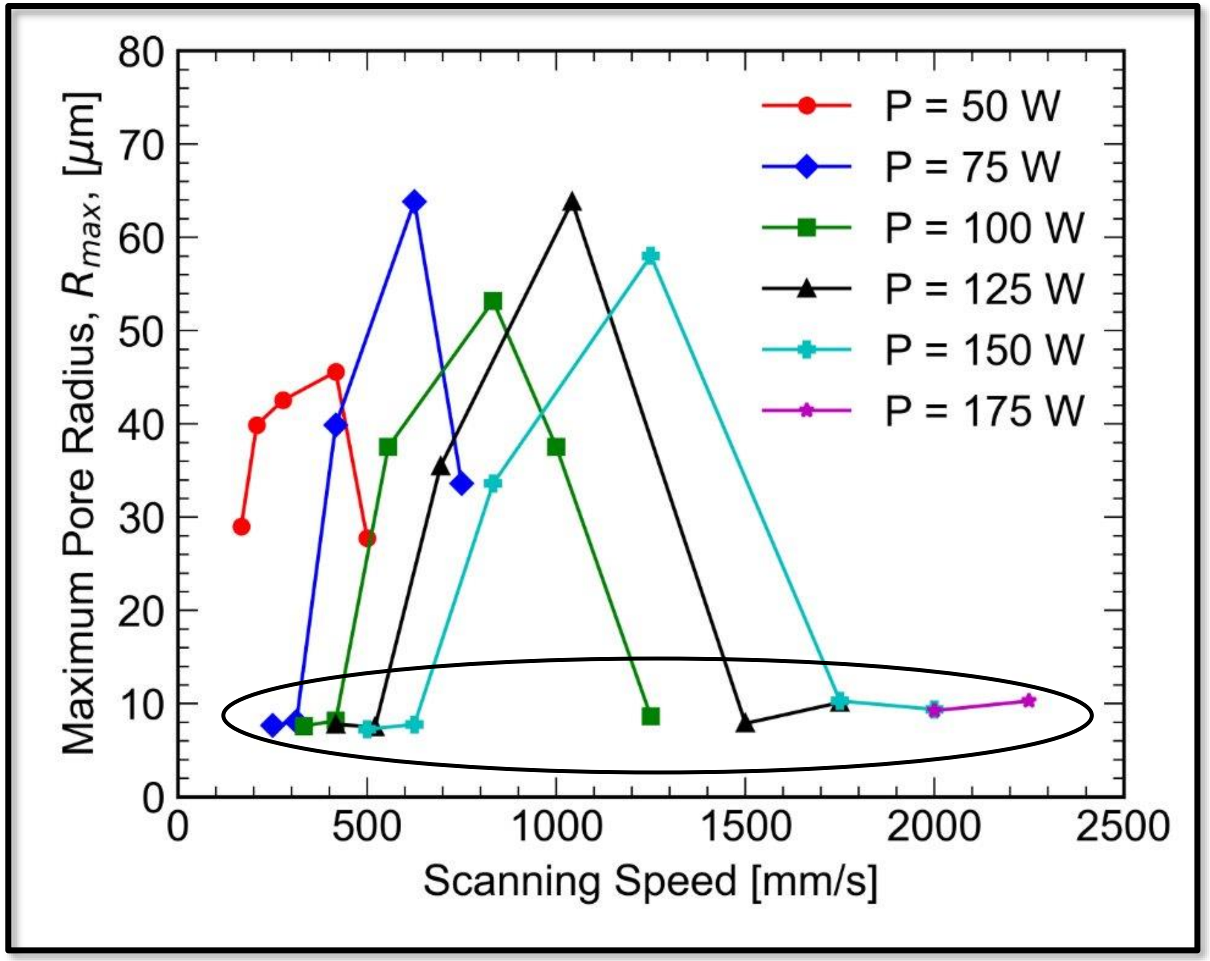
2. Flow Test
- Permeability

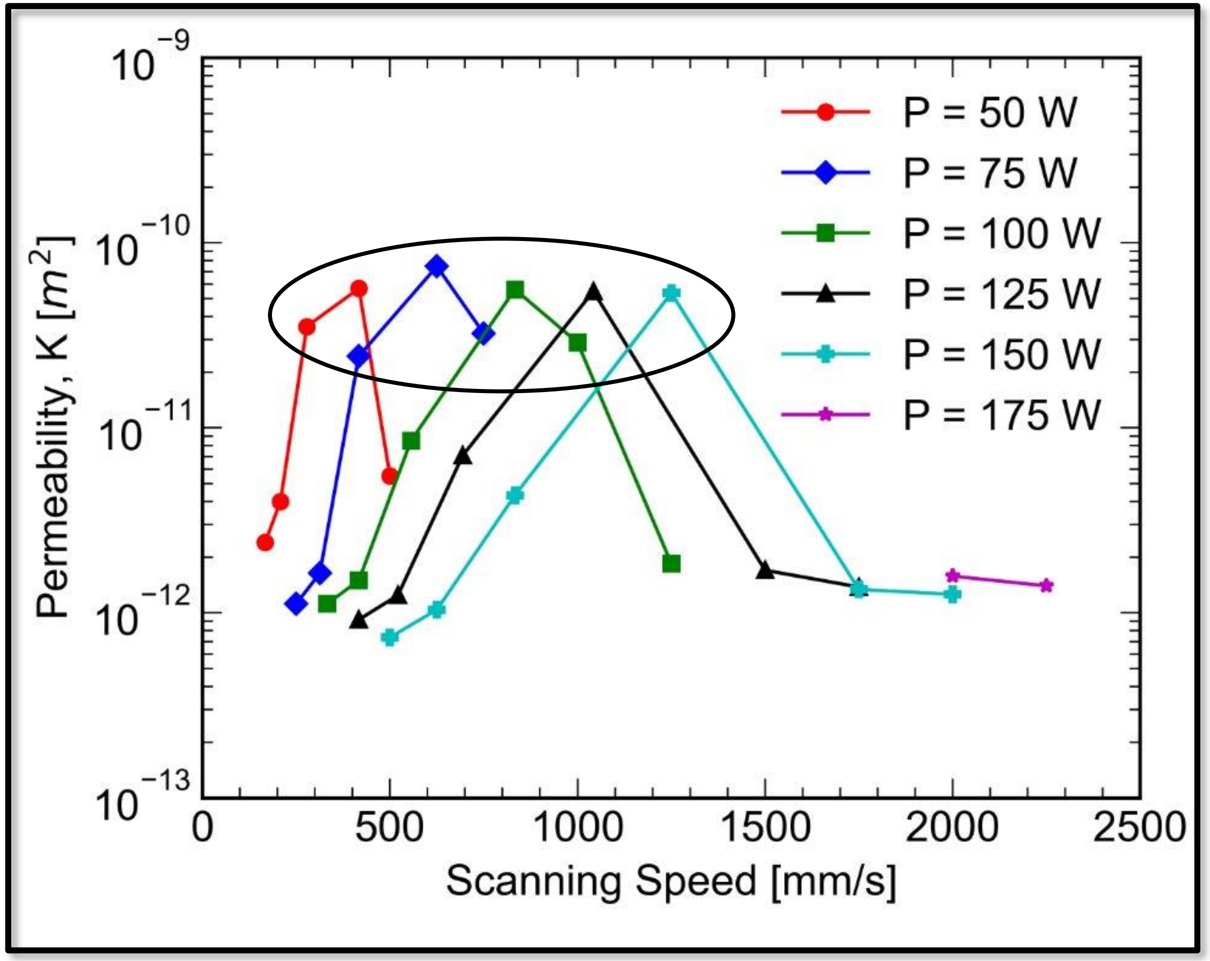
3. Gas Pycnometry
- Porosity



4. Metallography
- Pore Distribution

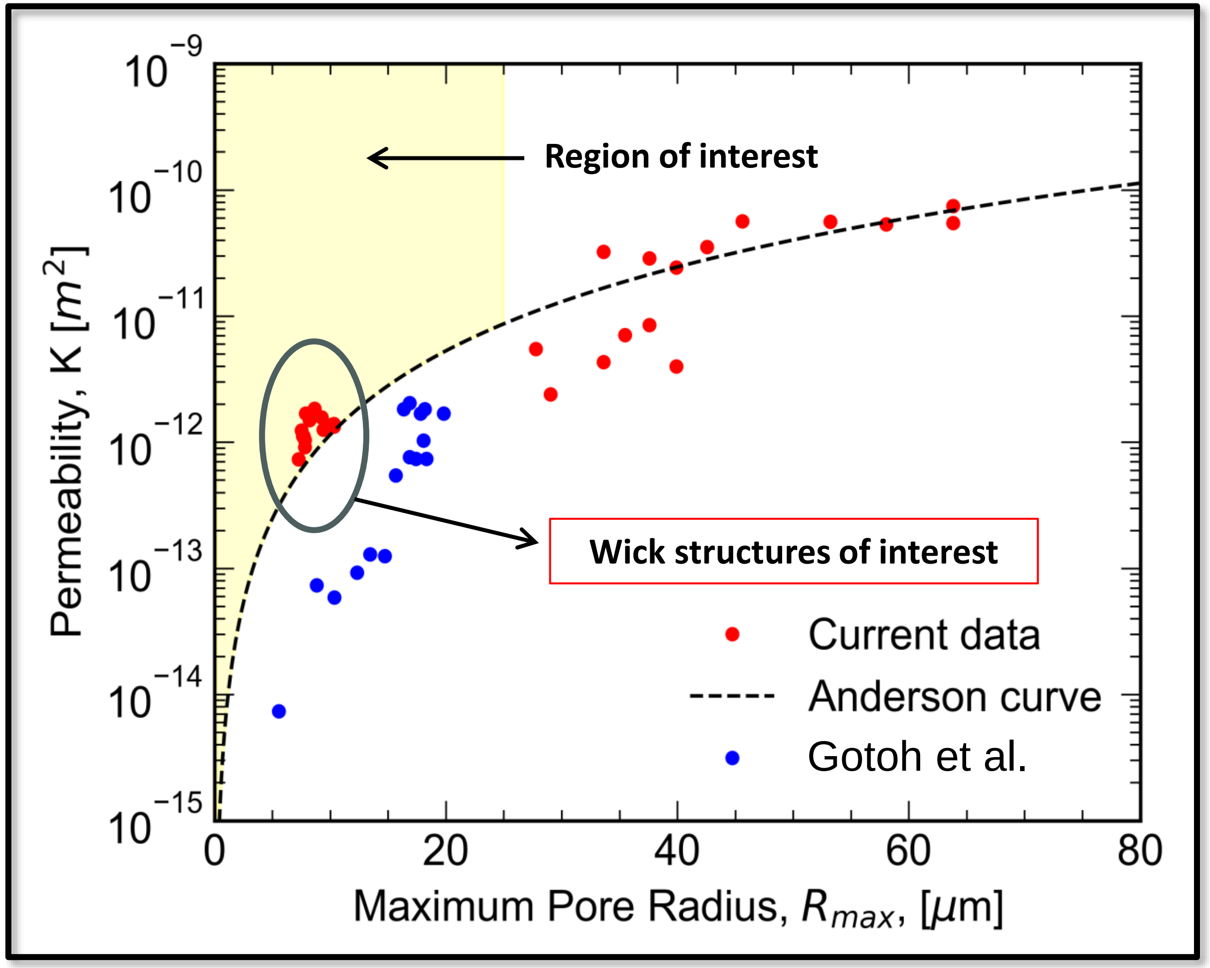
Results from Ti-6Al-4V Wicks

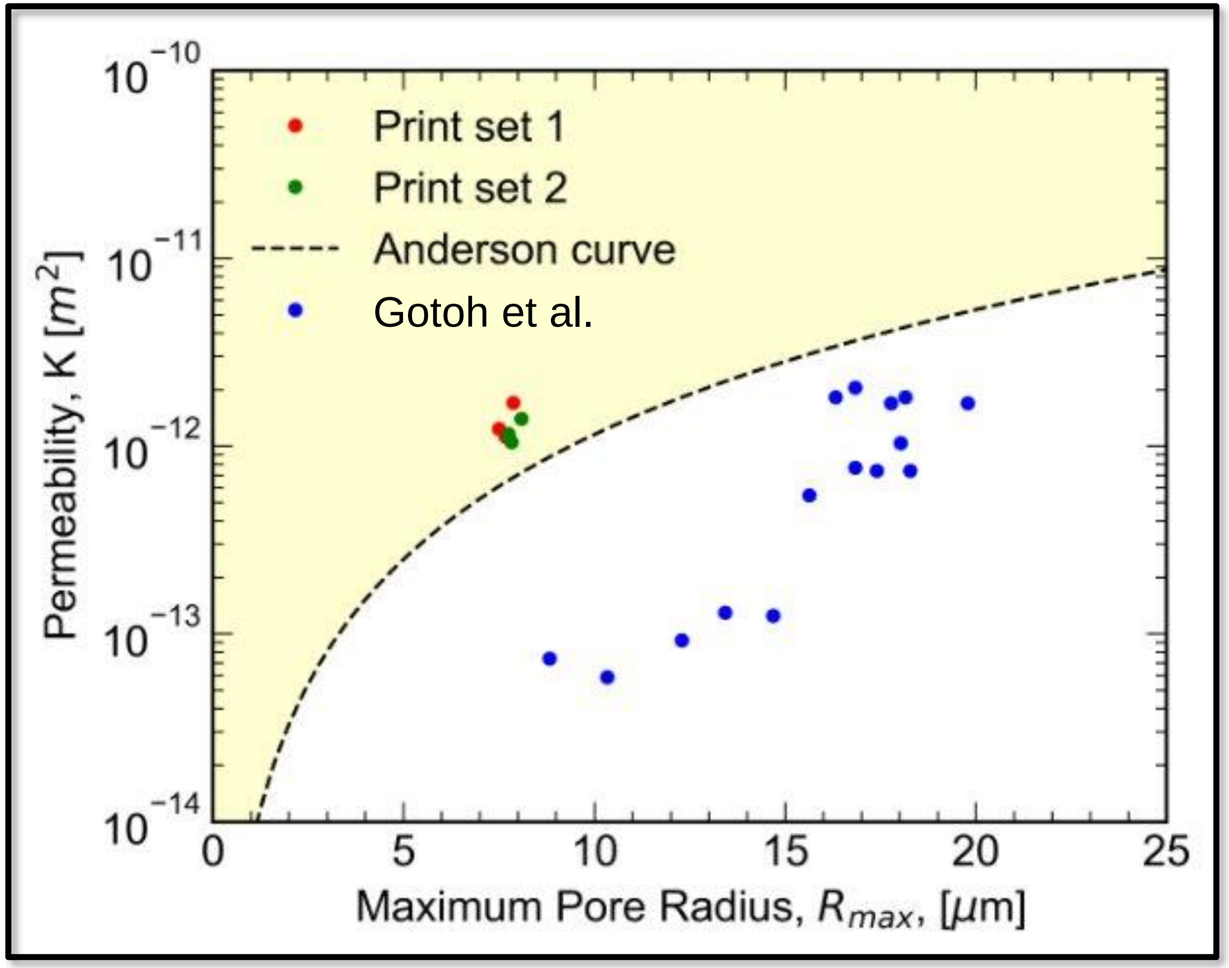




Wicks with low pore radii and high permeability are desirable, but these properties do not appear at the same time. Optimization of print parameters for best properties is needed.

Results from Ti-6Al-4V Wicks



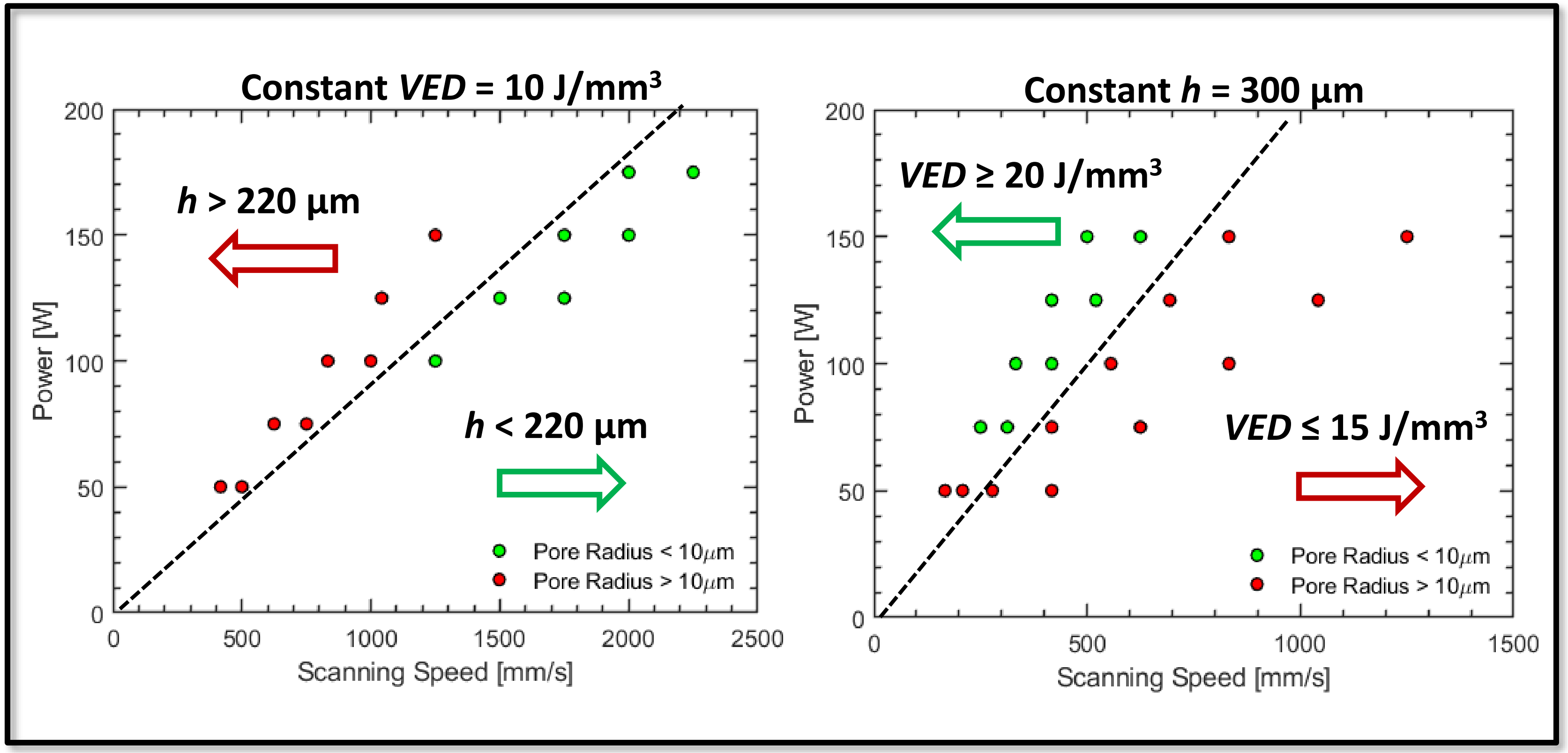


For the same characterization technique, the printing process is found to be highly repeatable

Results from Ti-6Al-4V Wicks

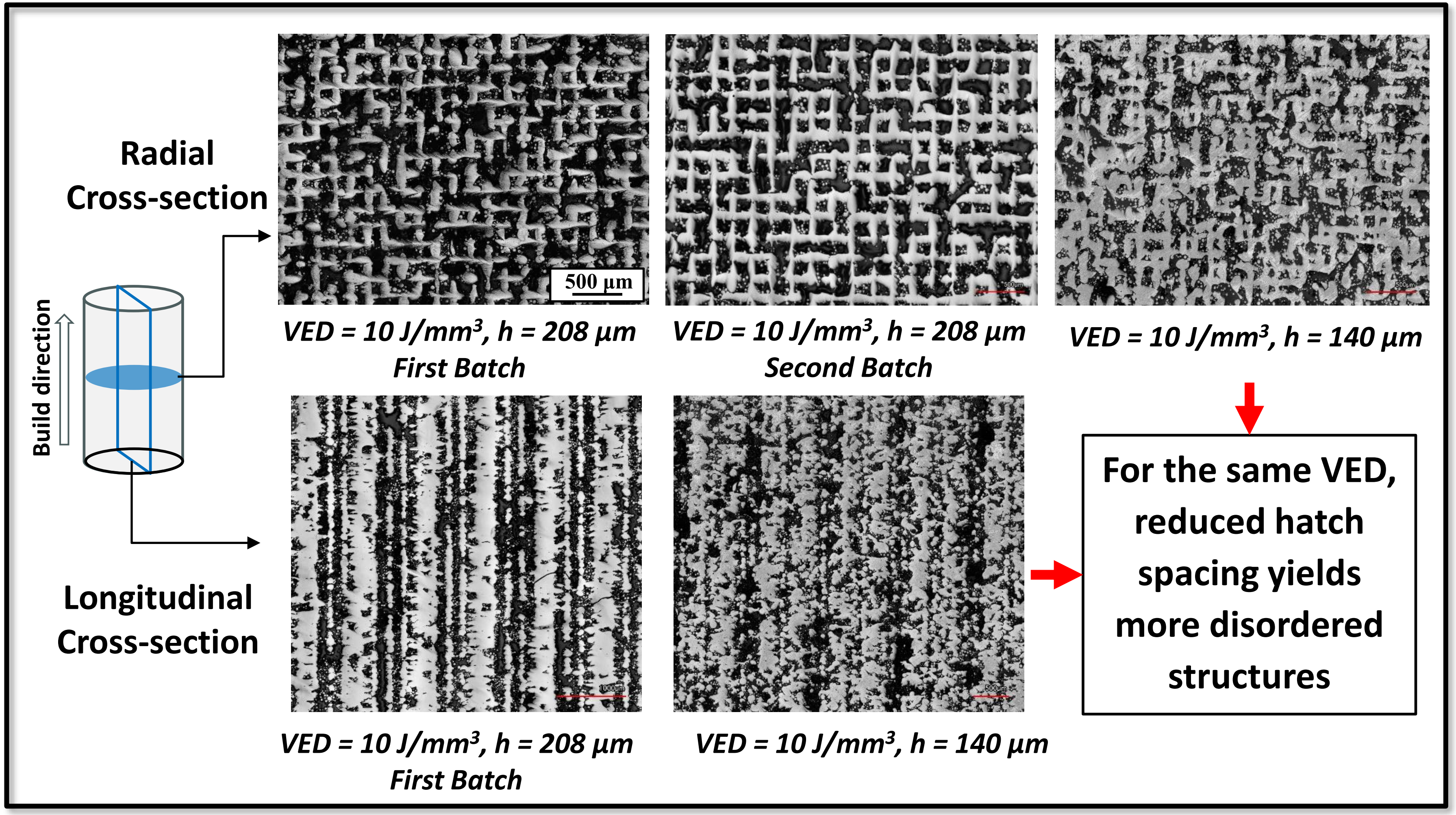
Results -

- Printed wick samples with low critical pore radius (<10μm) were classified as **good**, and the rest were classified as **bad**.
- At a low constant VED of 10 J/mm^3, a **lower hatch spacing (< 220 μm)**, i.e. closer tracks, is required to achieve a maximum pore radius ≤ 10 μm.
- At a constant hatch spacing of 300 μm, a **higher volumetric energy density (≥ 20 J/mm^3)**, i.e. a wider melt pool, is required to achieve a maximum pore radius < 10 μm.



Low pore radius can be achieved by low VED and low hatch spacing, or high VED and high hatch spacing

Ti-6Al-4V – Effect of Hatch Spacing



Additional samples with best parameters from 1st batch and with modified hatch spacings (*VED* = 10 J/mm^3) were printed.

Observations -

- Excellent repeatability in pore radius, permeability, and porosity
- Microstructure anisotropy is reduced for specimens with smaller hatch spacing

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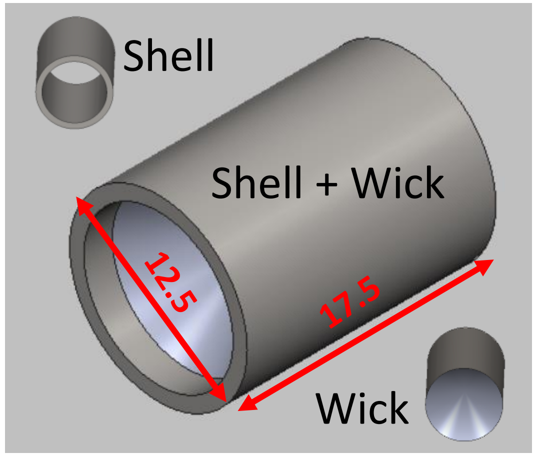
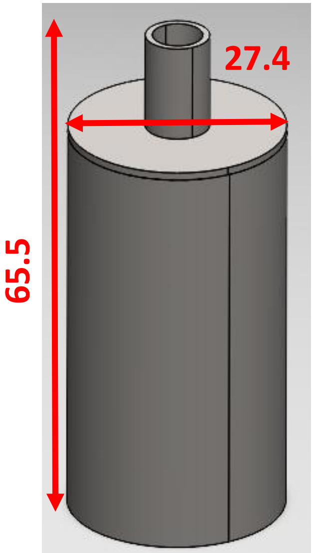
Printing of CP-Ti Wicks

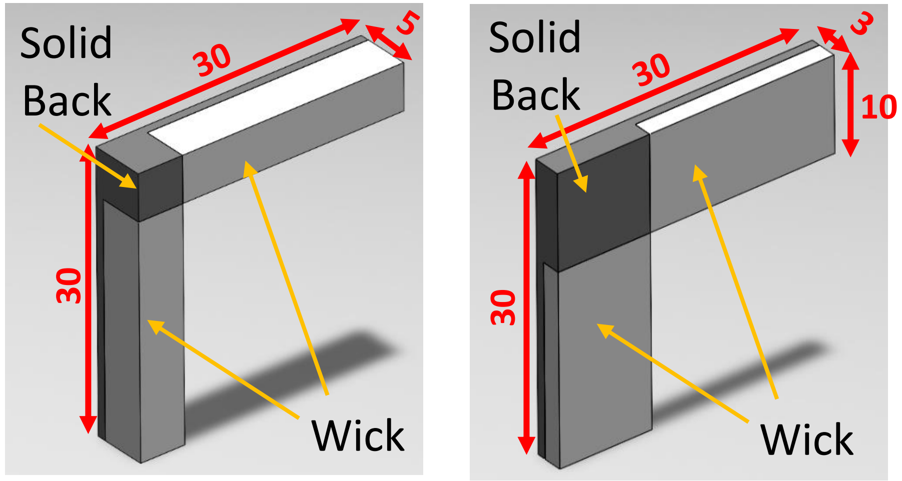


Wick Cylinders

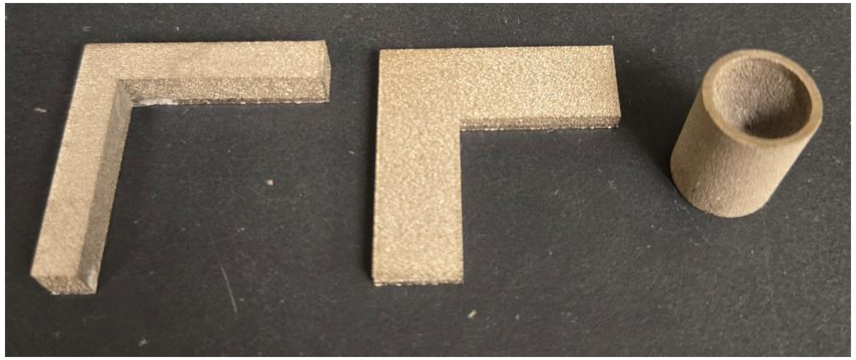


Evaporator

Technical Data for Printer	
Laser Power	500 W
Build Volume	275 x 275 x 420 mm
Layer thickness	30 µm or 60 µm
Scan Speed	Up to 8000 mm/s
Focus Diameter	60 µm



L-Wicks



Printed Parts

All dimensions in mm

Print Parameter Comparison between Batches

Material Properties

Property	Ti-6Al-4V	CP-Ti
k (W/mm·K)	6.7 x 10^{-3}	16.4 x 10^{-3}
ρ (g/mm^3)	4.43 x 10^{-3}	4.51 x 10^{-3}
c_p (J/g·K)	5.26 x 10^{-2}	5.23 x 10^{-2}
α (mm^2/s)	28.74	69.53

Print Parameters

Parameter	Machine 1	Machine 2
S (µm)	100	60
t (µm)	40	60
P (W)	50 – 175	80 – 400
v (mm/s)	165 – 3800	250 – 7000
h (µm)	115 – 300	60 – 325
VED (J/mm^3)	10 – 25	3 – 83

Standard Volumetric Energy Density Calculation

$$VED = \frac{P}{vht}$$

Modified Volumetric Energy Density Calculation

$$VED_{\mathrm{modified}} = \frac{P}{3\sqrt{\alpha \cdot v \cdot S \cdot h \cdot t}}$$

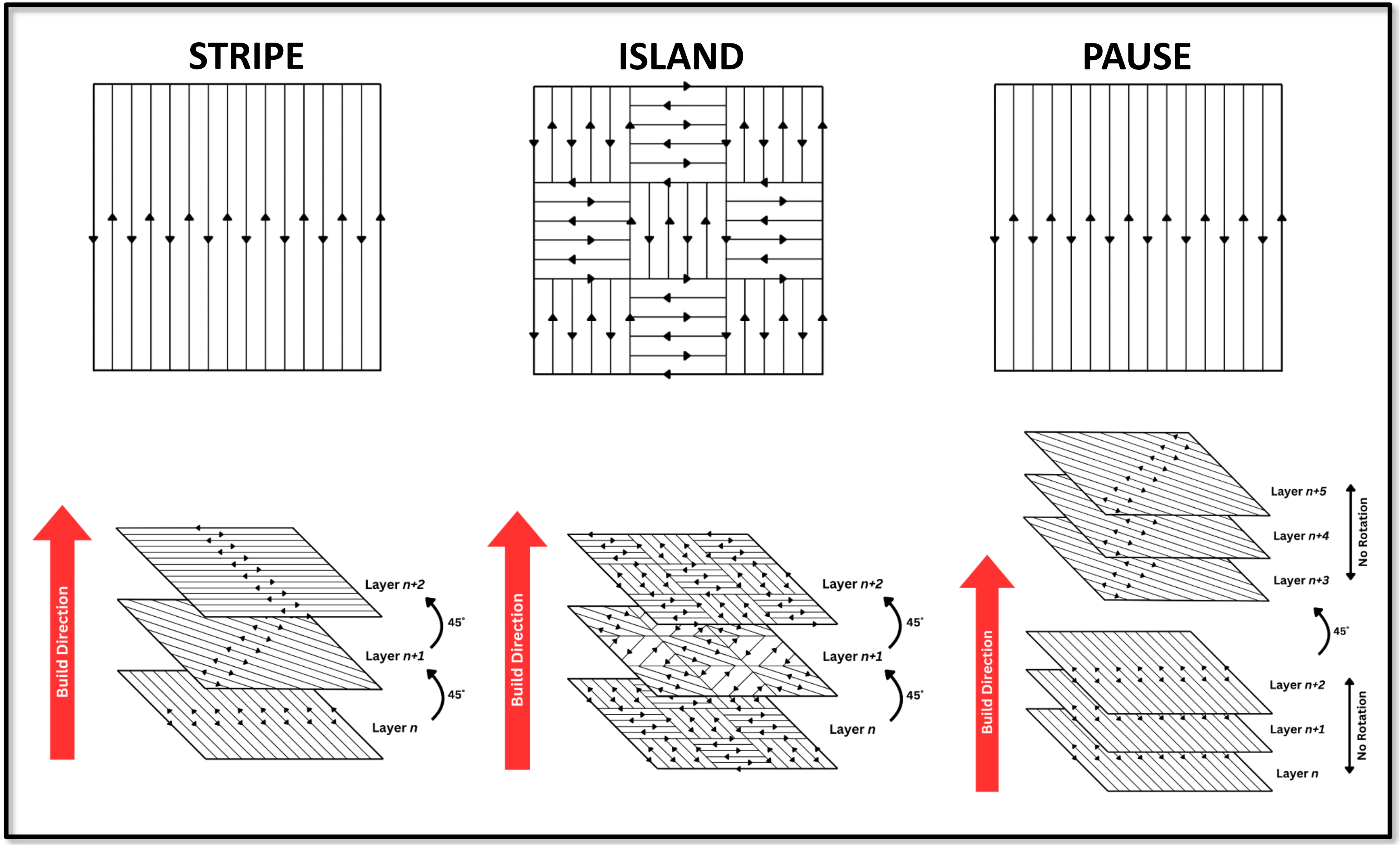
P – Laser Power
v – Scan Speed
h – Hatch Spacing
t – Layer Thickness
S – Laser Spot Size
α – Thermal Diffusivity

$$\alpha = \frac{k}{\rho c_p} = \frac{\text{thermal conductivity}}{\text{density} \cdot \text{specific heat}}$$

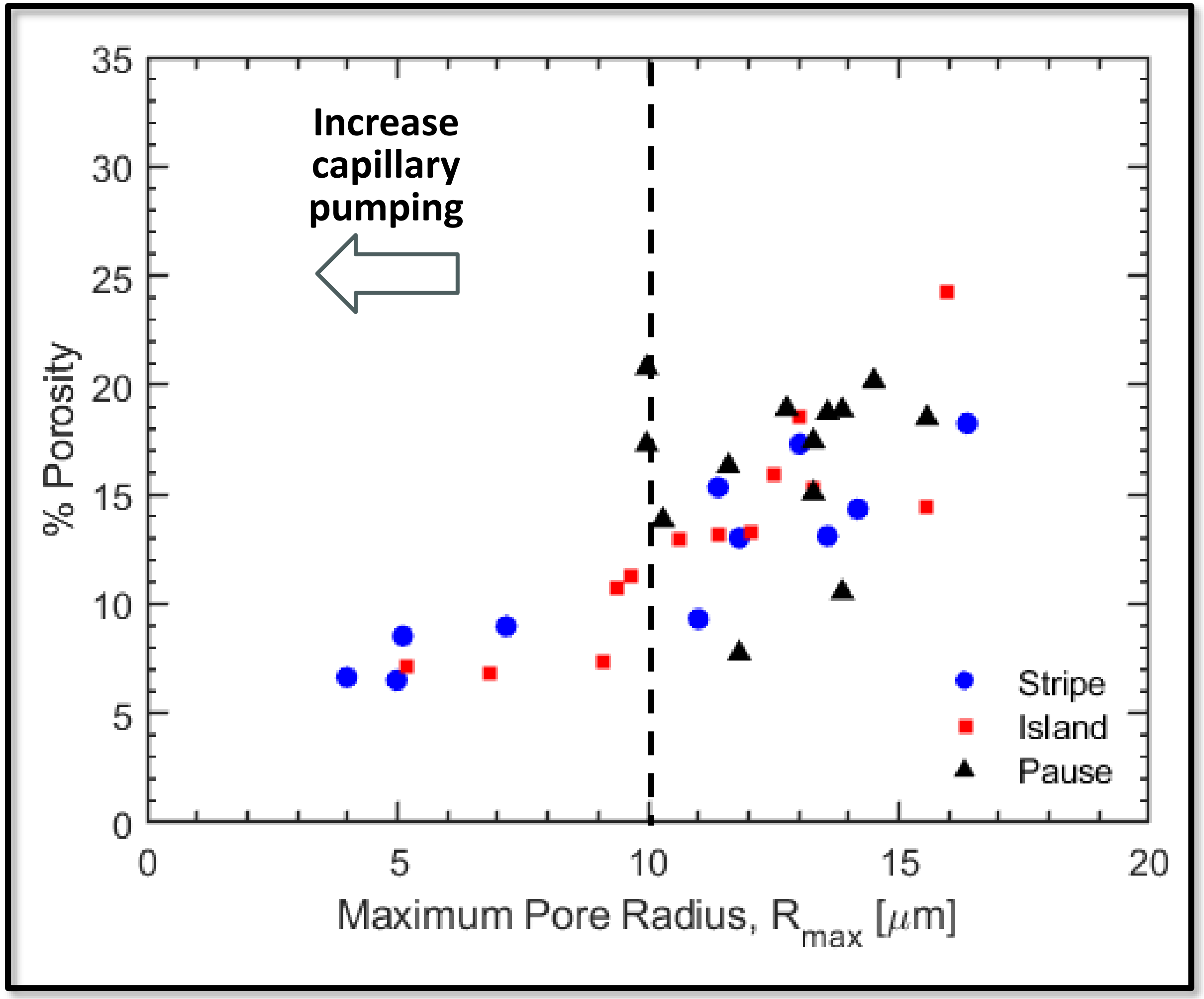
Scan Strategies

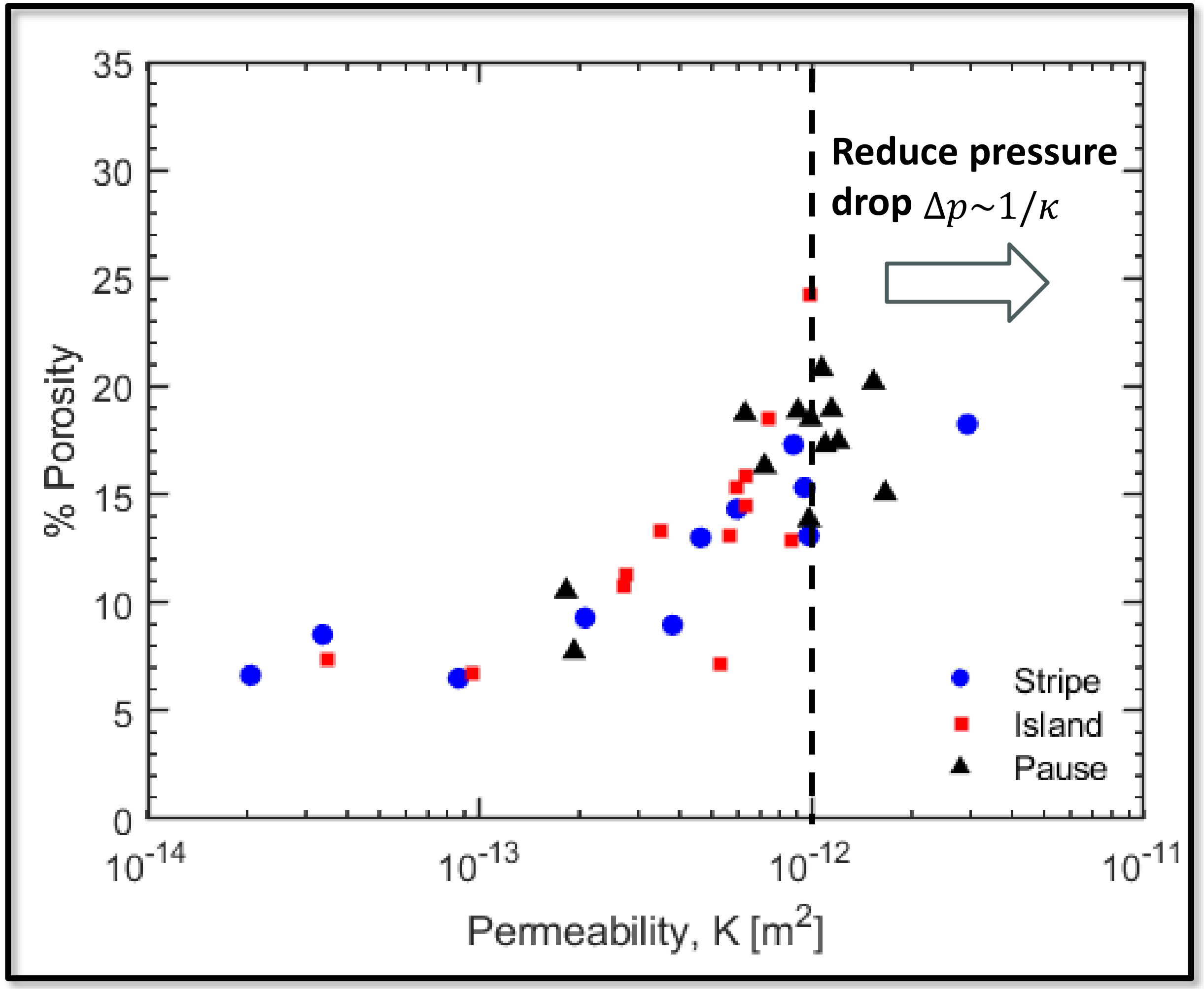
In order to reduce anisotropy in printed wicks, different scan strategies were explored:

- Stripe
- Island
- Pause



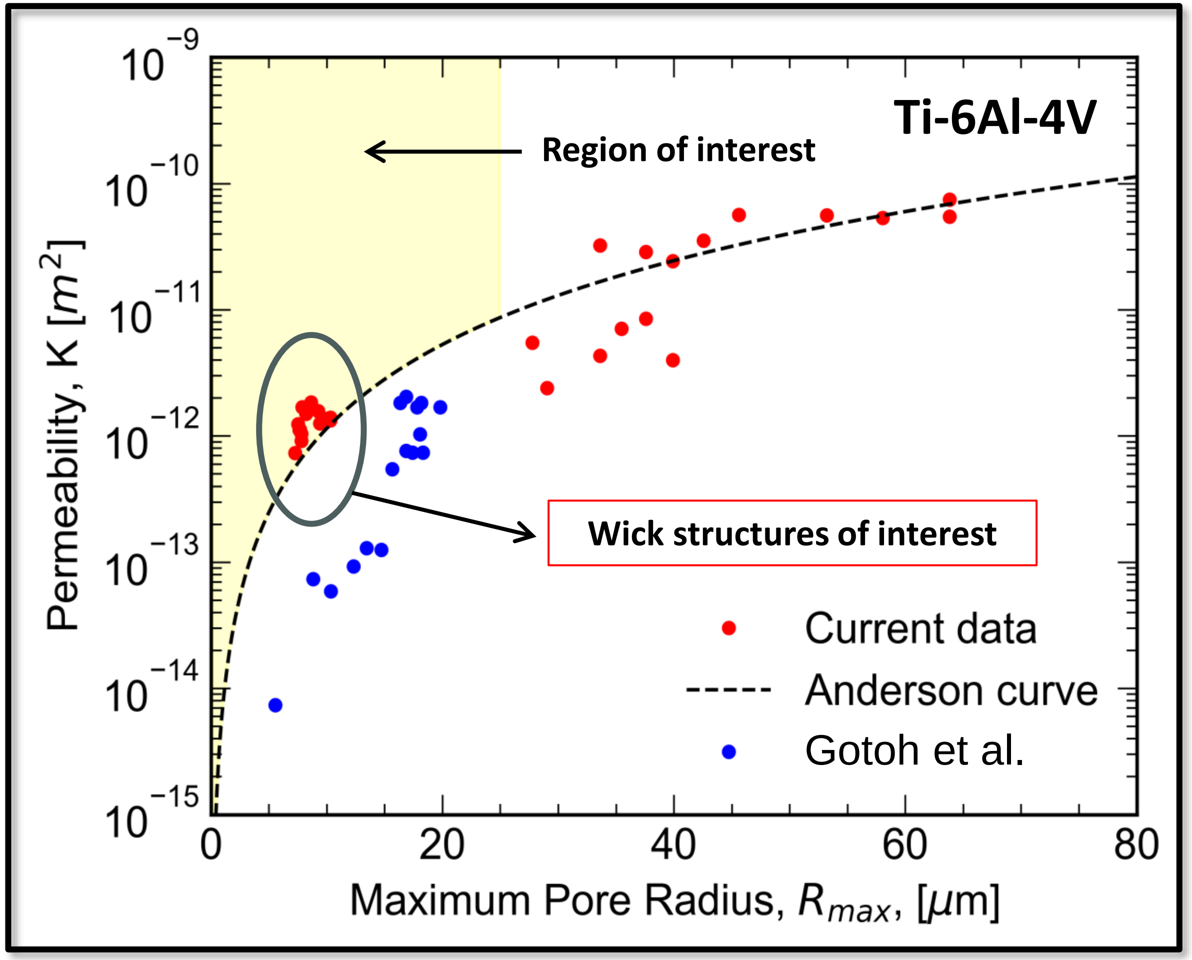
Results from CP-Ti Wicks

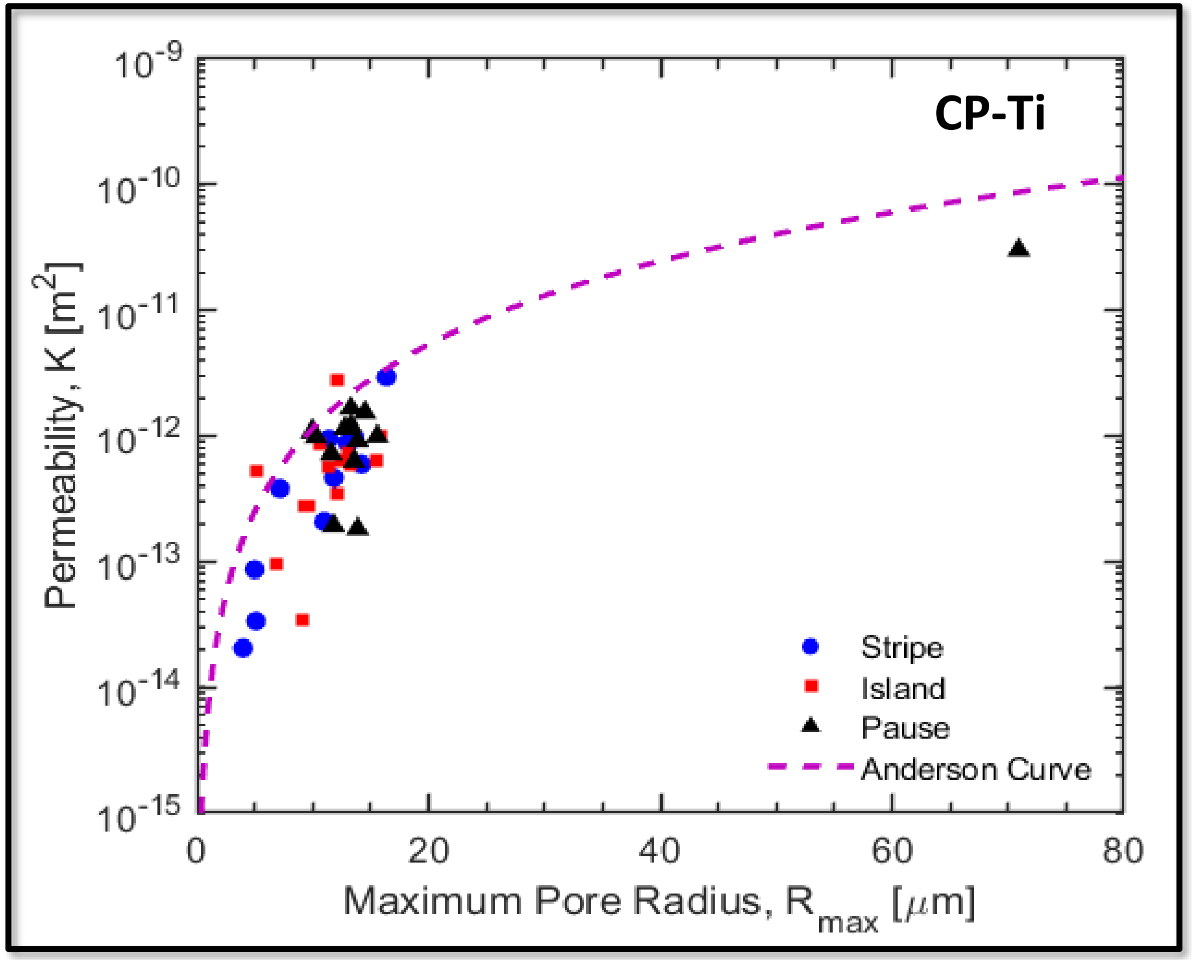




Island and Stripe strategies yield smaller pores but also smaller permeability in the build direction.

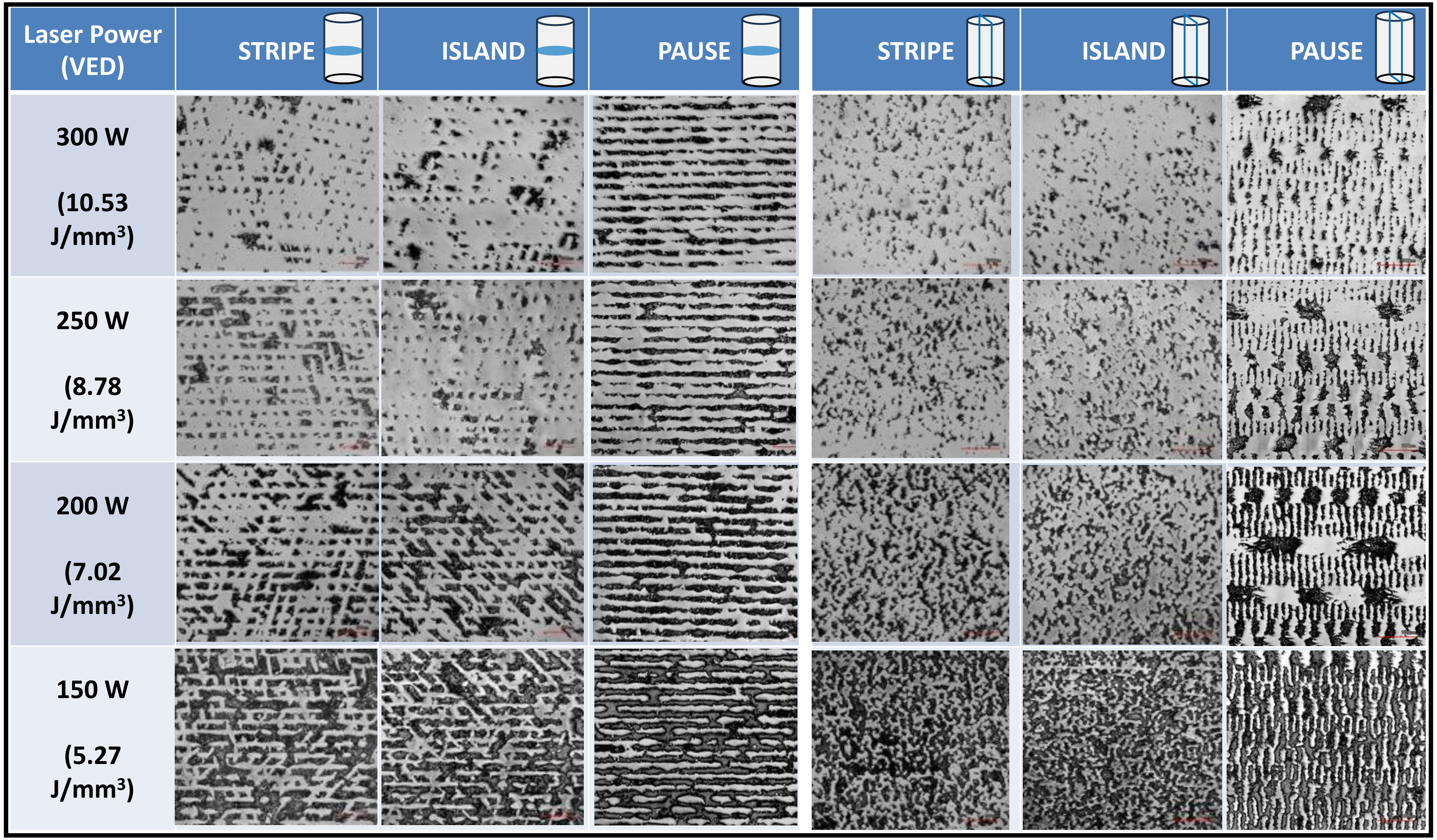
Permeability vs Max Pore Radius





The permeability of CP-Ti samples in build direction reduced compared to Ti-64 samples.

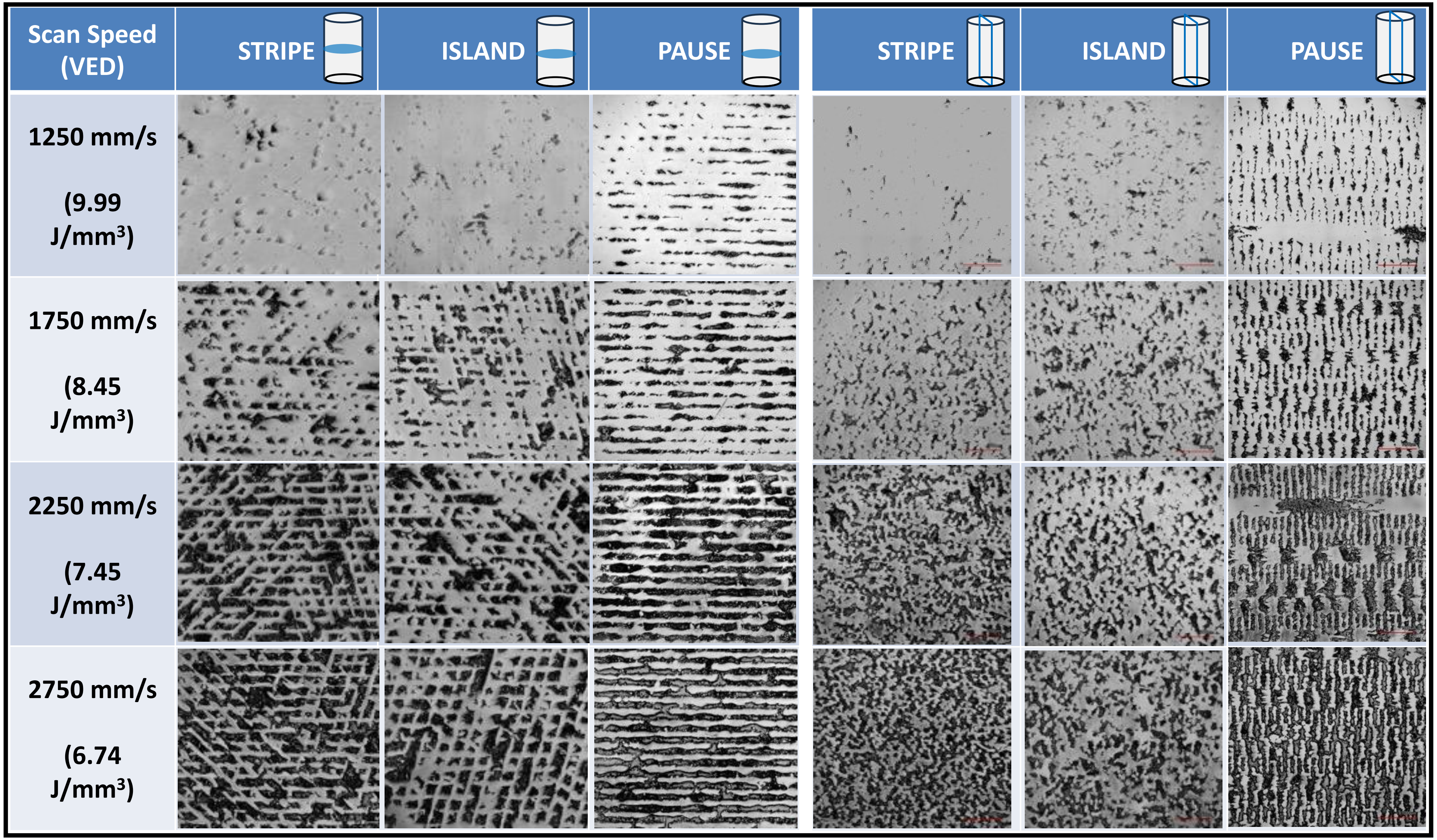
Microstructures – Laser Power



Reduce Laser Power

v = 2000 mm/s
h = 180 µm

Microstructures – Scan Speed

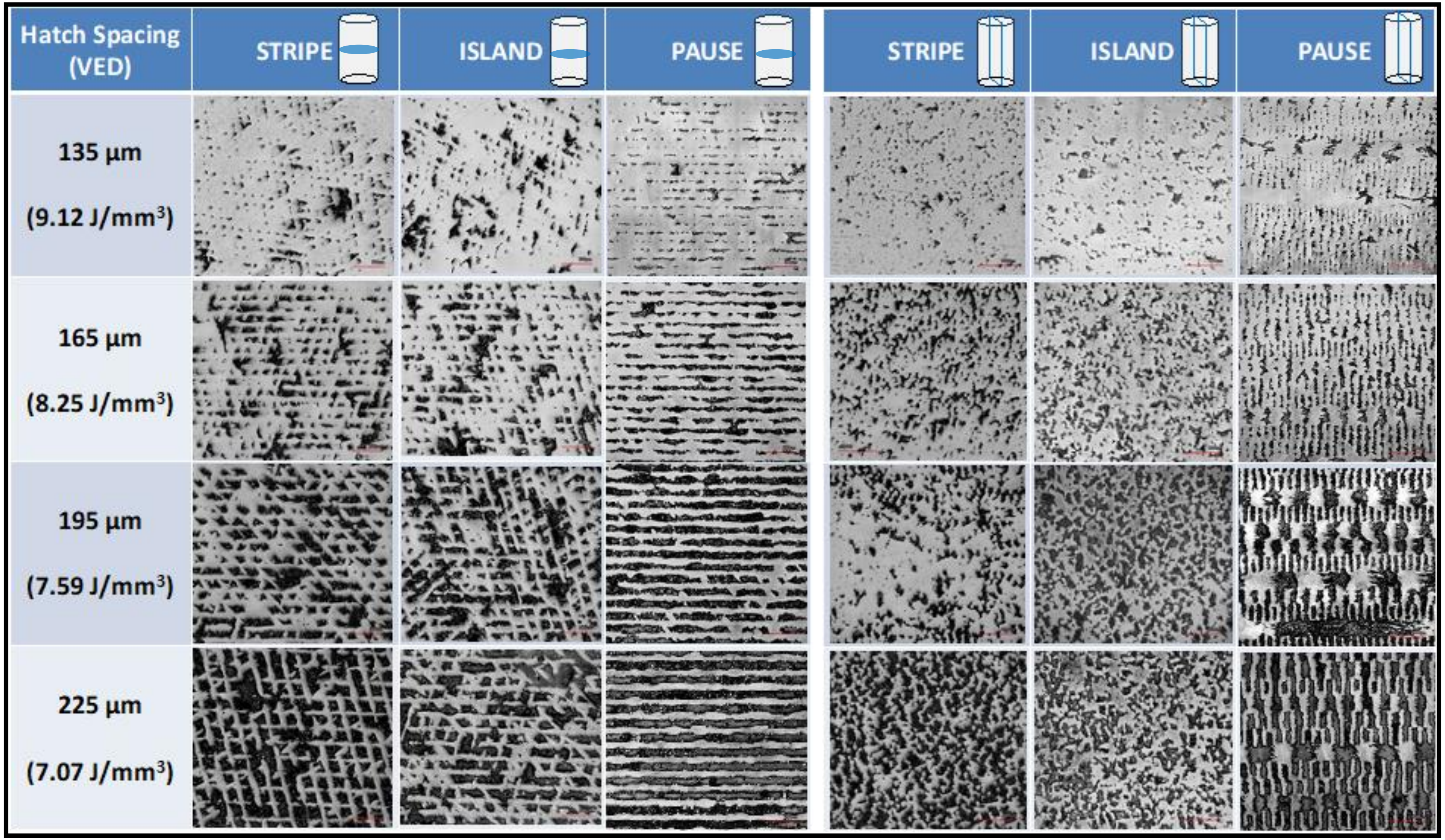


Increase Scan Speed

P = 225W
h = 180 µm

Microstructures – Hatch Spacing

Increase Hatch Spacing



P = 225W
v = 2000 mm/s

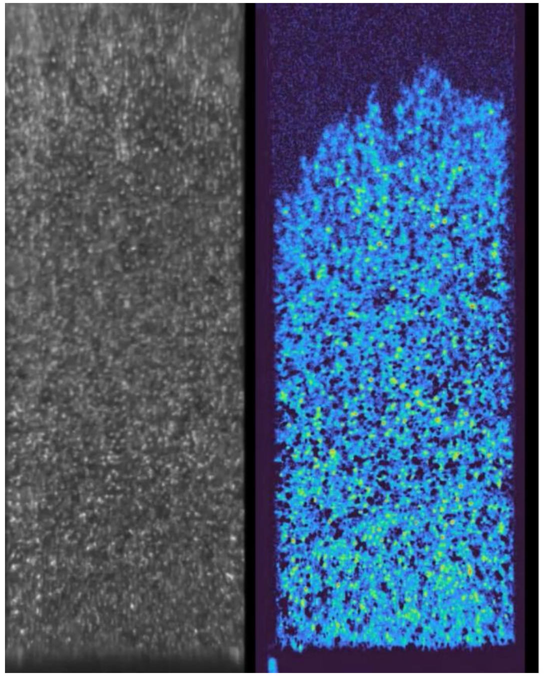
L-Wick Testing

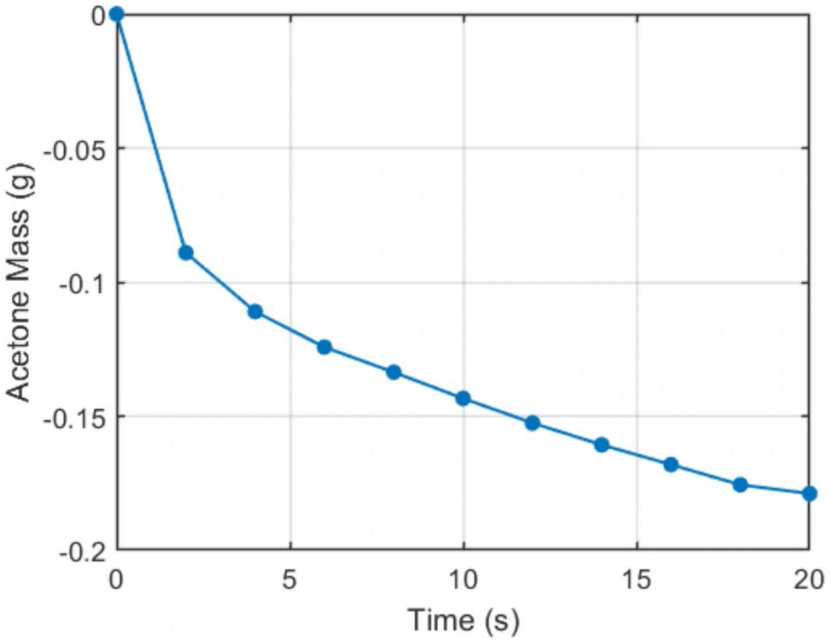
L-wicks were tested for wicking using acetone and the wavefront was captured using a high-speed camera.

The mass of acetone removed from container during wicking was recorded and plotted.

Lucas-Washburn Equation -

$$h_0 = \sqrt{\frac{r\sigma t\, cos(\theta)}{2\mu_W}} \Rightarrow h_0 \propto \sqrt{t}$$





Wick performance was demonstrated and quantitatively analysed.

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Spectrally Selective Radiator Coatings

Design Objective

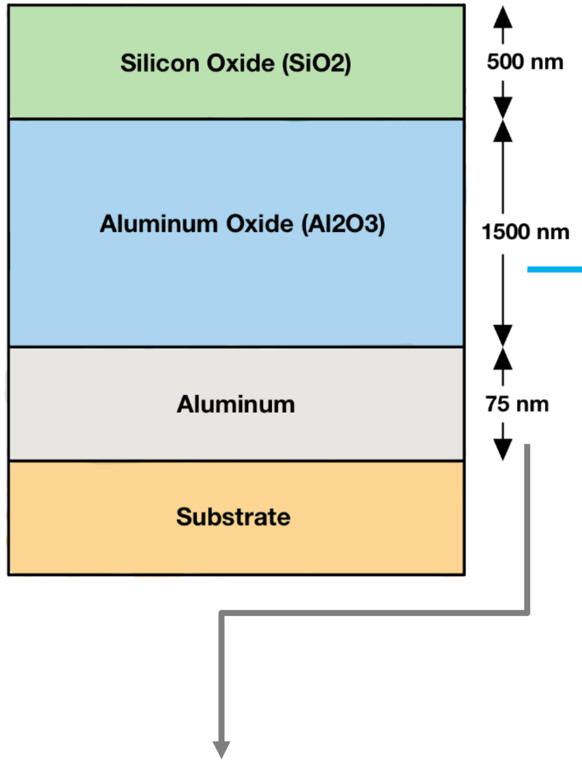
- Maximize IR emissivity (ε)
- Minimize Solar absorptivity (α)

Our suggested design is an *Oxide Composite System.*

Advantages of Oxide Composite System:

- More stable than other radiator coatings such as Teflon, especially from UV radiation.
- Can be applied to non-planar surfaces.
- No bonding layer needed for Aluminum

Oxide Composite System



Silicon Oxide

- Protects coatings from degradation

Aluminum Oxide

- Increases IR emissivity by increasing absorbance in the IR spectrum

Aluminum

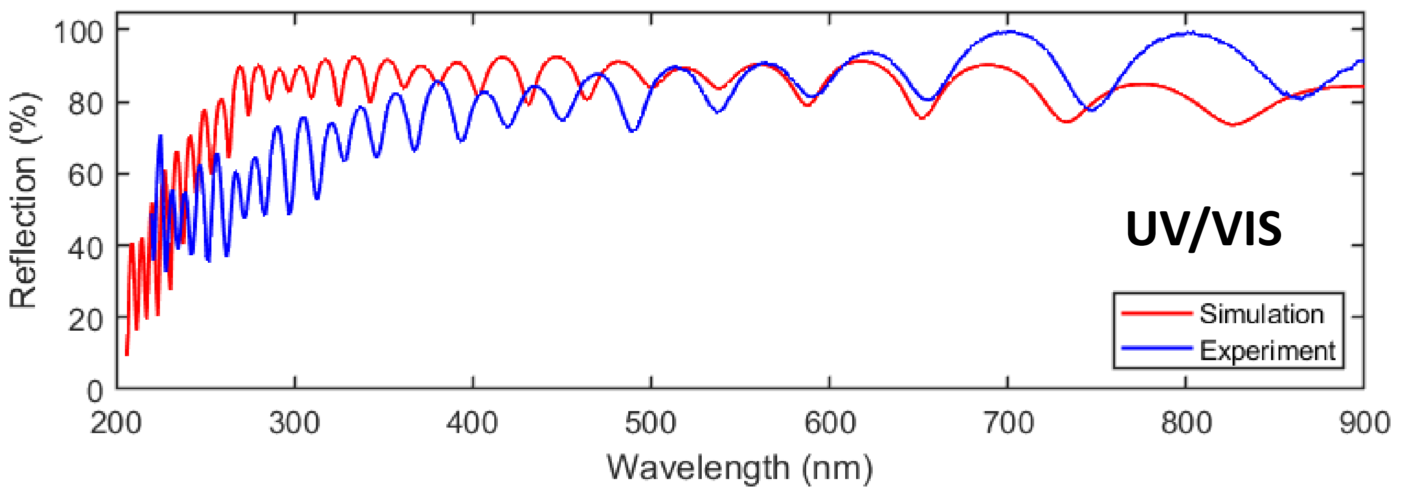
- Reduces solar absorptivity by reflecting solar UV/Vis radiation

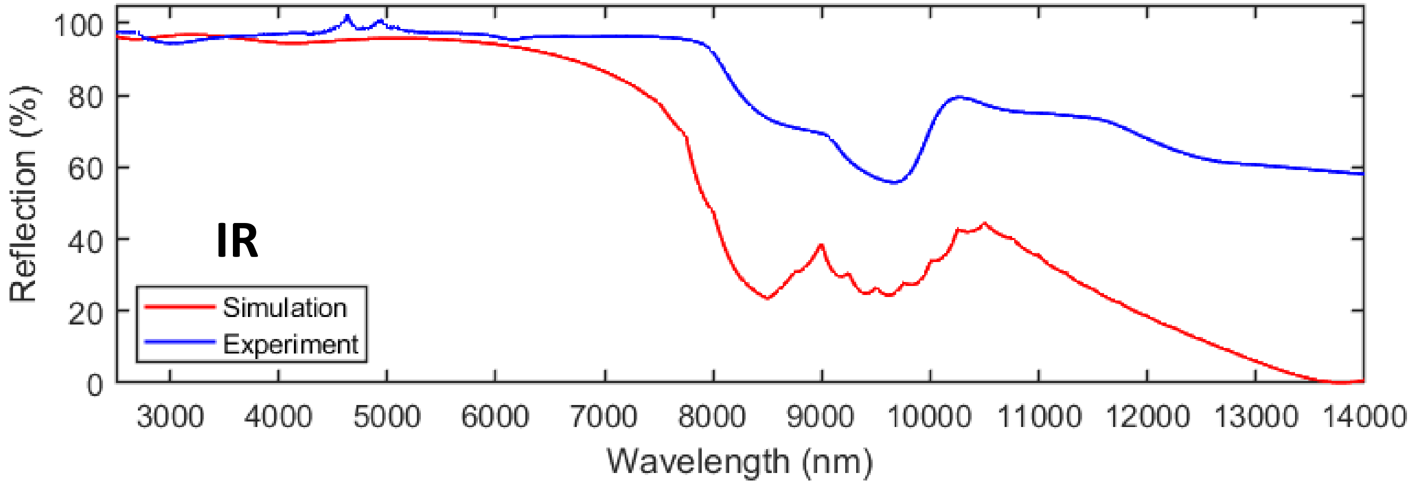
Spectrally Selective Radiator Coatings

Specimens coated on Si wafers using e-beam evaporation were tested and compared against simulation results from Thin Film Cloud.

Coated Specimens

Further optimization of layer thickness is needed to achieve simulation results, especially in IR.





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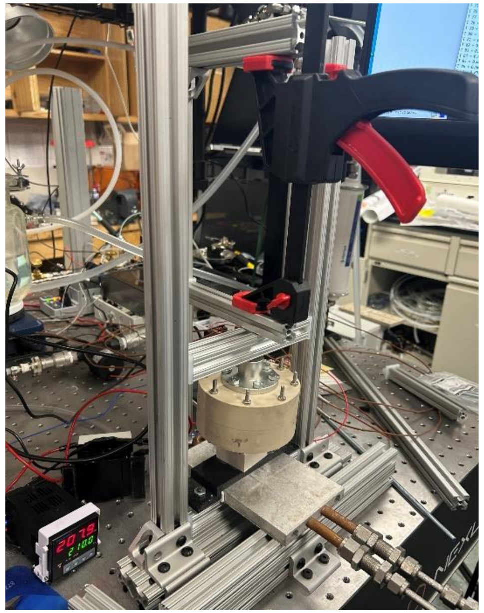
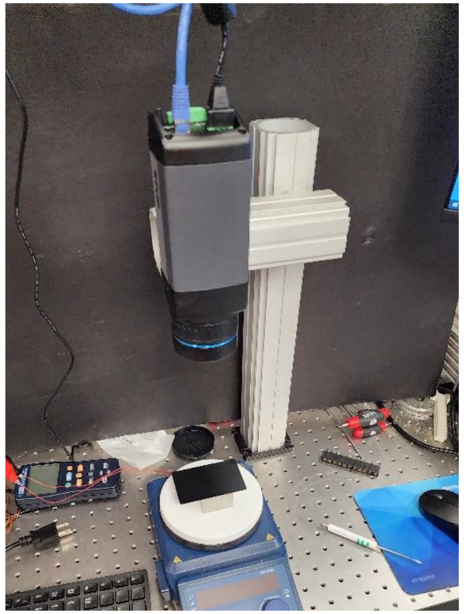
Development and Testing of Titanium-Graphite Radiator Fins

Objectives:
- Composite Fin Manufacturing
- Thermal characterization of materials



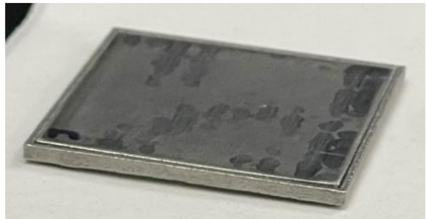
Out-of-plane k

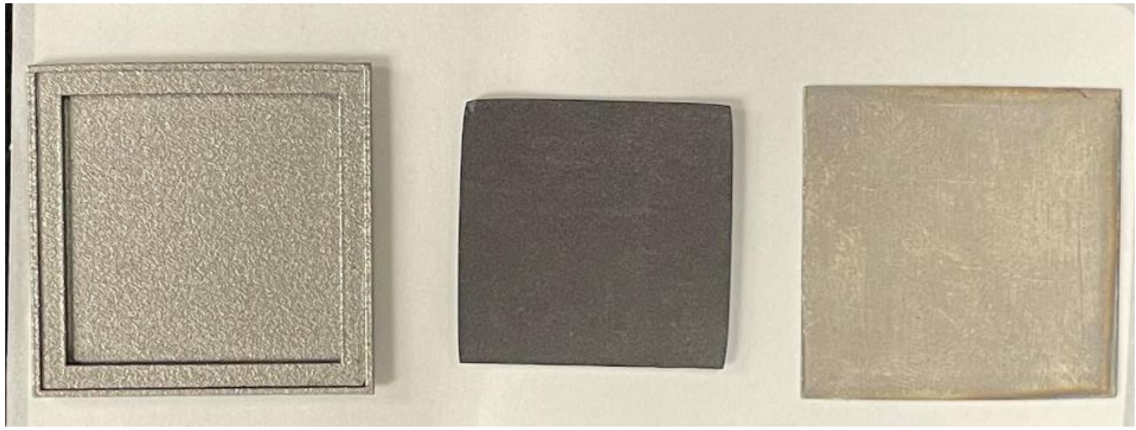


In-of-plane k

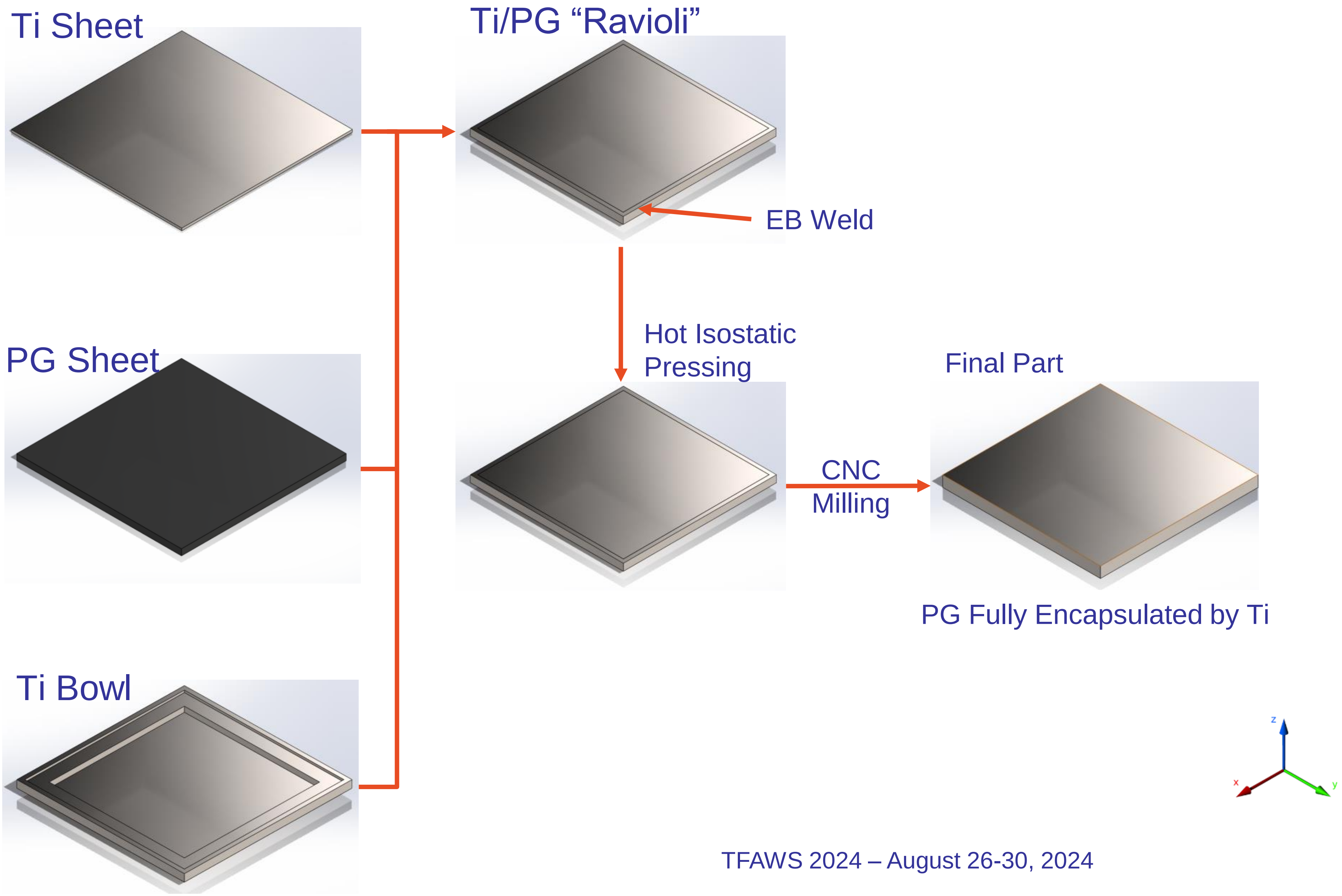
- Manufacturing: i) "Ravioli" method; ii) DMLS (Direct Metal Laser Sintering) vs. FFF (Fused Filament Fabrication)-Sintering
- Thermal characterization: i) Out-of-Plane k w/ ASTM D5470 ii) In-Plane k w/ coupled IR imaging & FEM modeling

"Ravioli" method:
Ti-encapsulated PG





Ti-Encapsulated PG Fin Development – “Ravioli” Method



Benefits:

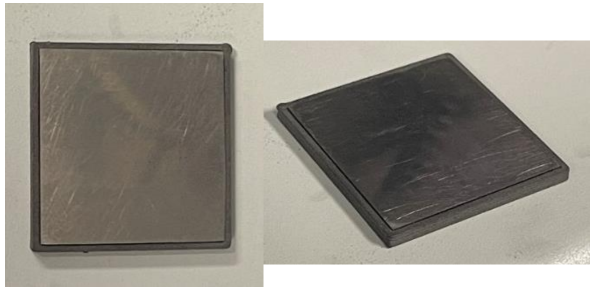
- Allows encapsulation of PG within titanium fully without weld seams in final product.
- Final wall thickness within X-Y plane is determined by CNC tolerances
- Reduces contact resistance between Ti/PG
- Can be scaled up.

Challenges:

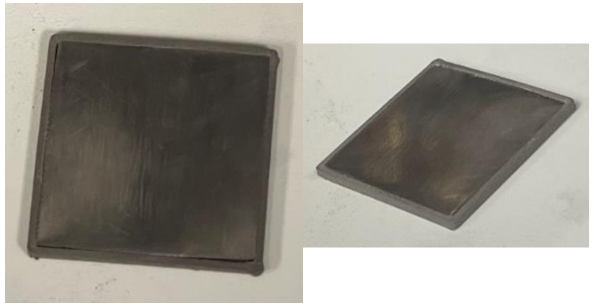
- Potentially expensive
- Resolution is dependent on 3D printing method.

Comparison Between Different "Ravioli" Manufacturing Methods

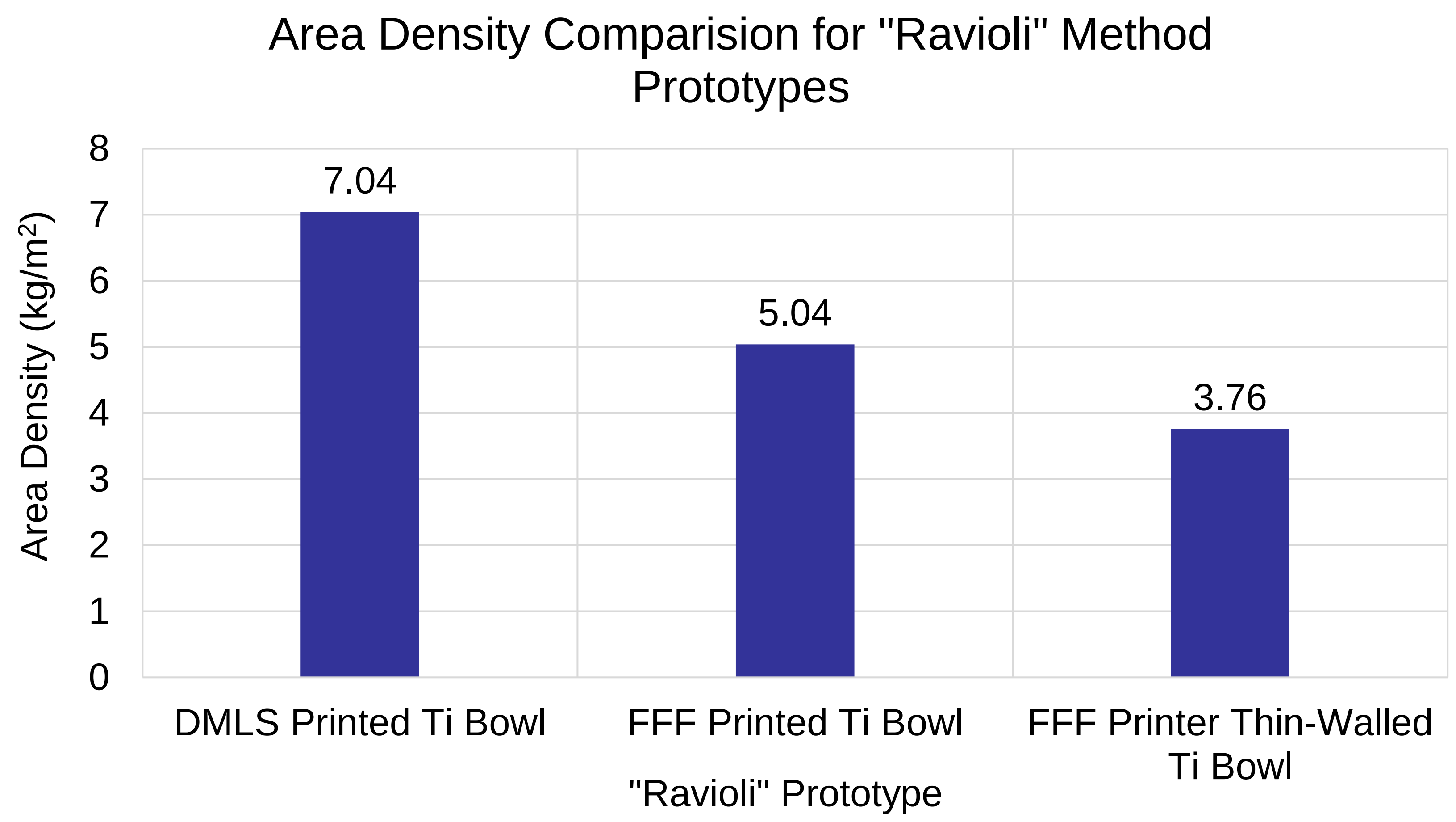
DMLS Printed Ti Bowl



FFF Printed Ti Bowl

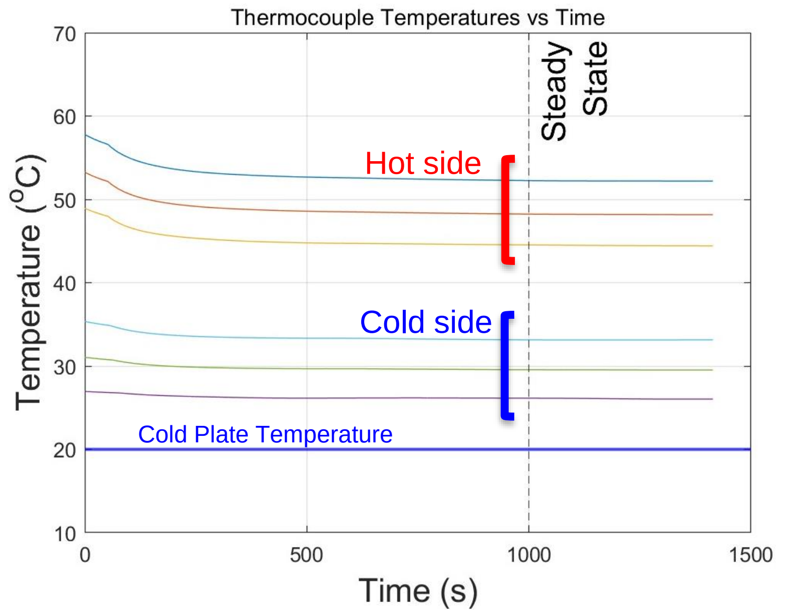


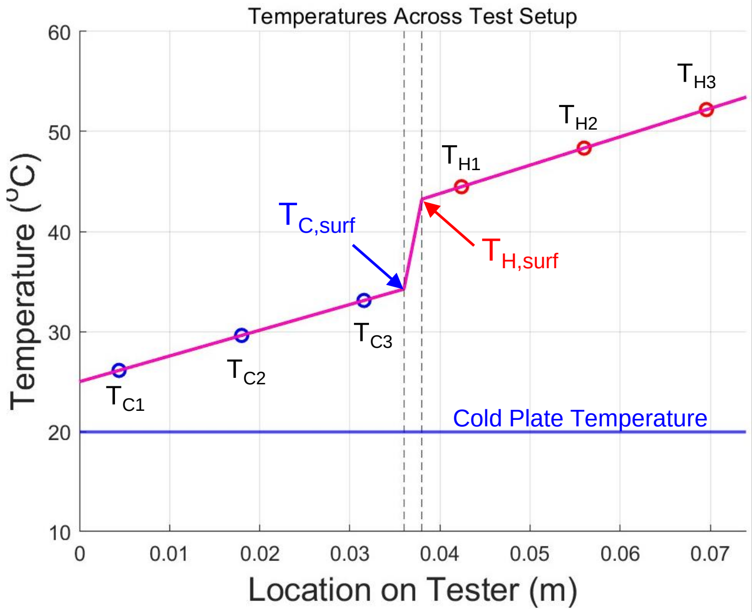
FFF Printed Thin-Walled Ti Bowl

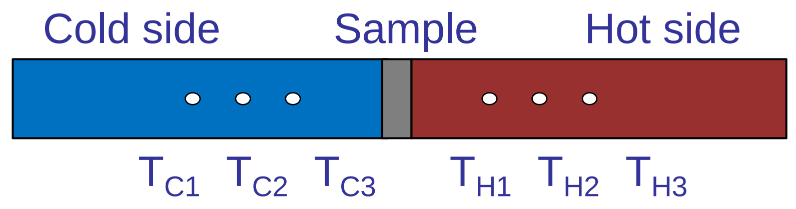


Target Area Density = 2 kg/m^2

Out-of-Plane Thermal Conductivity Measurement

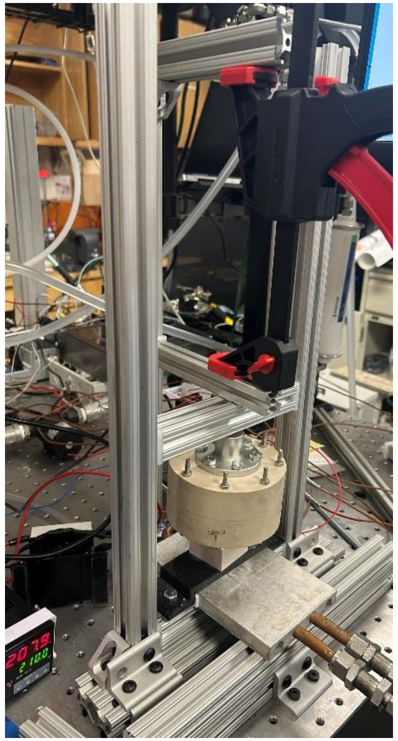






- Hot side: Constant heat load of 20W with heater.
- Cold side: Chiller with water flow at 20 °C

Facility
ASTM D5470



Steady-state temperature gradient (linear regression) ⇨ *Heat flux calculation* ⇨ *Thermal resistance calculation (Temp. drop by extrapolation)*

Cold side: $T_c(z) = m_1 z + b_1$

Hot side: $T_h(z) = m_2 z + b_2$

$$q''_c = k_{Al} m_1$$

$$q''_h = k_{Al} m_2$$

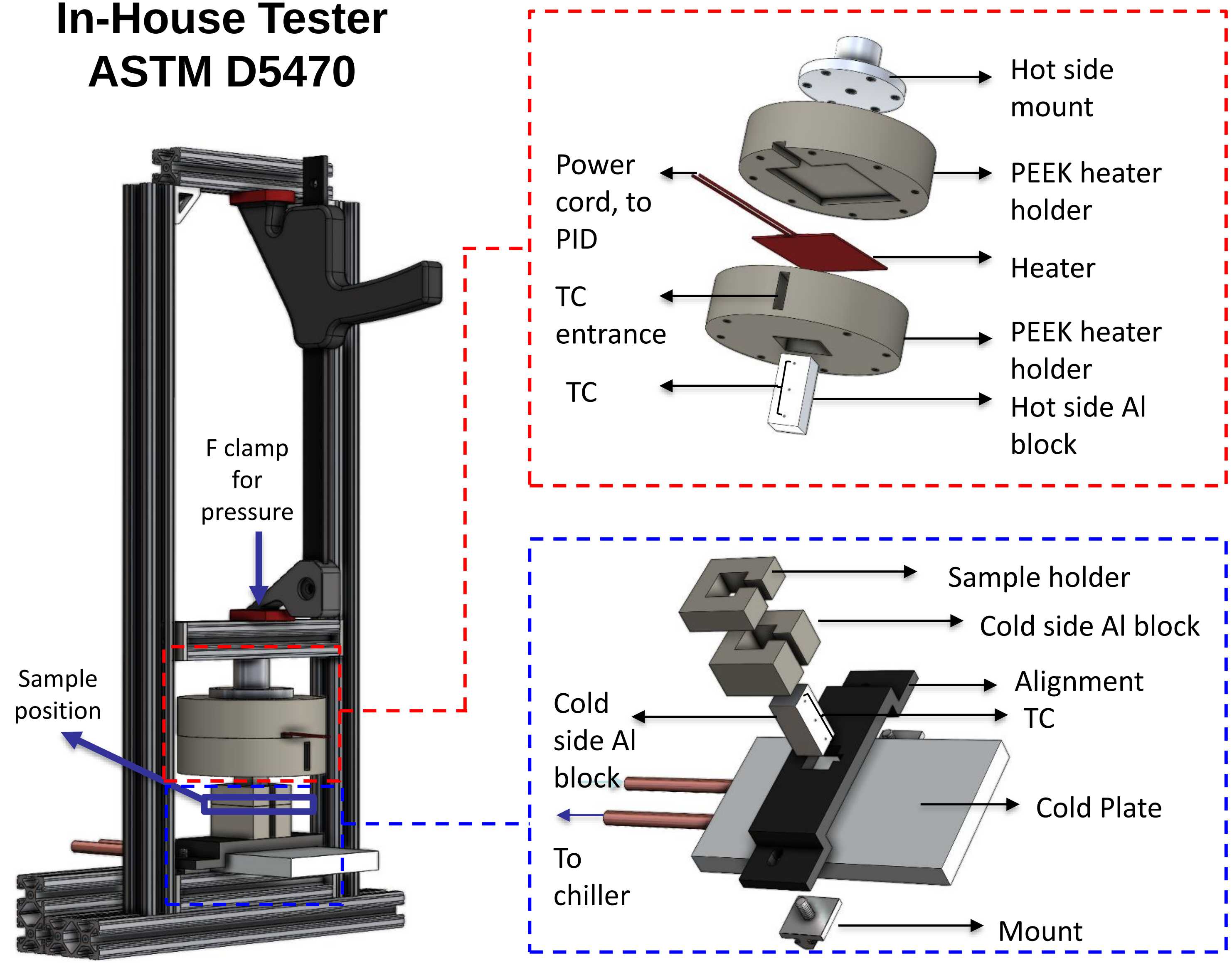
$$q''_{ref} = (q''_c + q''_h)/2$$

$$\Delta T_{sample} = T_{h,surf} - T_{c,surf}$$

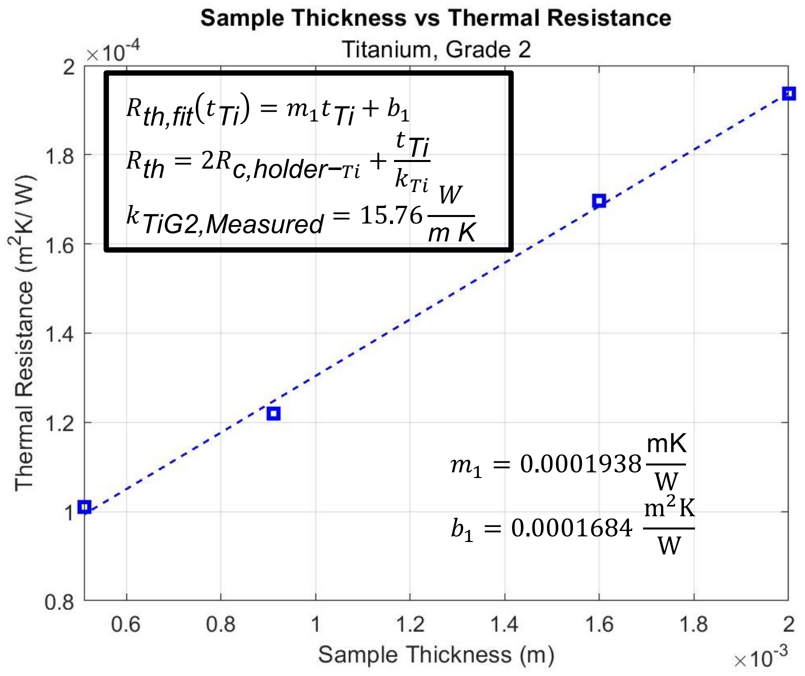
$$R_{th} = \frac{\Delta T_{sample}}{q''_{ref}}$$

Out-of-Plane k Measurement: Tester Development

In-House Tester ASTM D5470



Tester Calibration



Calibration using Grade-2 titanium

- $k_{TiG2,\ Measured}$ = 15.76 W/m K
- $k_{TiG2,Actual}$ = 16.40 W/m K

Error = 3.902%

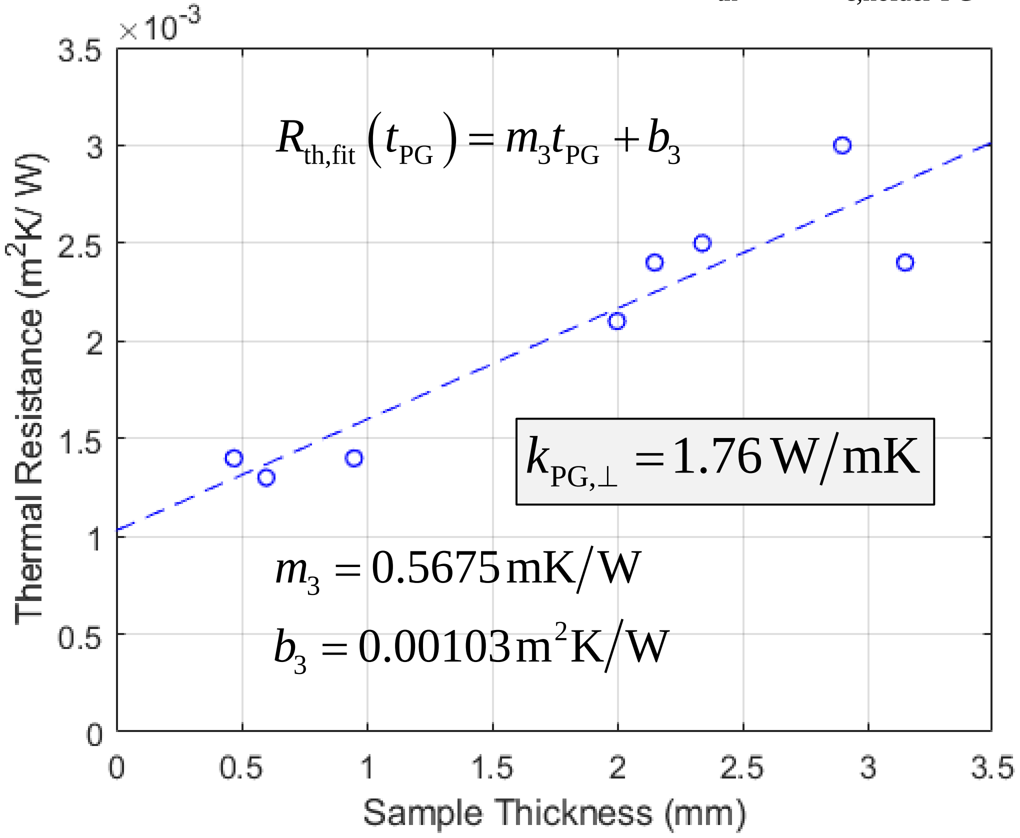
Tester is properly calibrated.

Out-of-Plane k Measurement: PG vs. Ti-PG-Ti

PG

Pyrolytic Graphite Sheet

$$R_{th} = 2R_{c,holder\text{-}PG} + \frac{t_{PG}}{k_{PG,\perp}}$$



Ti

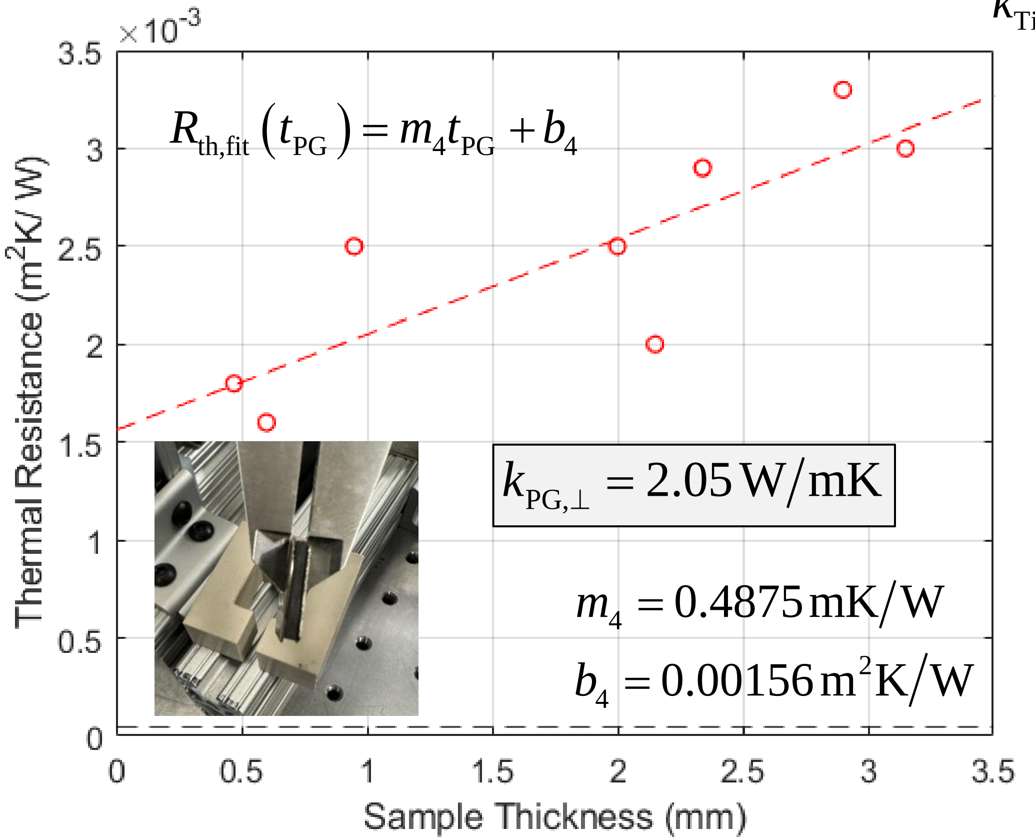
PG

Ti

Ti-PG-Ti

Ti Sandwich Assembly

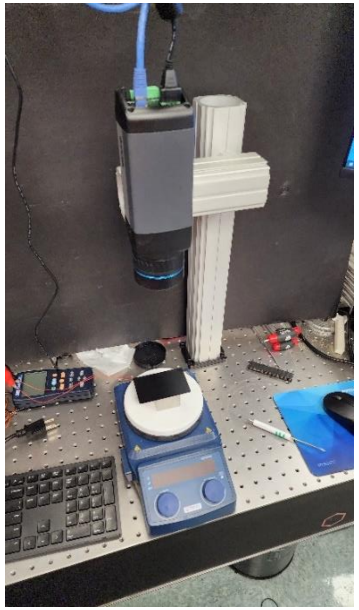
$$R_{th} = 2R_{c,holder\text{-}Ti} + 2R_{c,Ti\text{-}PG} + \frac{2t_{Ti}}{k_{Ti}} + \frac{t_{PG}}{k_{PG,\perp}}$$

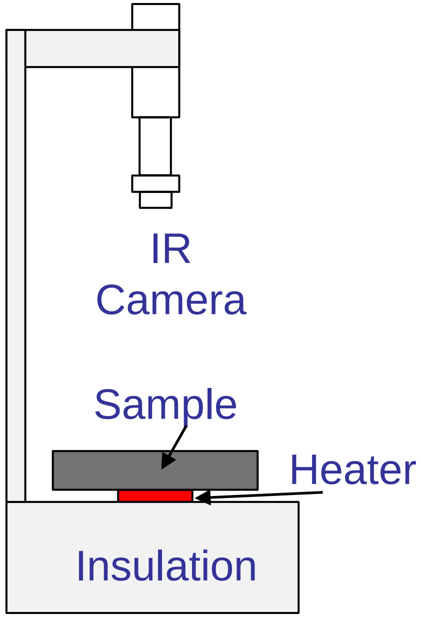


In-Plane k Measurement: Coupled IR & FEM Simulation

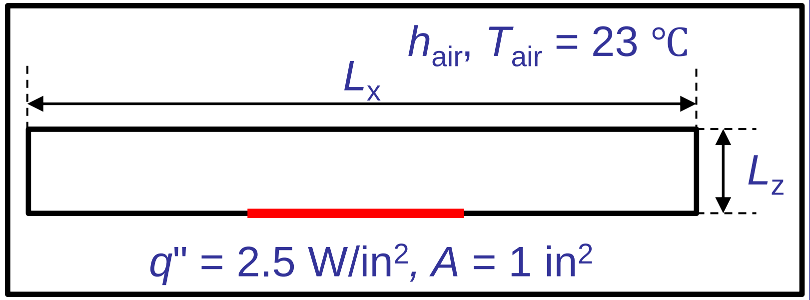
Coupled IR imaging and FEM simulation for high k measurement

- Dataset: Temperature field from experiments;
- Unknown parameters: in-plane thermal conductivity ($k_{in\text{-}plane}$), air-side heat transfer coefficient (h_{air})





Model setup:



Governing equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\cancel{q_V}=\rho c_p\cancel{\frac{\partial T}{\partial t}}$$

Boundary condition:

- Heat load: flux boundary
- Heat loss: convective boundary

Material properties:

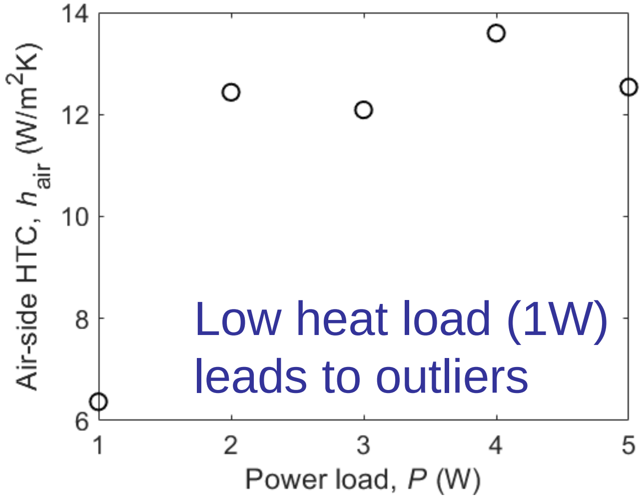
- $k_x = k_y = k_{in\text{-}plane}$
- $k_z = k_{out\text{-}of\text{-}plane}$
- h_{air}

Air-side heat transfer coefficient

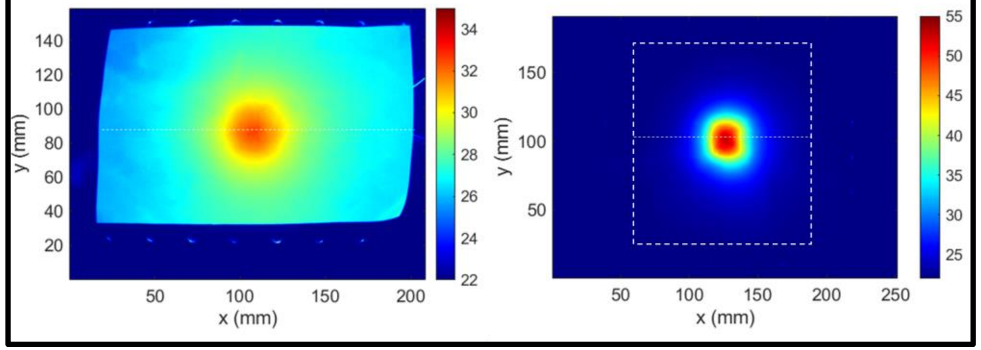
$$P_{load} = \sum_{surface} h_{air} A_{surf} (T_{surf} - T_{air})$$

$$h_{air} = \frac{P_{load}}{A_{surf,tot} (\bar{T}_{surf} - T_{air})} = 12.76 \frac{\text{W}}{\text{m}^2\text{K}}$$

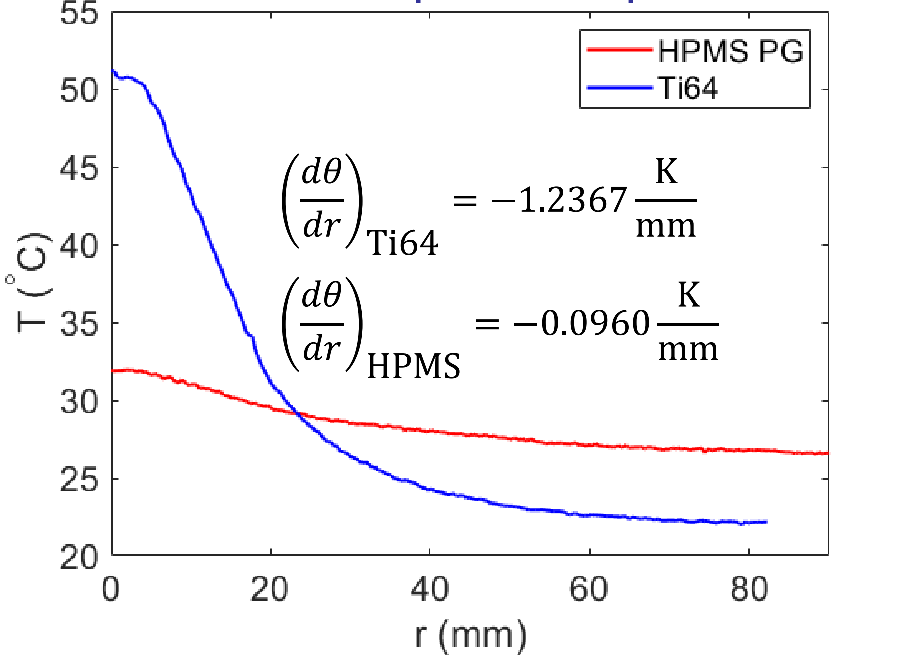
The mean surface temperature is measured using IR



HPMS PG In-Plane Thermal Conductivity Measurement



Radial temperature profile



Scaling analysis

$k_{Measured}$ = 1112 W/m K

k_{Target} = 1750 W/m K

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)+\frac{h}{k}\left(T-T_{\infty}\right)=0$$

$$-k\left(\frac{dT}{dr}\right)_{r=r_0}=q_0$$

$$\frac{d\theta}{dr}=-\theta_0\sqrt{\frac{h}{k}}J_1\left(\sqrt{\frac{h}{k}}r\right)\qquad\left(\theta=T-T_{\infty}\right)$$

$$k\sim\left(\frac{d\theta}{dr}\right)^{-2}$$

$$k_{\text{HPMS}}\approx\left[\frac{\left(d\theta/dr\right)_{\text{Ti64}}}{\left(d\theta/dr\right)_{\text{HPMS}}}\right]^2 k_{\text{Ti64}}=1{,}112\,\text{W/mK}$$

where $k_{\text{Ti64}}=6.7\,\text{W/mK}$

Interpreting Thermal Conductivity Measurement Results

- $k_{\text{Out-of-Plane, } \mathbf{Target}}$ = 18 W/m K
- $k_{\text{Out-of-Plane, } \mathbf{Measured}}$ = 1.76 W/m K

- $k_{\text{In-Plane, } \mathbf{Target}}$ = 1750 W/m K
- $k_{\text{In-Plane, } \mathbf{Measured}}$ = 1112 W/m K

- Measured k values are lower than the target values.

- New PG samples will be tested.

- In-house PG production will be explored to optimize In-Plane and Out-of-Plane k values and minimize CTE (Coefficient of Thermal Expansion).

Presentation Agenda

- Project Overview and Innovative Aspects
- Additive Manufacturing of Ti Wicks
  - Printing of Ti-6Al-4V Wicks
  - Printing of CP-Ti Wicks
- Spectrally Selective Radiator Coatings
- Ti-encapsulated Pyrolytic Graphite Radiator Fins
- **Conclusions**
- **References**

Conclusion

- By modification of L-PBF print parameters, it is possible to get part features smaller than machine parameters would allow.
- Changes in scan strategy can greatly affect anisotropy of printed wicks.
- Island and stripe strategies yield smaller pores but also result in smaller permeability in the build direction.
- Layer thicknesses in the oxide composite need to be further optimized.
- A low-cost, high-throughput metal-encapsulated pyrolytic graphite fabrication method (i.e., the “Ravioli” method) is developed.
- The in-plane and out-of-plane thermal conductivities can be measured using a coupled IR and FEM simulation method and a steady-state heat conduction method, respectively.

References

- Gotoh, R., Furst, B. I., Roberts, S. N., Cappucci, S., Daimaru, T., & Sunada, E. T. (2022). Experimental and analytical investigations of ALSI10MG, stainless steel, Inconel 625 and ti-6al-4v porous materials printed via powder bed fusion. *Progress in Additive Manufacturing*, *7*(5), 943–955. https://doi.org/10.1007/s40964-022-00269-8
- NASA. (n.d.). Thermal materials and coatings for near Rectilinear Halo Orbit (NRHO) - NASA technical reports server (NTRS). NASA. https://ntrs.nasa.gov/citations/20205006183
- Dobson, S. (2024). Linking laser powder bed fusion additive manufacturing surface condition to internal structure and melting behavior [Doctoral dissertation, University of Cincinnati]. OhioLINK Electronic Theses and Dissertations Center. http://rave.ohiolink.edu/etdc/view?acc_num=ucin1712917474420949

Thank you for your attention

Questions?