NATIONAL ENERGY TECHNOLOGY LABORATORY

University Turbine Systems Research

Project Title: Integrated Transpiration and Lattice Cooling Systems developed by Additive Manufacturing with Oxide-Dispersion-Strengthened Alloys

Project No.: FE0031277, 10/1/2017 -9/30/2022 (w no cost extension)

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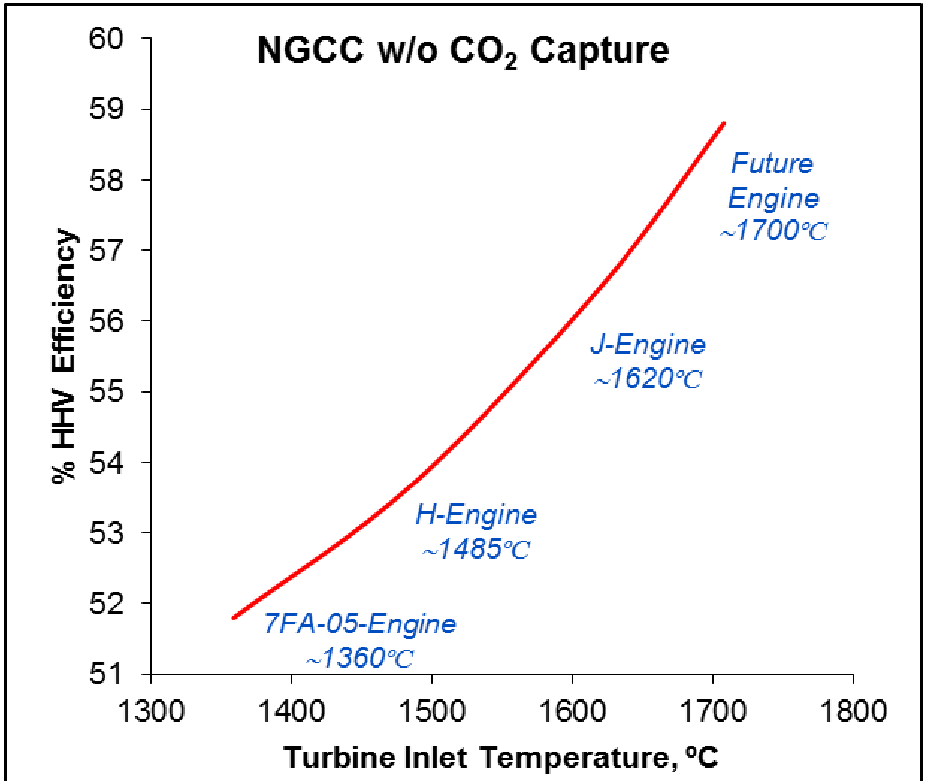
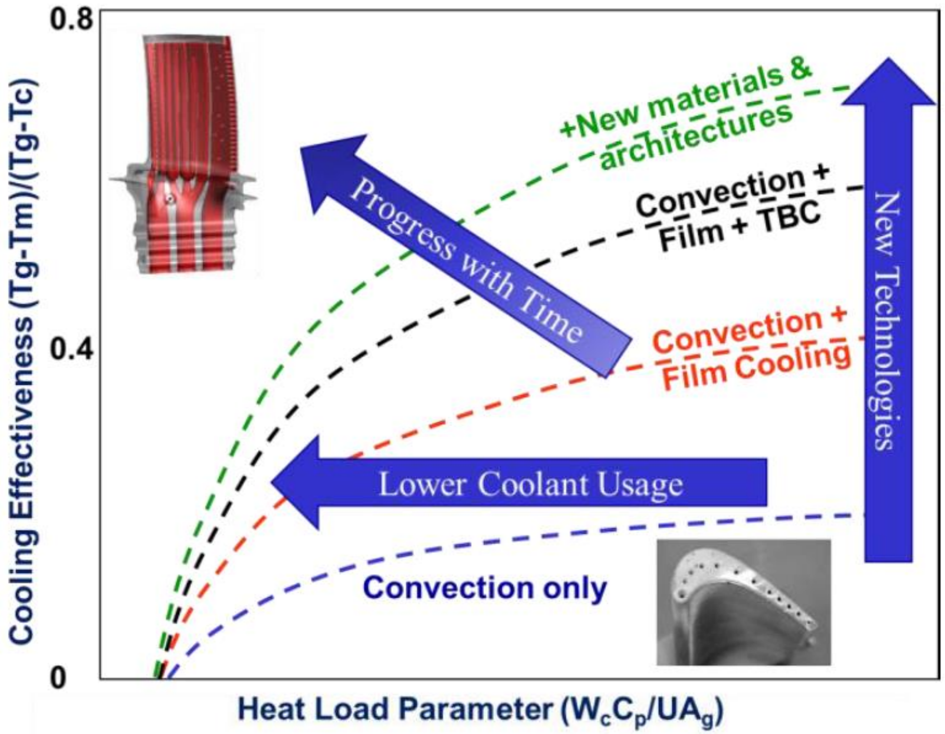
Outlines

- **Background, Challenges, Objectives, Benefits of Technology, Research Task Plans**
- *Additive Manufacturing Processes*
- *Summary of Transpiration Cooling Results*
- *Summary of Lattice Cooling Results*
- *Heat Transfer Results: Integrated Cooling*
- *ODS Powder Development*
- *DMLS using ODS Powder*

Need for Turbine Cooling



– W.Shelton, NETL Communication December 2011 –



Bunker RS. Evolution of Turbine Cooling. ASME. Turbo Expo: Power for Land, Sea, and Air, Volume 1: Aircraft Engine; Fans and Blowers; Marine; Honors and Awards ():V001T51A001. doi:10.1115/GT2017-63205.

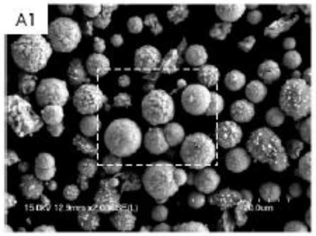
Airfoil metal temperature distributions (in K)
h_c=3000W/m²-K

- ***Gas temperature: Hydrogen-fired turbine (~1430°C)***

Near surface 'skin cooling' or 'double-wall' internal cooling **arrangement leads to a significant reduction of metal surface temperature, ~50 – 100°C, compared to conventional serpentine cooling designs**

One key will be the marriage of design and manufacturing to bring about the concurrent use of engineered micro cooling or transpiration, with the ability of additive manufacturing. If successful, this combination could see a further 50% reduction in coolant usage for turbines.

Proposed Technologies

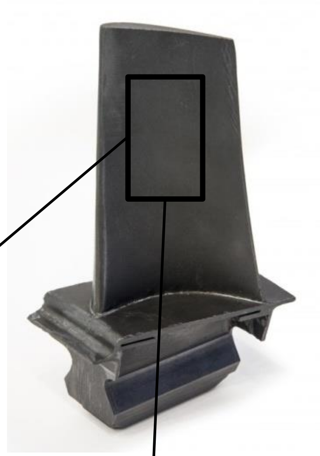


ODS

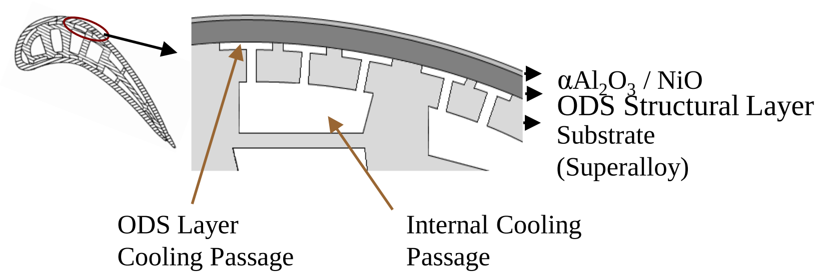
Enhanced oxidation resistance and high temperature strength

Advanced Additive Manufacturing

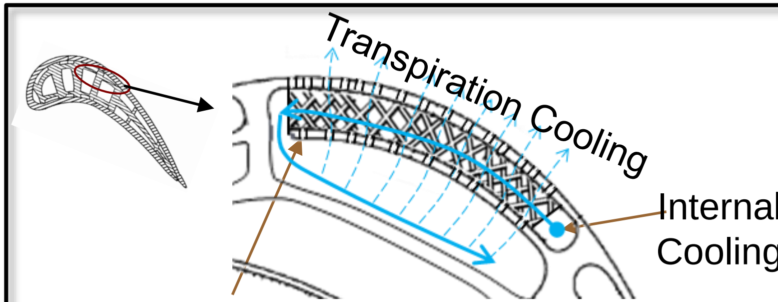
Intricate Heat Transfer Enhancement Features



Near Surface Embedded Cooling Channel (NSECC)



Integrated Transpiration and Lattice Cooling Systems



ODS with AM

- *Both internal and external protection.*
- *Oxidation Resistance*
- *Realized with additive manufacturing*

Novel ODS Surface Coating

- *Ultra-High Temperature (1200℃) Strength: thinner outer wall for better cooling*
- *Oxidation Resistance*
- *Higher turbine inlet temperatures*

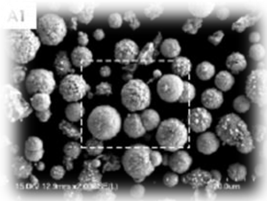
Enhanced Heat Removal

- *NSECC: high internal heat transfer and higher coolant flow near hot end wall.*
- *Lattice and transpiration combined conjugate cooling: ~2x of state-of-the-art film cooling.*

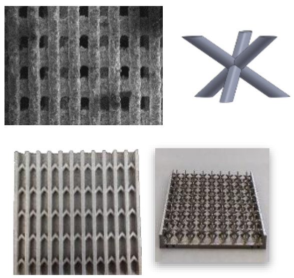
Project Breakdown

Goal: Enhanced Oxidation Resistance and Thermal Protection of Turbine Blades

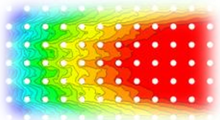
ODS Powder Fabrication and Characterization
- MCB/BM for powders fabrication
- Characterization



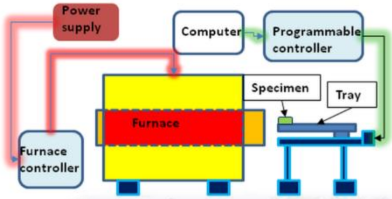
Cooling Geometry Design
- Transpiration and Lattice Geometry development and optimization

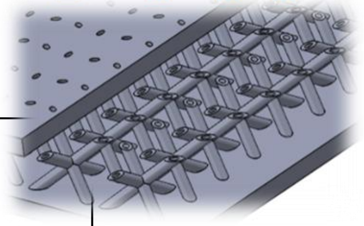


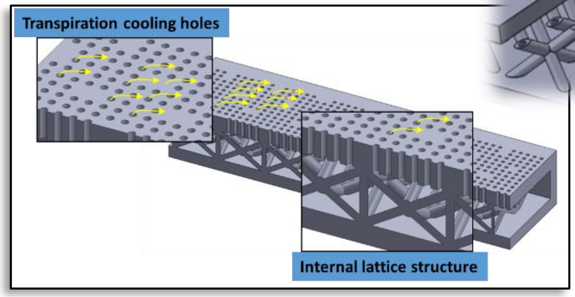
Lab-Scale Heat Transfer Characterization
- CFD modeling & steady state and scaled TLC testing
- Mini/micro scale cellular units



Thermal Cyclic Testing
- In-situ non-destructive micro indentation facility
- Thermal Cyclic Tests, Micro-hardness







Process Optimization to Fabricate ODS Transpiration and Lattice Structures
- DMLS, BJT printing parameters
- Posting printing characterization
- OM, SEM

Milestones

Milestone Title	Planned Date
A - Identify prototypes for integrated transpiration and internal cooling	6/30/2018
B - Identify optimal configurations for integrated transpiration and internal cooling	9/30/2019
C - Integrate new unit types into the optimization algorithm for ODS lattice structure	12/30/2019
D - Identify the capability of AM equipment to print ODS Structure	9/30/2018
E - Develop successful approach to make ODS Structure for integrated transpiration and internal cooling	5/31/2022
(Descoped) **F - Complete high temperature experiments for integrated cooling structures made from ODS**	
G - Develop successful approach to produce ODS powder suitable for additive manufacturing and lattice structures	9/30/2019
H - Complete thermal cyclic loading tests	5/31/2021

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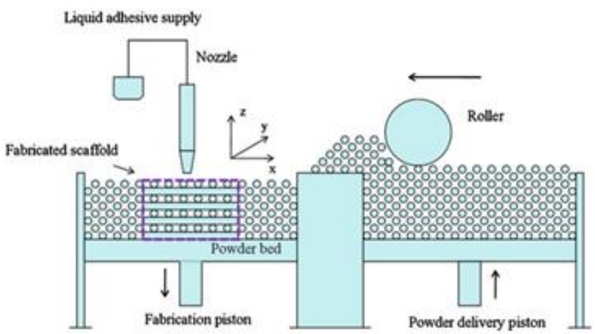
AM Processes

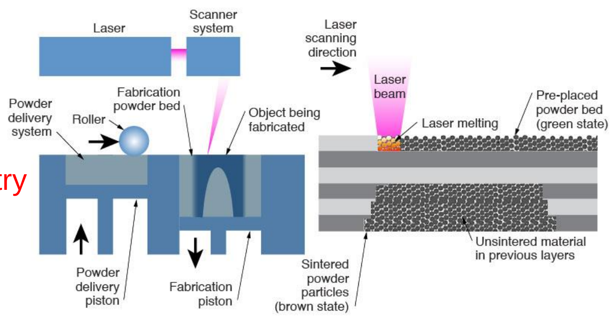
Bind Jetting (EXOne)

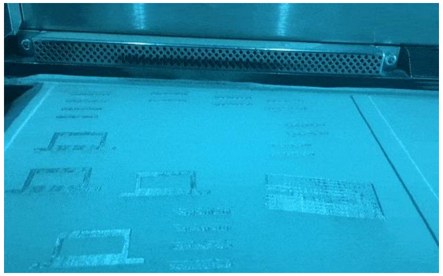
Pros: geometry free
cons: high porosity



Direct Metal Laser Sintering(EOS)

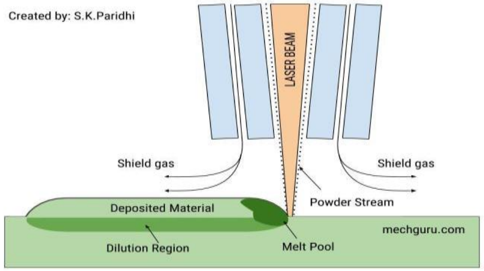
Pros: complex geometry
cons: single material

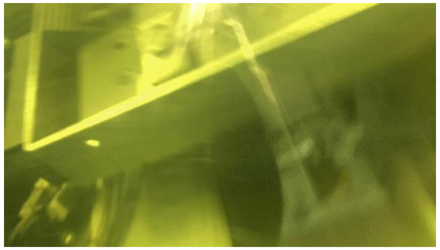




Direct Energy Deposition (LENS)

Pros: multiple materials
cons: no overhangs or unsupported structure





As metallic additive manufacturing technologies advance significantly over the recent past, complex metal products, such as turbine components, can be manufactured by this innovative technology.

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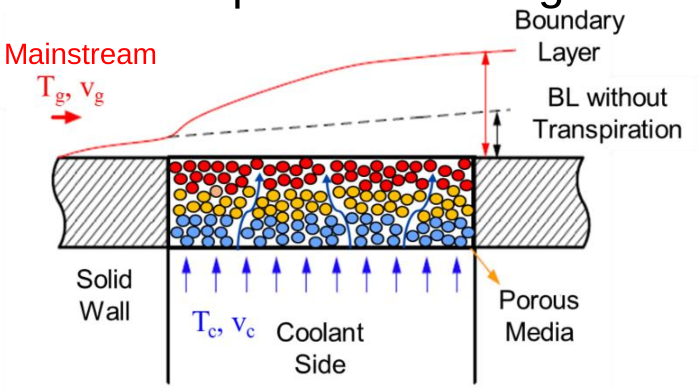
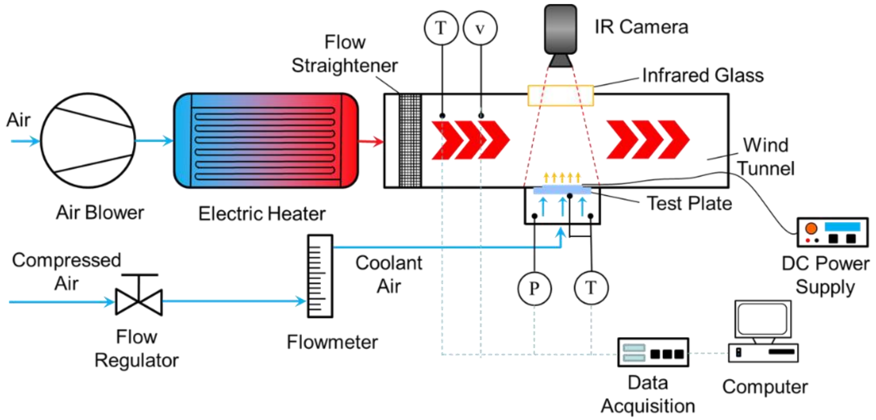
Transpiration Cooling

- Concept: The coolant was forced through a porous wall or multiple micro-cooling channels to form an insulating layer of coolant film between the outer wall surface and hot stream.



- Uniform coolant film coverage
- Enhanced heat removal ability due to higher inner-wall heat transfer

$$\varphi = \frac{T_g - T_w}{T_g - T_c} \qquad M = \frac{\rho_c u_c}{\rho_g v_g} = 0.125, 0.25, 0.5$$



- Challenges
  - Oxidation due to Vortex Mixing with Hot Gas
  - Mechanical Strength Concern with Porous Media
  - Manufacturing Difficulties

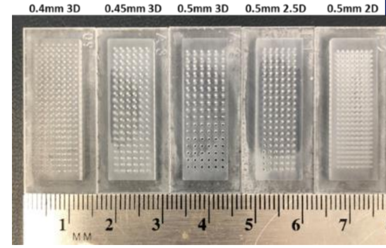
- High Anti-oxidation Resistance ✓
- High Temperature Mechanical Strength ✓

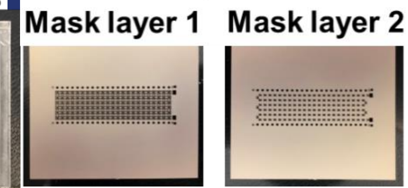
} ODS

- Comparable Strength with Casting ✓
- Complexity and Design Freedom ✓
- Fast and Low-cost Fabrication for Intricate Features ✓

} AM

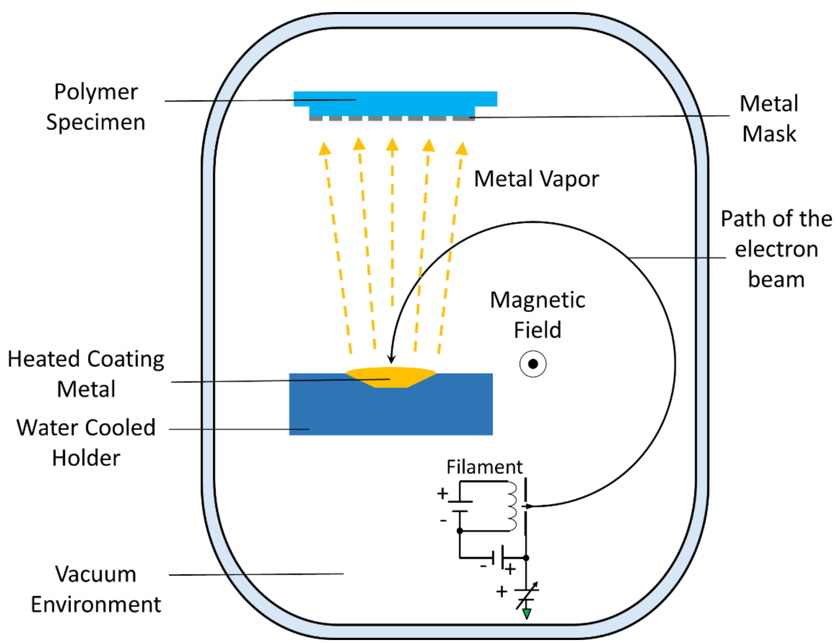
Surface Heater (HTC)

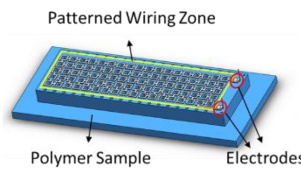


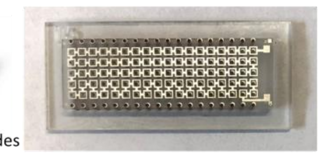


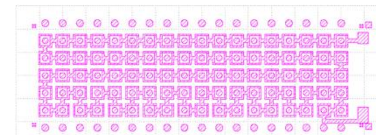
- *Photo Sciences, Inc.*

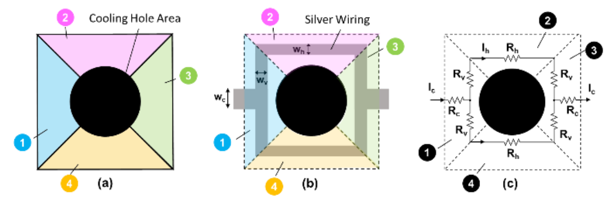
1. SLA printed resin samples with low thermal conductivity
   - Reduction of conductive heat loss
2. Micro-lithography fabrication for surface heater
   - Direct deposition of silver coil onto the target surface
   - No blockage/plugging of the outlets











$$P_1 = I_c^2 R_c + 2 I_h^2 R_v \quad = \quad P_2 = I_h^2 R_h$$

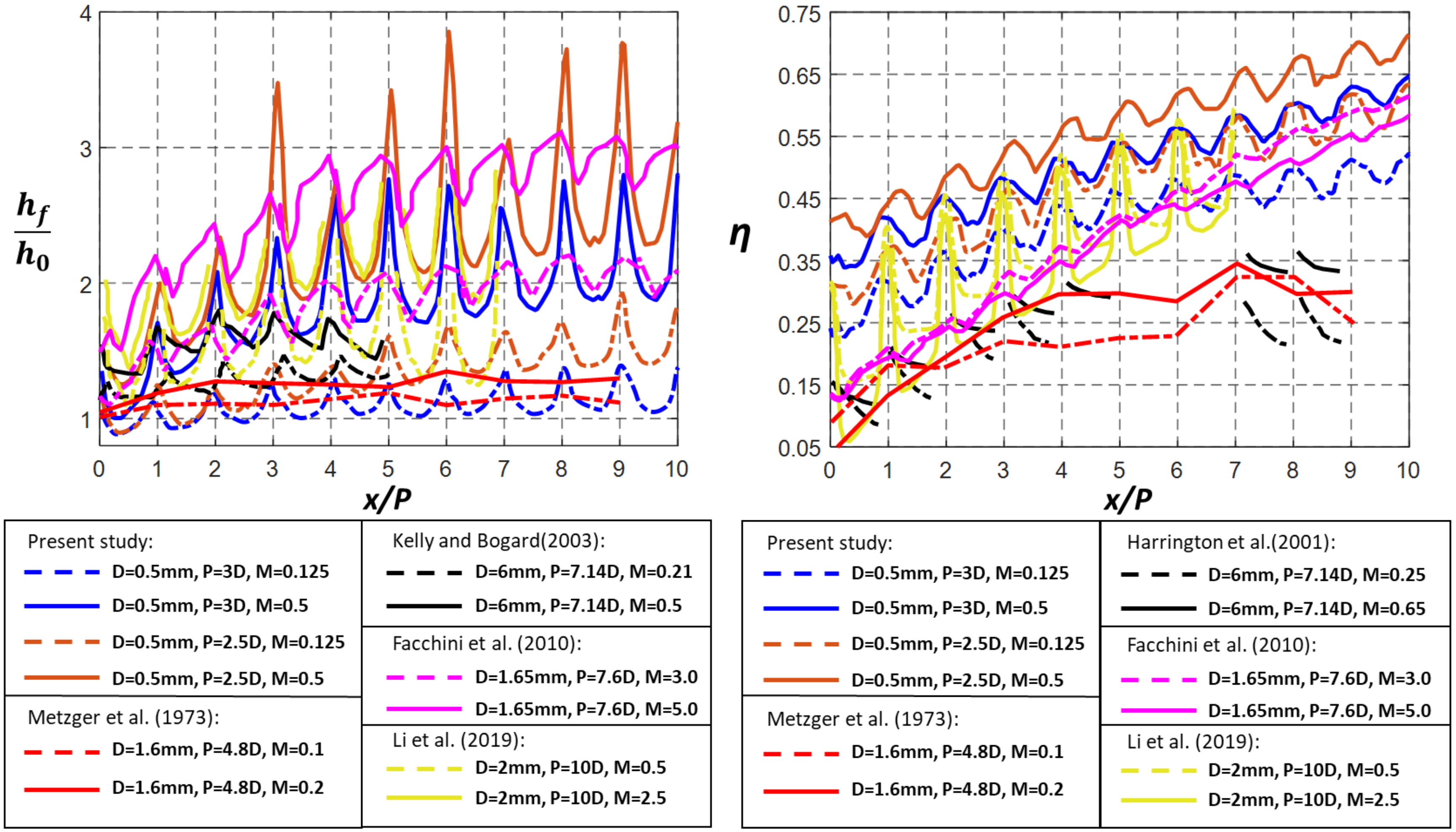
$$R_c = \rho \frac{L_c}{w_c t}$$

$$R_v = \rho \frac{L_v}{w_v t}$$

$$R_h = \rho \frac{L_h}{w_h t}$$

- *Plassys Electron Beam Evaporation System*

Comparison with Film Cooling



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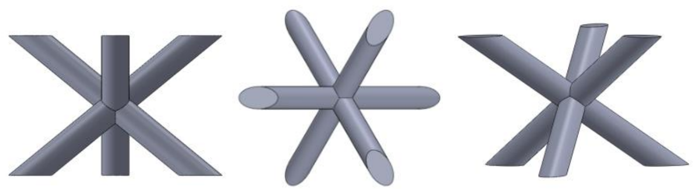
Overview of Unit Cells

Advantages
- High heat transfer surface area
- Promote turbulence in the bulk flow
- Provide structural rigidity

Kagome

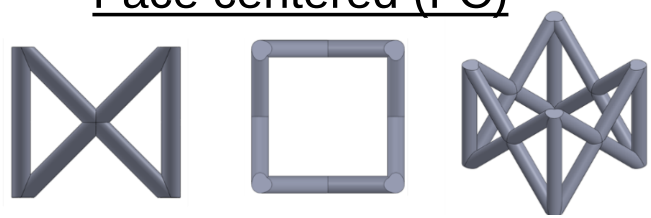


Front View Top view Perspective

Body centered (BC)

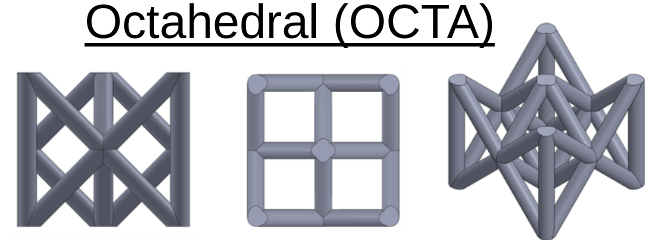
Front View Top view Perspective

Face centered (FC)

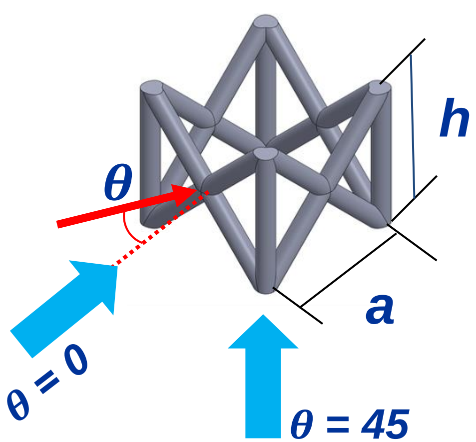


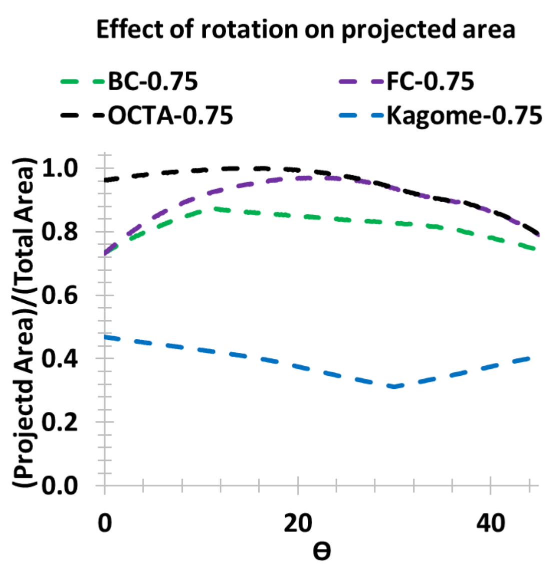
Front View Top view Perspective

Octahedral (OCTA)



Front View Top view Perspective

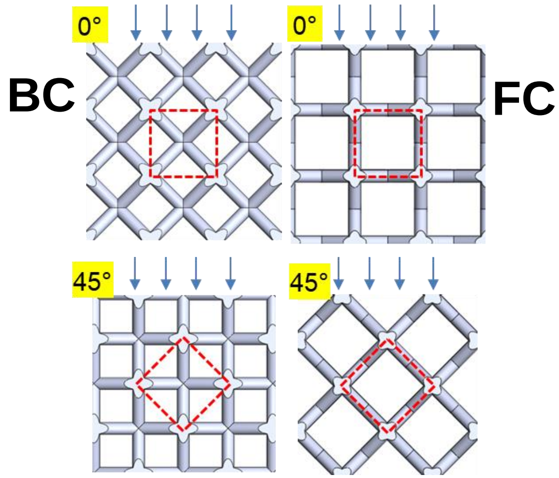




h = 2.54 mm
a = 4 mm
d = 0.5 mm, 0.75 mm
θ = 0^0, 45^0, min/max projected area

True –Scale Geometries

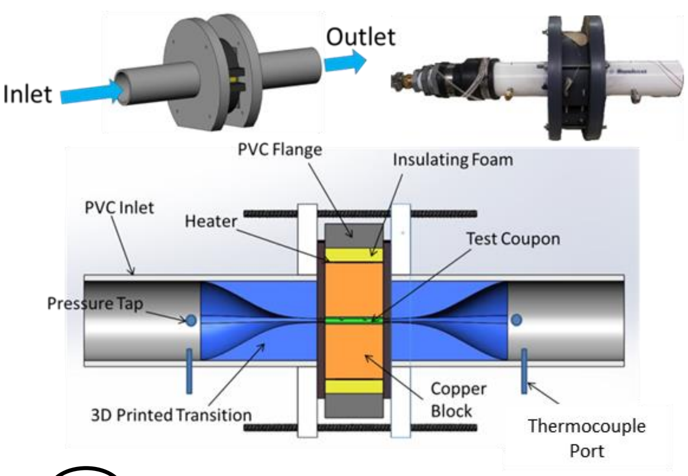
- True scale geometries fabricated using DMLS additive manufacturing process
  - varying diameter and build orientation



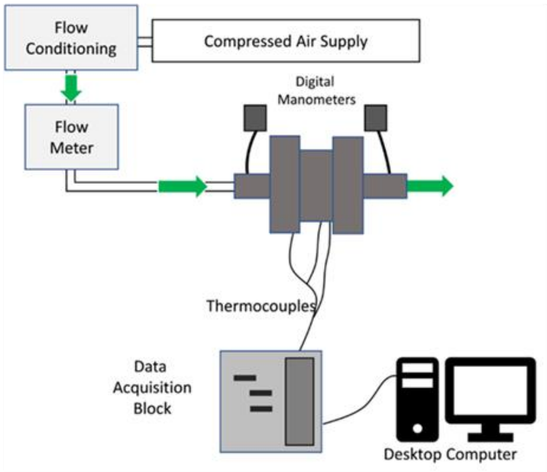
45º build orientation selected for fabrication

- Steady state conjugate heat transfer tests

Test Rig

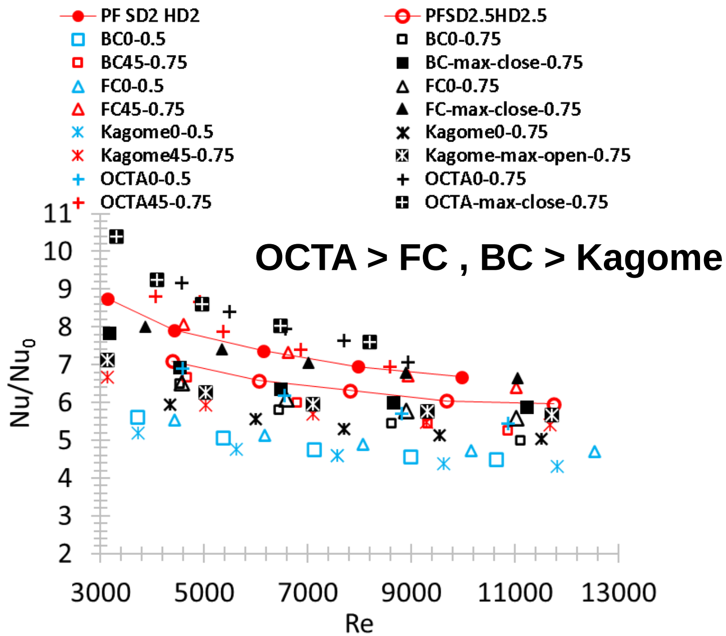


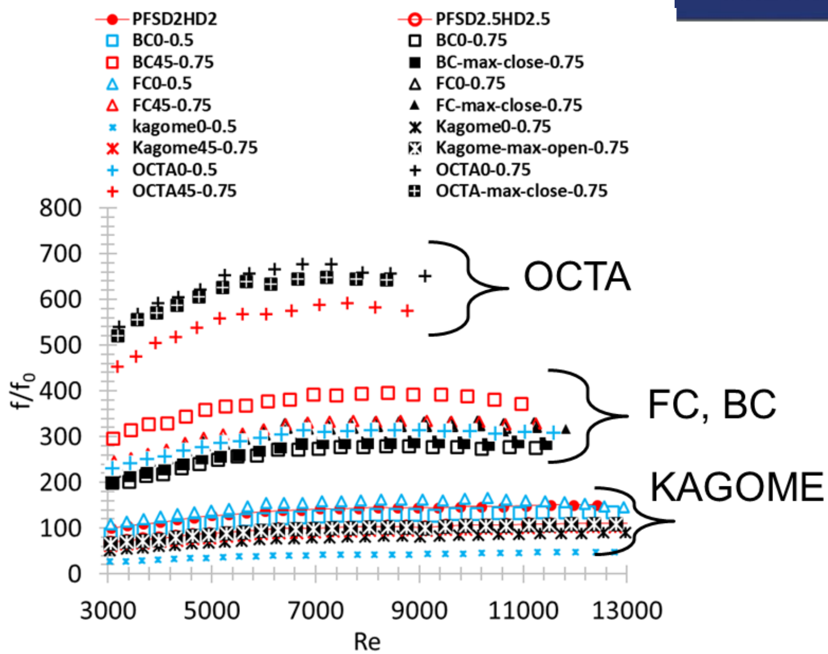
Test Setup Layout

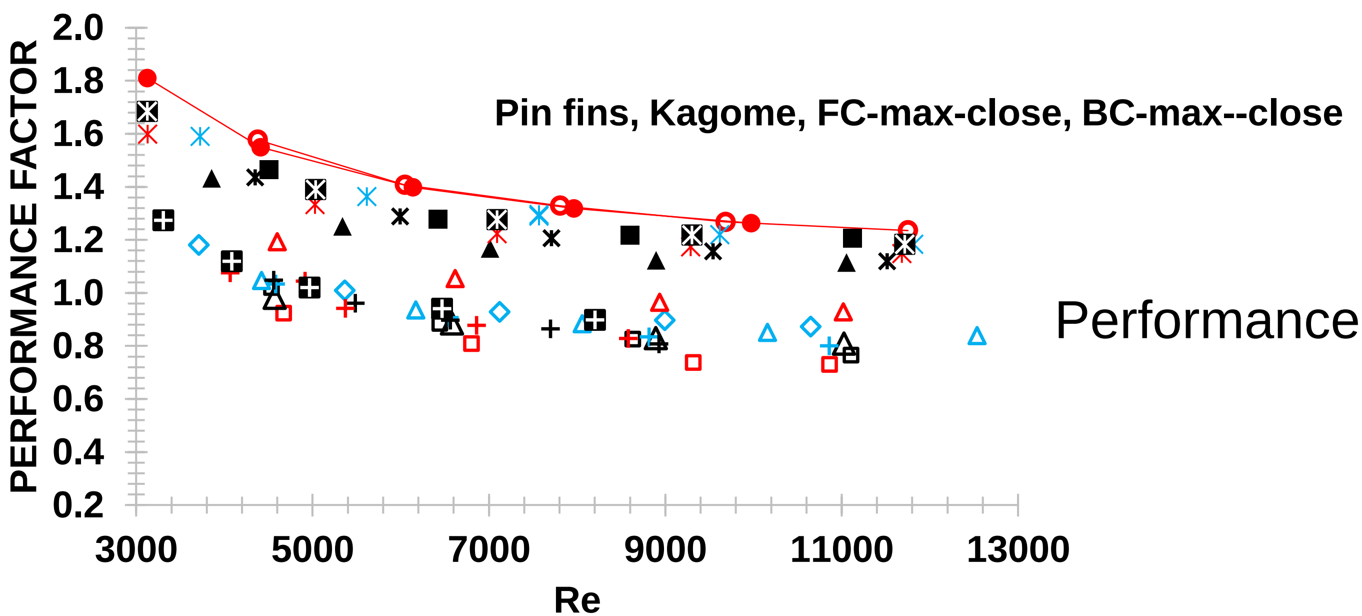


- True-scale test coupons for conjugate heat transfer analysis
- LMTD analysis
- Obtain overall heat transfer
- Re_{ch} : ~3000 to ~13,000

Nu and f Augmentation







$$\text{Performance factor} = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_0}\right)^{1/3}}$$

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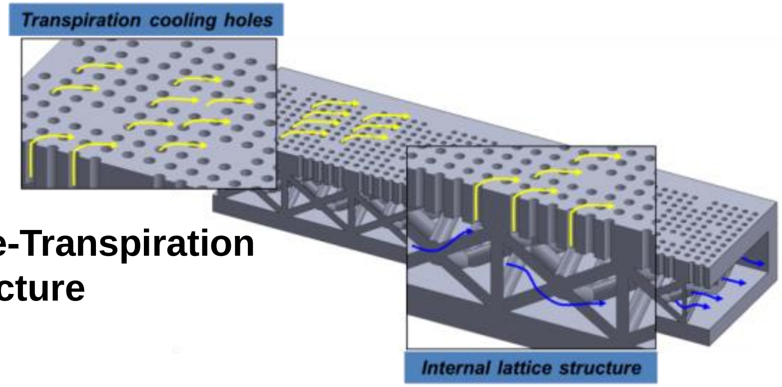
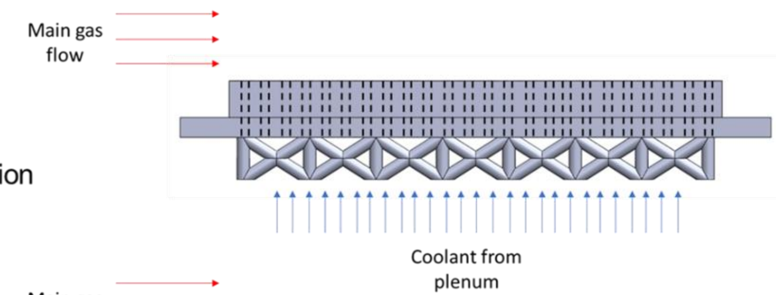
Integrated Cooling

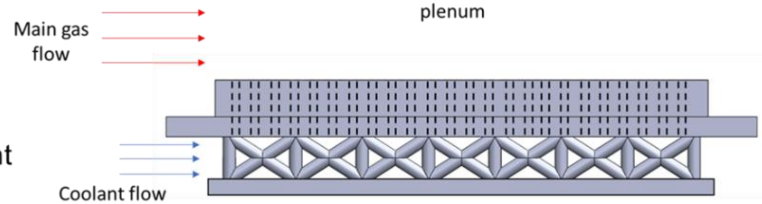


Integrated Lattice-Transpiration Architecture



Plenum fed

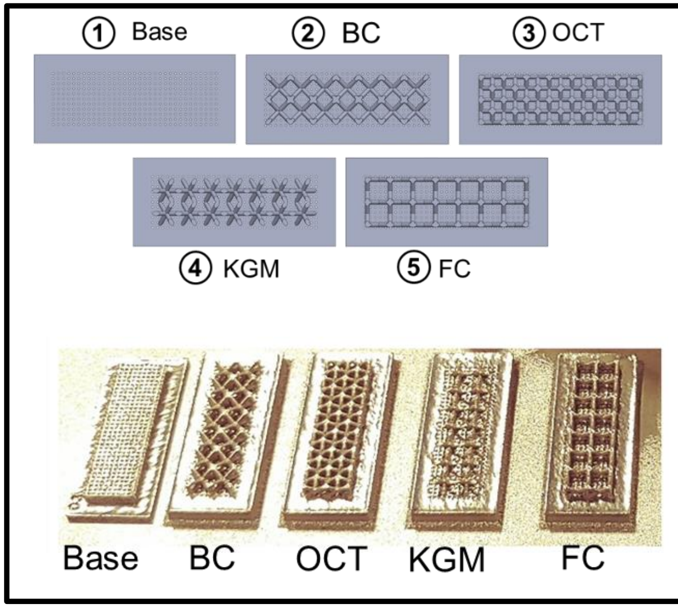
- Uniform pressure distribution



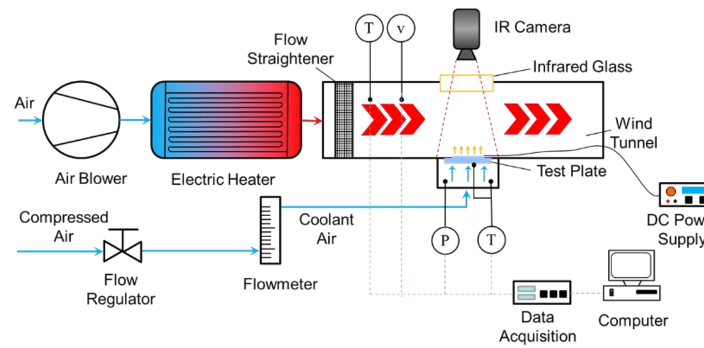
Crossflow fed

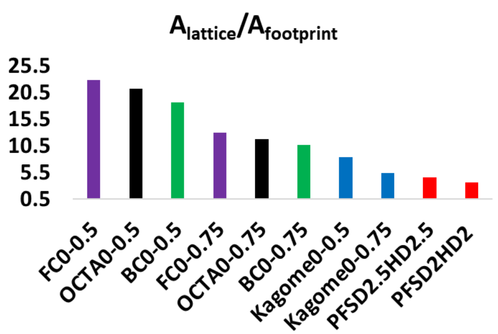
- Pressure drop along coolant direction

$$Q_{tot} = Q_{tran} + Q_{CF}$$



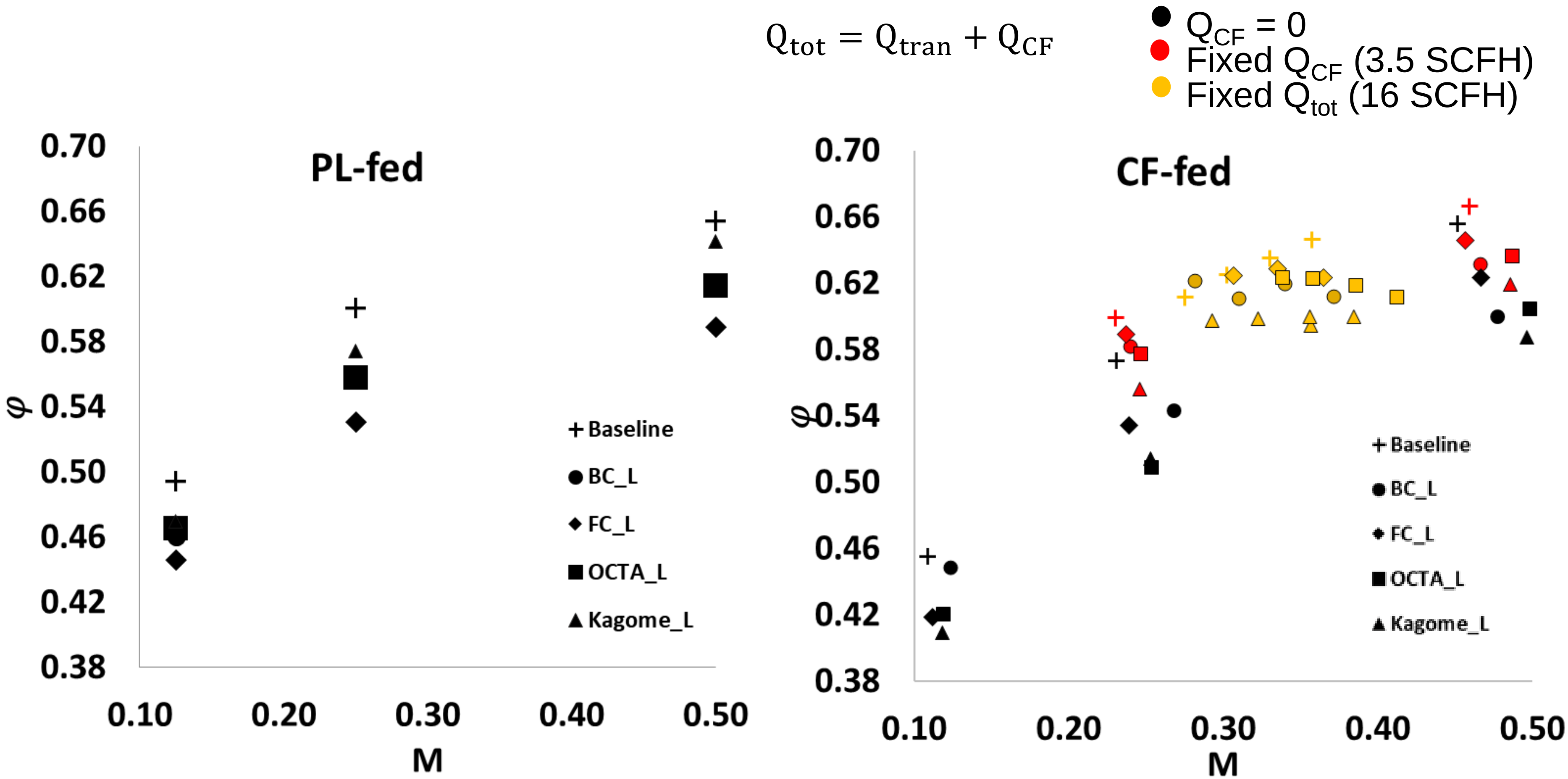
Test Rig





Overall Cooling Effectiveness

$$Q_{tot} = Q_{tran} + Q_{CF}$$



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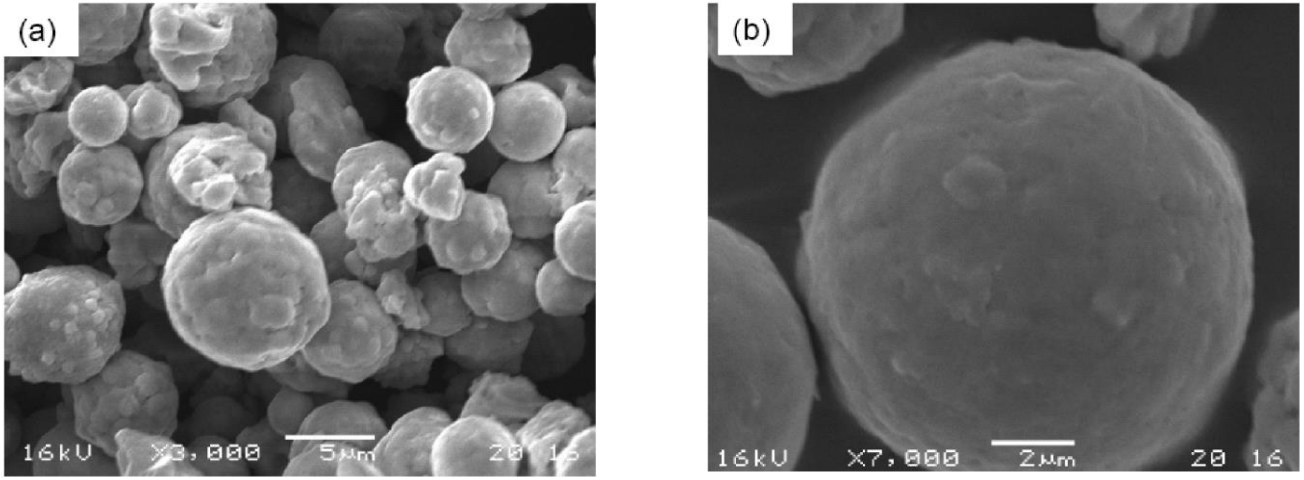
ODS 754 powders by Mechano-Chemical Bonding (MCB)

Cr (7.5~10 μm)	Al (4.5 ~ 7 μm)	Y_2O_3 < 50nm	W (~1 μm)	Ni (4 ~ 8 μm)
20	5	1.5	3	70.5

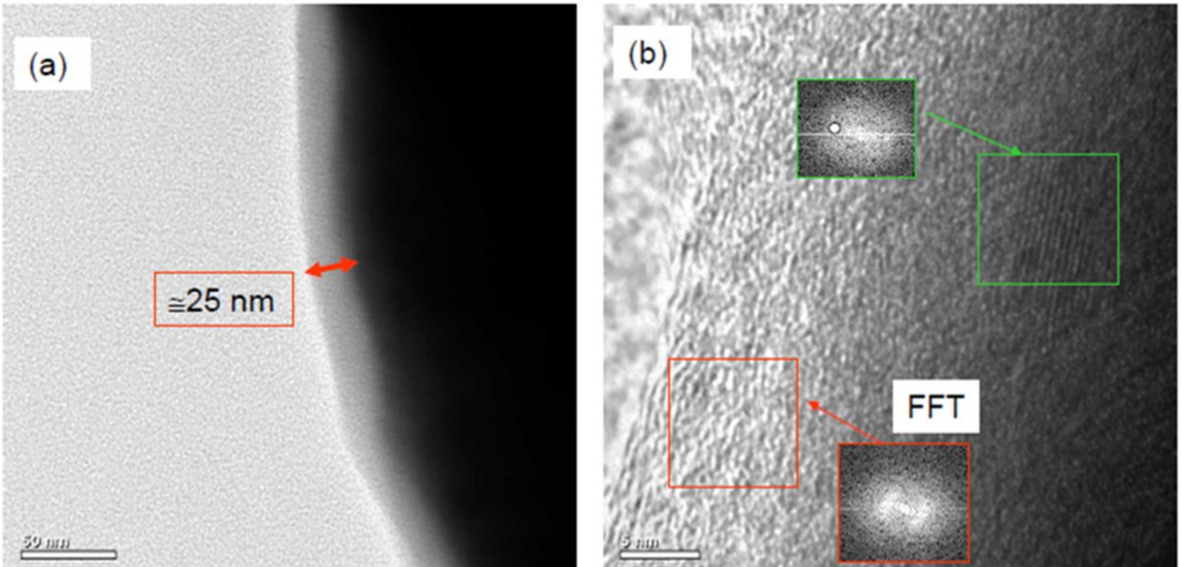


*Challenge: uniform dispersion of nano-sized Y_2O_3

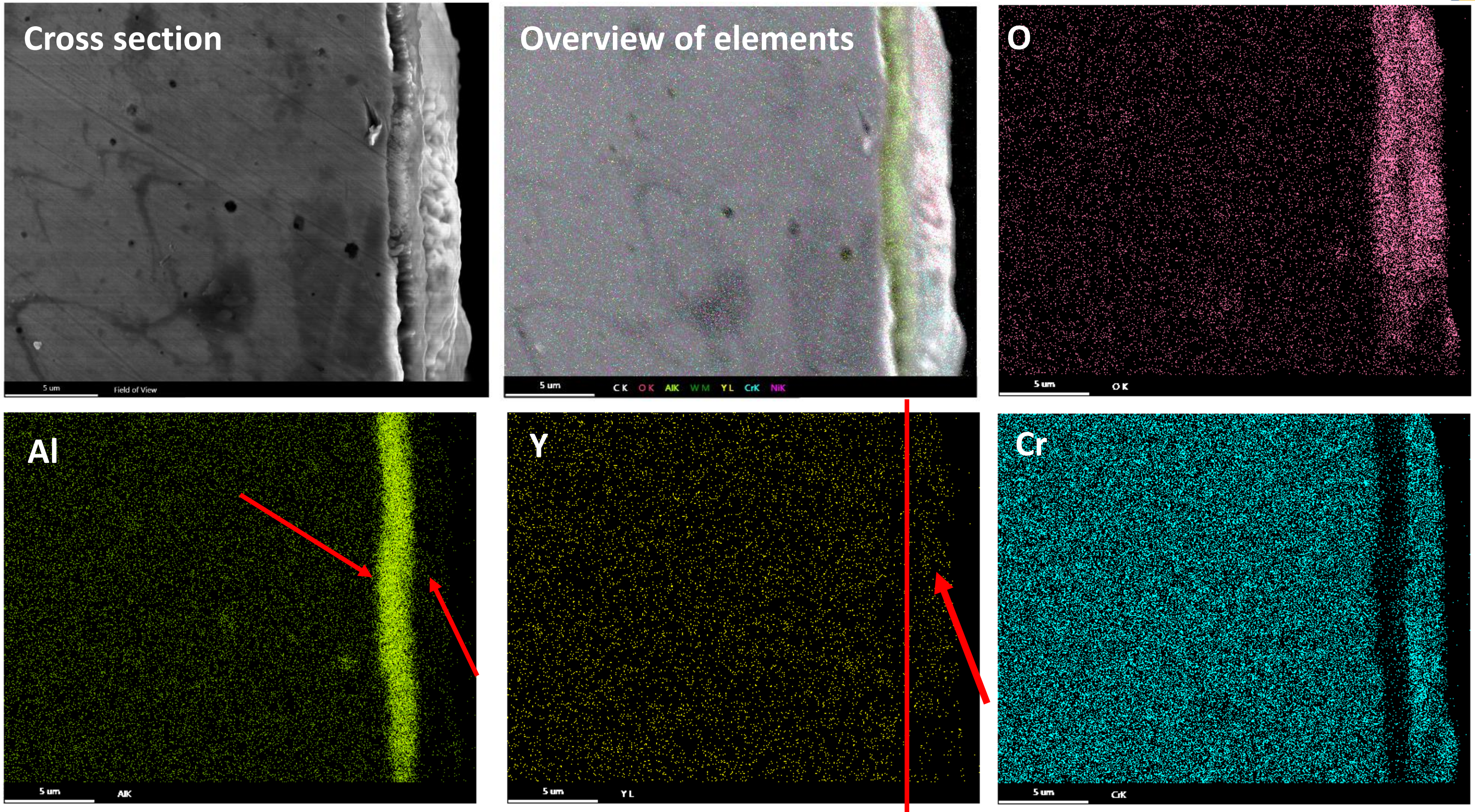
SEM micrographs of MCB processed ODS 754 powder sample

(a). As-processed from MCB; (b) close view of (a)

TEM BF and HREM imaging



250W (MCB only) ODS 754, 1280 cycles-Weight gain
Scanning Speed 0.5 in/s,100 W In-situ Laser Heat Treatment

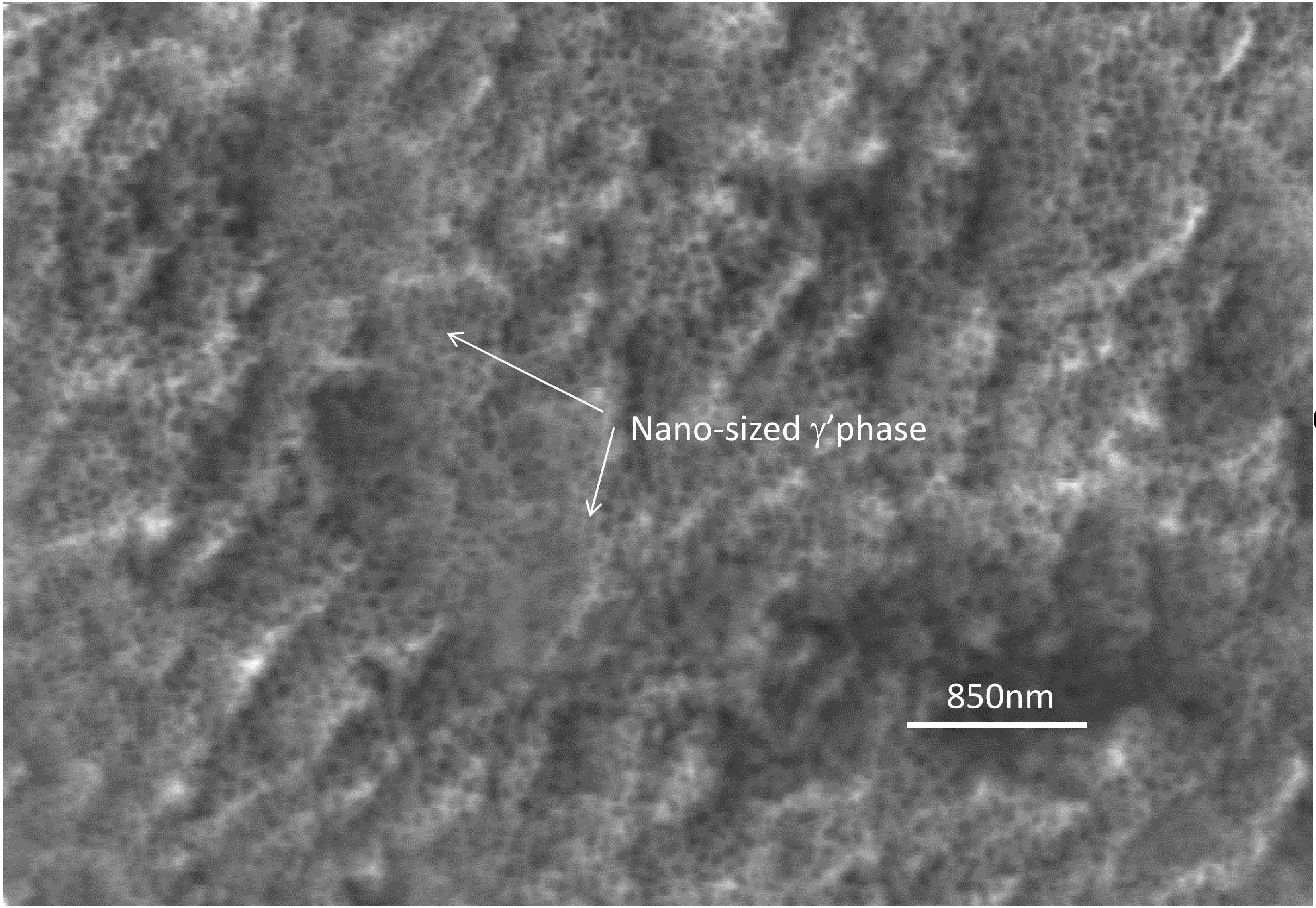


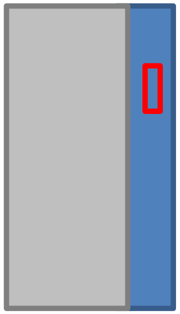
EDS of cross section shows a dense alumina stables at 1280 cycles.

Yttrium element can be detected in ODS samples and oxide layer, **more Yttrium can be detected in chromium oxide than in alumina, as indicated by red arrow.**

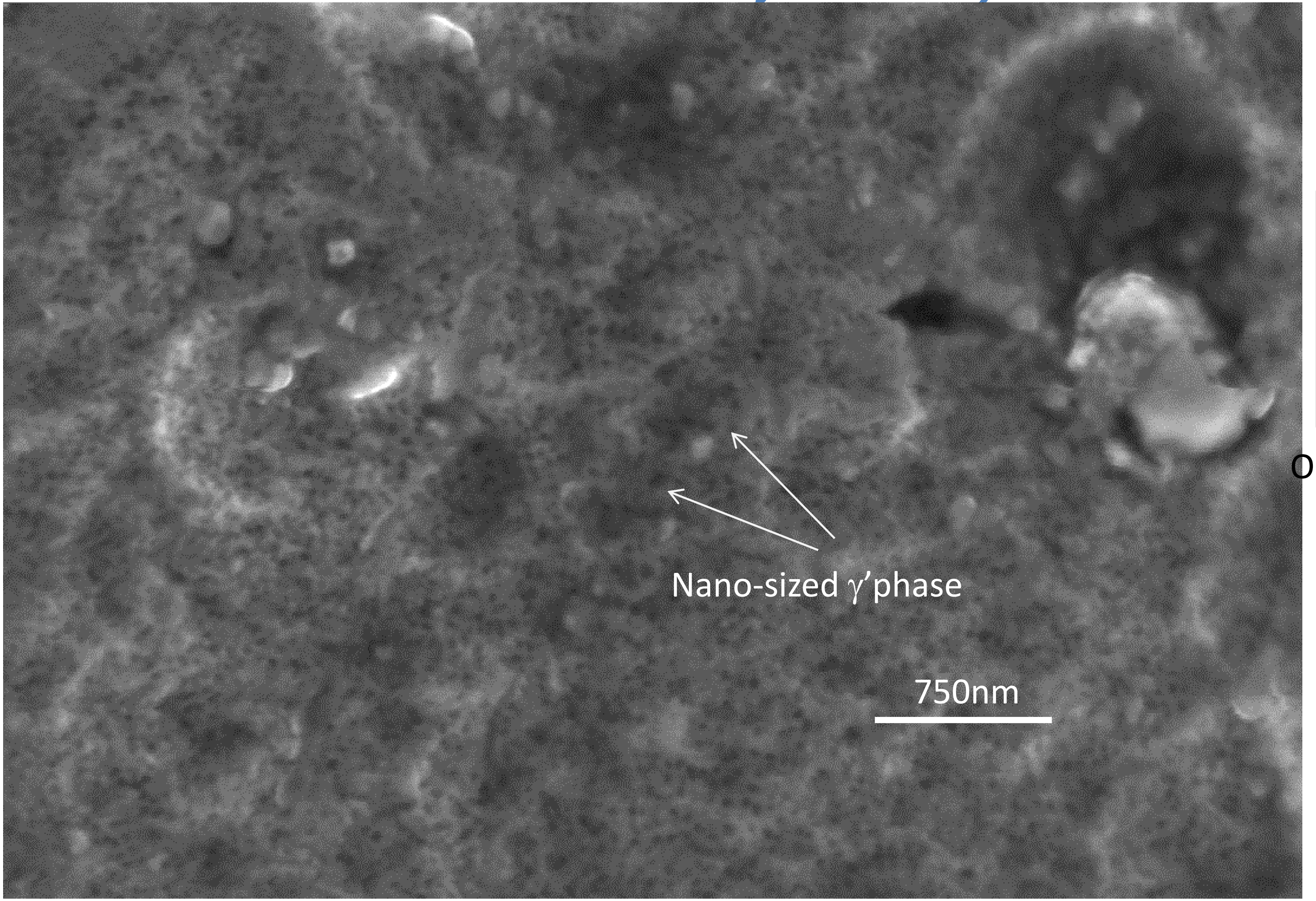
Aluminum also can be found in chromium oxide layer, this can be explained by the formation of Y-Al-O particles in chromium oxide layer, which can low oxidation rate of oxide layer. This is one reason of excellent stability of ODS oxide layer.

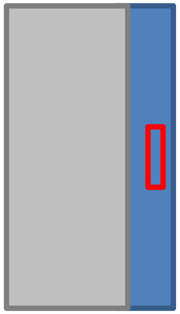
200W ODS 754 – AM Printed, Fresh





200W ODS 754 – after 2200 cycles

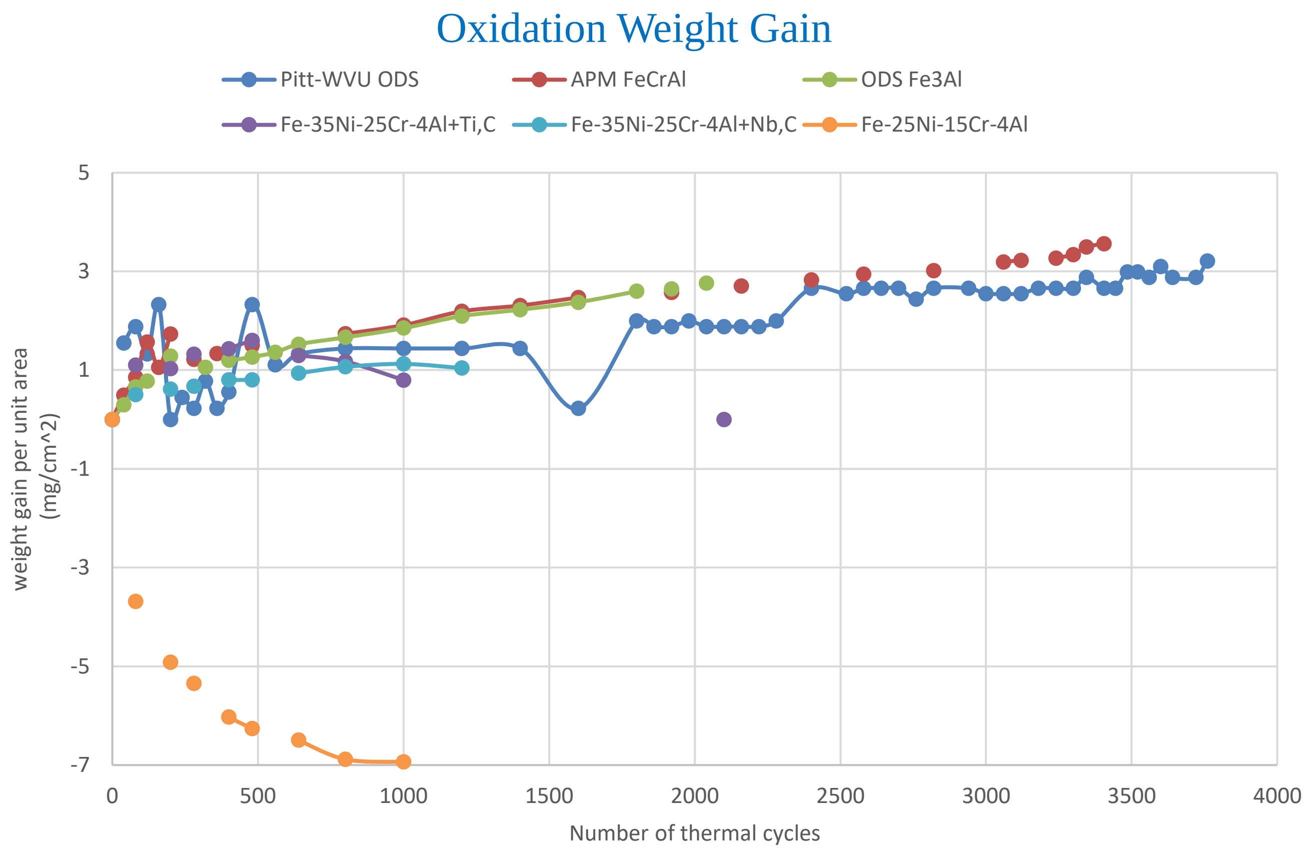




Nano-sized γ'phase preserved at ODS costing after 2200 cycles

***** Each cycle consists of moving test sample to the furnace within 15 minute and kept at 1100 °C for 45 minutes and moved out within 15 minutes, kept for 45 minute at room temperature.***

Weight Gain Comparison (ODS 754)



Pitt-WVU ODS: Ni-20Cr-5Al-3W-1.5Y2O3(Thermal cyclic Test at 1100 degree C)
APM FeCrAl: Fe-20.42Cr-5.54Al-0.08Mn-0.03Ti-0.23Si-0.03C(cyclic-oxidation tests,1100 degree C)
ODS Fe3Al: Fe–28Al–2Cr–0.5Y2O3(cyclic-oxidation tests,1100 degree C)
Fe-35Ni-25Cr-4Al+Ti,C/Fe-35Ni-25Cr-4Al+Nb,C/Fe-25Ni-15Cr-4Al(Mass change at 1100 degree C in air with 10% H2O vs. time (100 h cycles)

[1] Wright, I.G., Pint, B.A. & Tortorelli, P.F. Oxidation of Metals (2001) 55: 333. https://doi.org/10.1023/A:1010316428752
[2] Brady, M.P., Muralidharan, G., Yamamoto, Y. et al. Oxid Met (2017) 87: 1. https://doi.org/10.1007/s11085-016-9667-3

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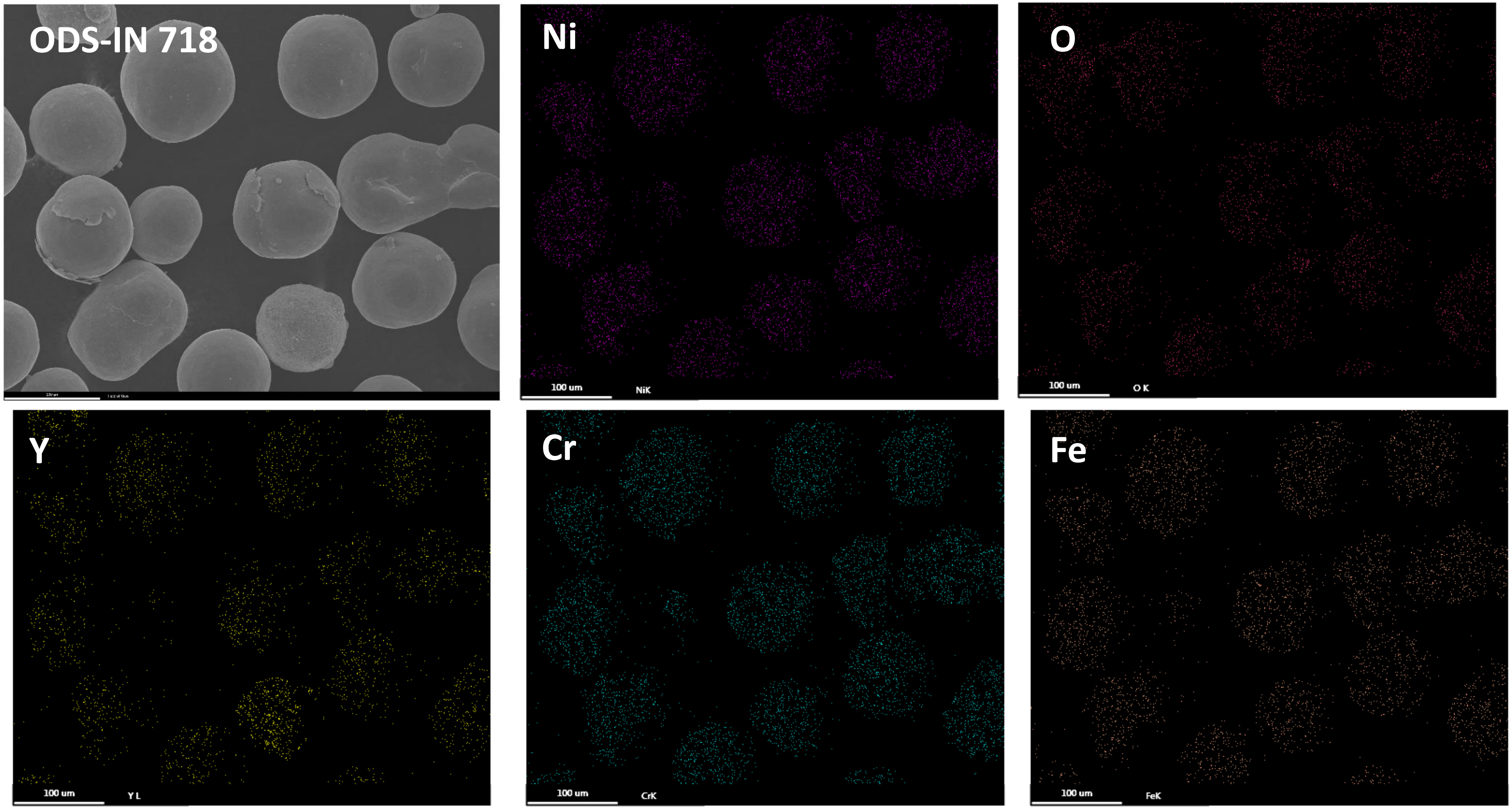
METHOD OF UNIFORMLY COATING SELECTIVE STRENGTHING PHASE TO GAS-ATOMIZED POWDERS FOR ADDITIVE MANUFACTURING

(research activity after 2021)

MCB-processed ODS IN 718 powders (with 0.5 wt.% Y_2O_3)



Uniform distribute of yttrium element using MCB process (depending on processing parameters).

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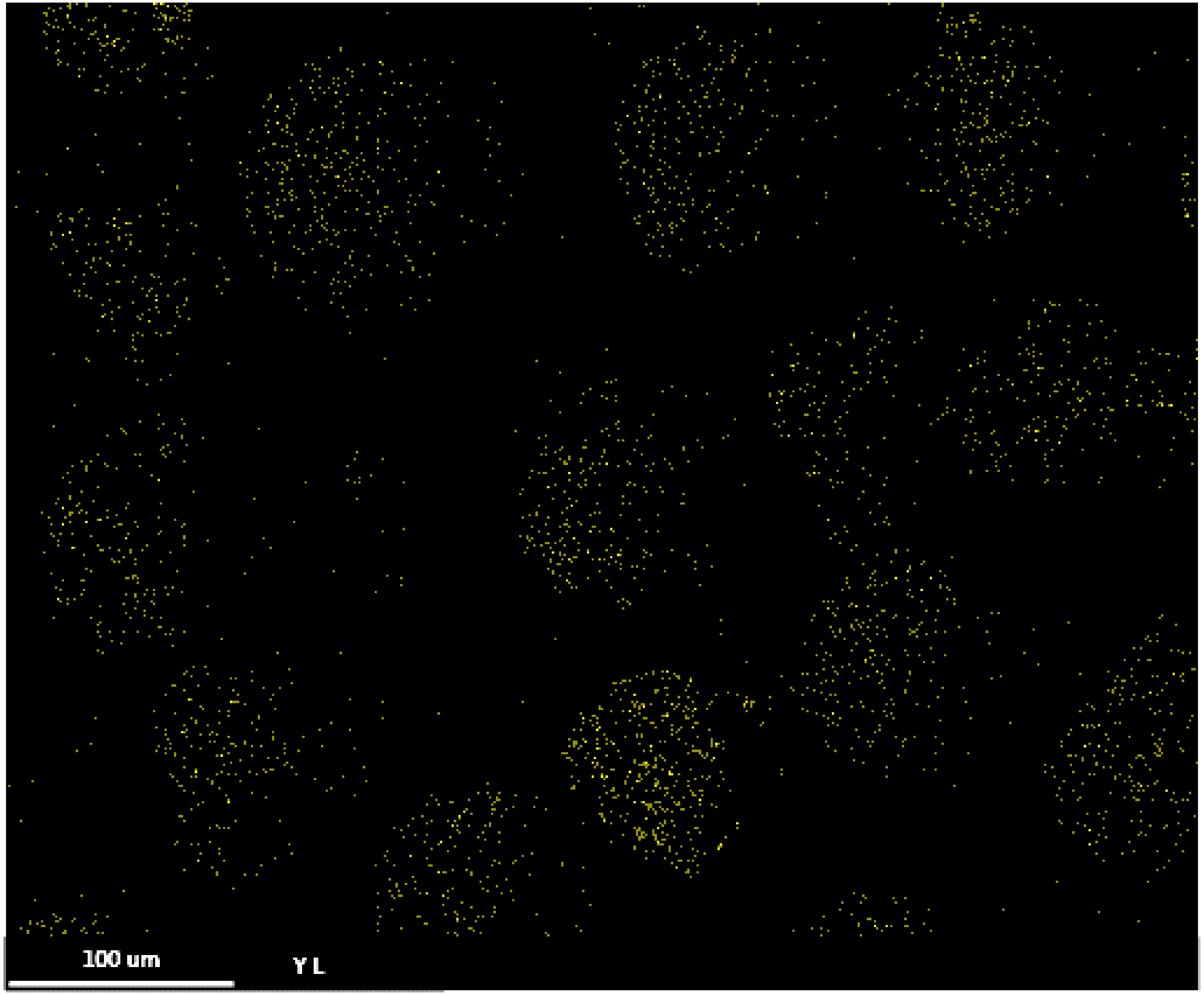
MCB-processed ODS IN 718 powders (with 0.5 wt.% Y_2O_3), enlarged view of nano-sized Yttrium distribution on each as-received IN 718 particle



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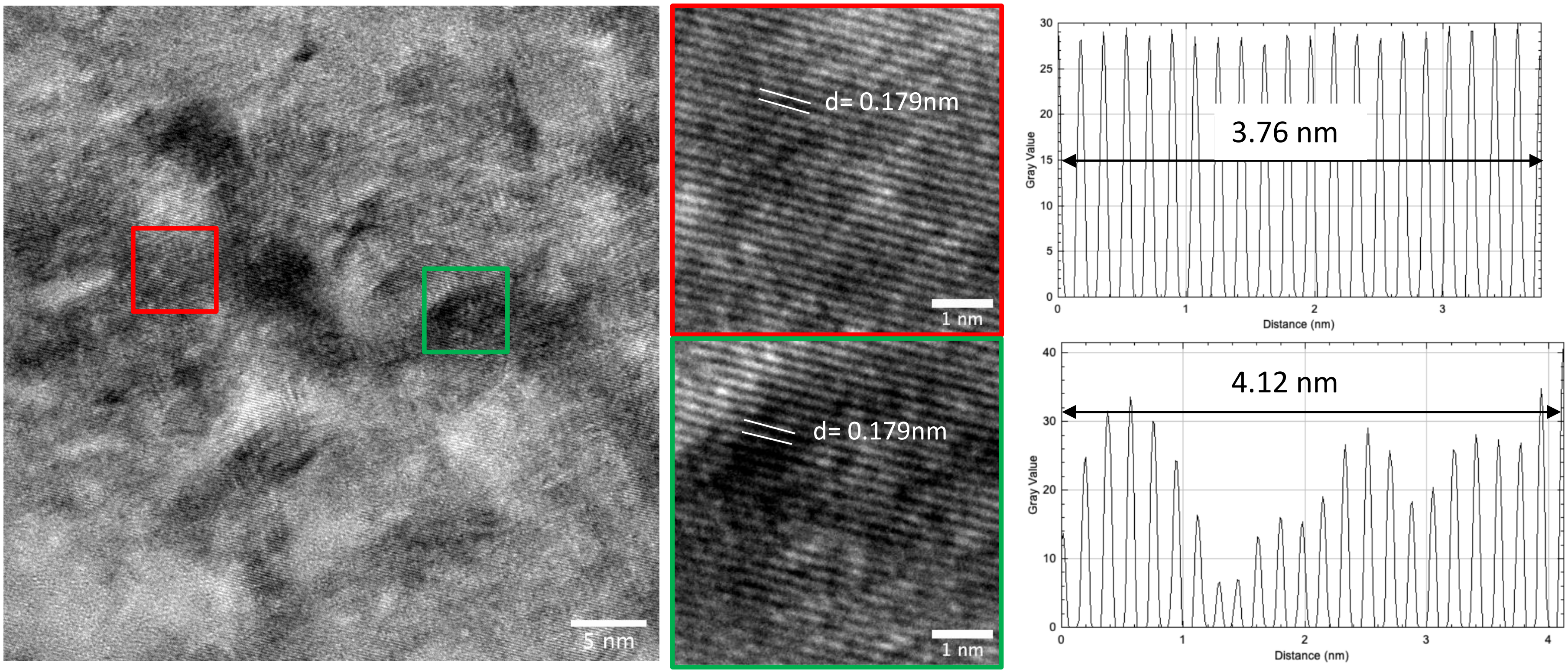
TEM of DED-printed ODS IN718 (0.5 wt.% Y_2O_3) alloy by Synergy Additive

Standard $Al_2Y_4O_9$:

(-2 5 2)	d= 0.1793nm
(5 1 1)	d= 0.1793nm



Y_2O_3 reacted with Al to form $Al_2Y_4O_9$, thus reduced Ni_3Al density and strength of ODS IN718

Data analysis method [https://www.youtube.com/watch?v=kOQevYUzMLE]

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Outlines

- *Background, Challenges, Objectives, Benefits of Technology, Research Task Plans*
- *Additive Manufacturing Processes*
- *Summary of Transpiration Cooling Results*
- *Summary of Lattice Cooling Results*
- *Heat Transfer Results: Integrated Cooling*
- *ODS Powder Development*
- ***DMLS using ODS Powder***

Milestone E

Milestone E: Develop Successful approach to make ODS Structure for integrated transpiration and internal cooling

DMLS of ODS IN718 using EOSM290

Volumetric Energy Density (VED)

$$VED = \frac{P}{Vht} \text{ J/mm}^3$$

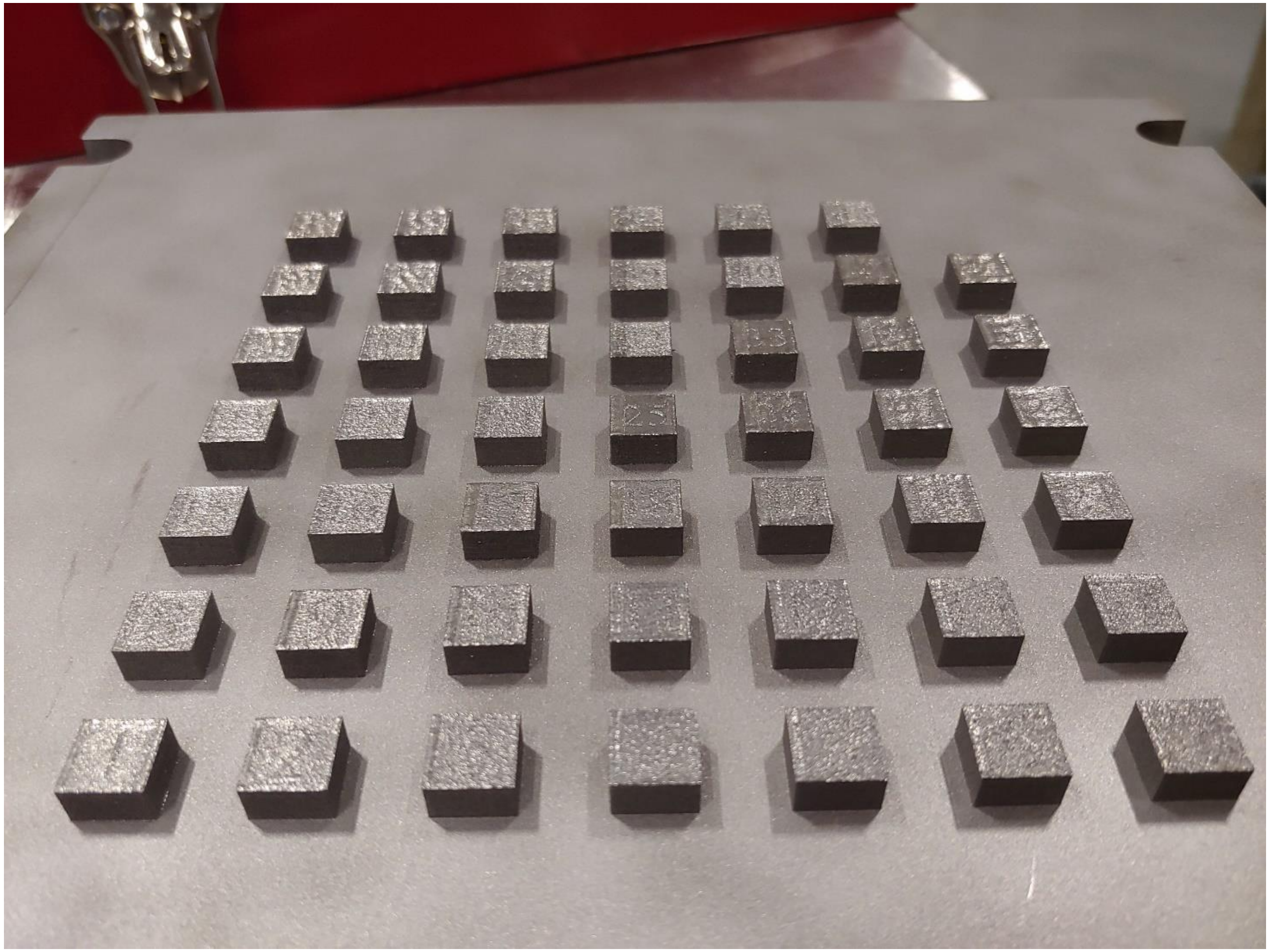
P = laser power
V = scan velocity
h = hatch spacing
t = layer thickness

t = 0.04 mm h = 0.11 mm

Scan speed (mm/s)	Power (W) 270	285	300	315	330	345
560	109.6	115.7	121.8	127.8	133.9	140.0
640	95.9	101.2	106.5	111.9	117.2	122.5
720	85.2	90.0	94.7	99.4	104.2	108.9
800	76.7	81.0	85.2	89.5	93.8	98.0
880	69.7	73.6	77.5	81.4	85.2	89.1
960	63.9	67.5	71.0	74.6	78.1	81.7
1040	59.0	62.3	65.6	68.8	72.1	75.4
1120	54.8	57.8	60.9	63.9	67.0	70.0

Typical value to print as-received IN718 powder

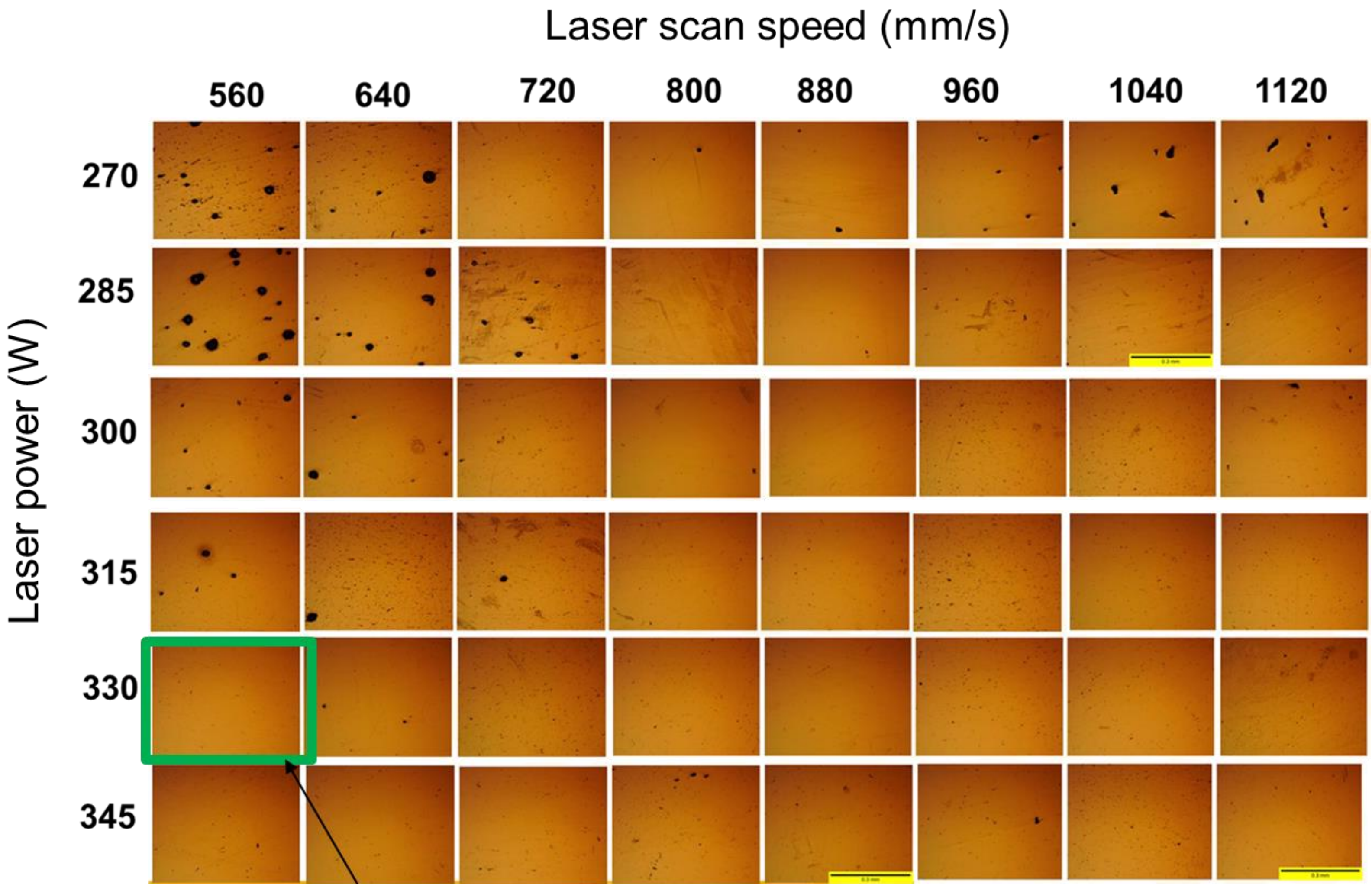
First Stage: Calibration Coupons



Dimensions: 10 mm x 10 mm x 5mm (l x w x h)

Successful print without any visible defect in the coupons

Microhardness and Porosity Analysis (WVU)



Highest hardness and low porosity

330 W and 560 mm/s (133.9 J/mm^3)

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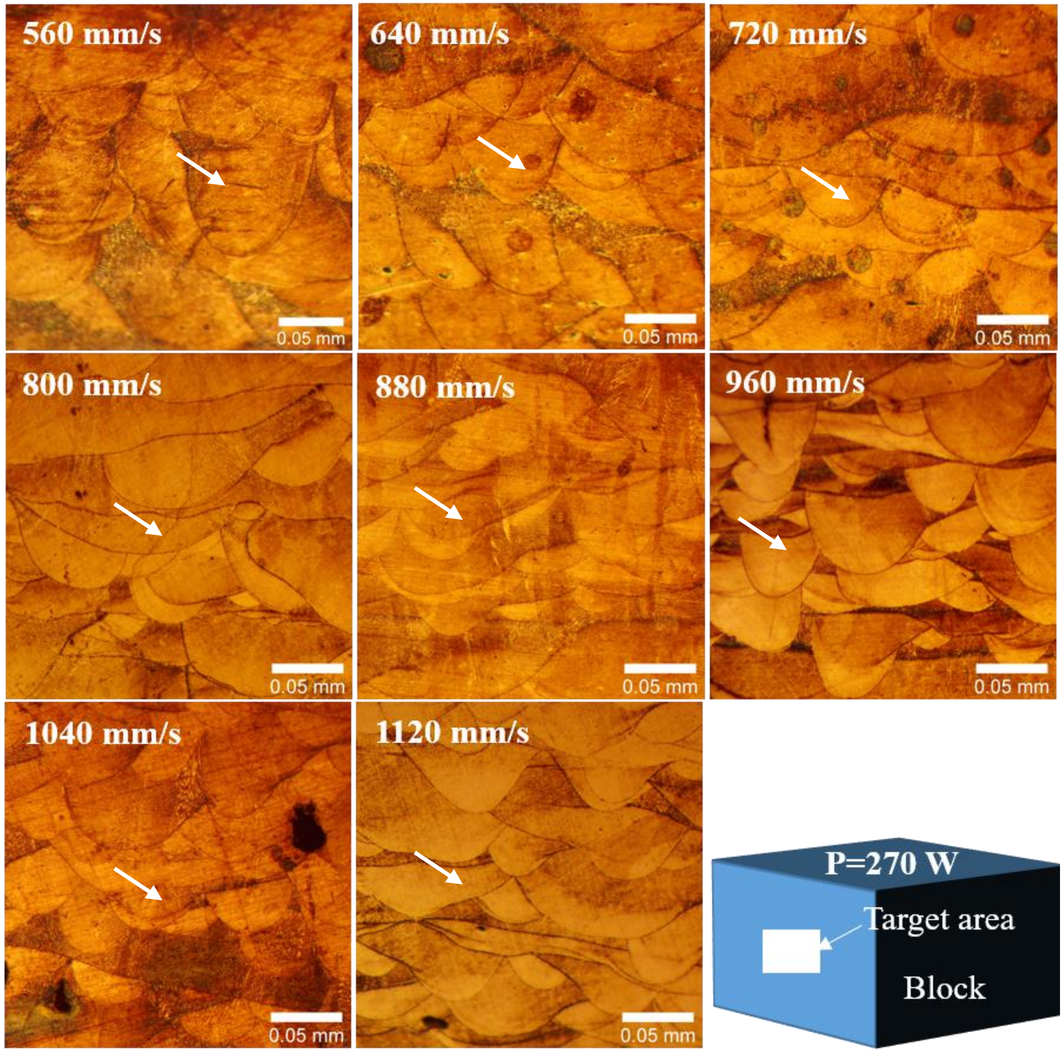
Microstructure of Pitt's EOS-printed ODS IN718 (0.5 wt% Y_2O_3)

Increasing scan speed favors smaller melt pool (White arrows) in EOS printed ODS IN718 owing to the decrease of volumetric energy density (VED)

$$VED = \frac{\mathrm{P}}{\mathrm{Vht}}$$

P:laser power (W)
V:scan speed (mm/s),
H: hatch spacing (mm)
t : layer thickness (mm)



Scan speed effects on melt pool of EOS printed ODS IN718 at 270 W.

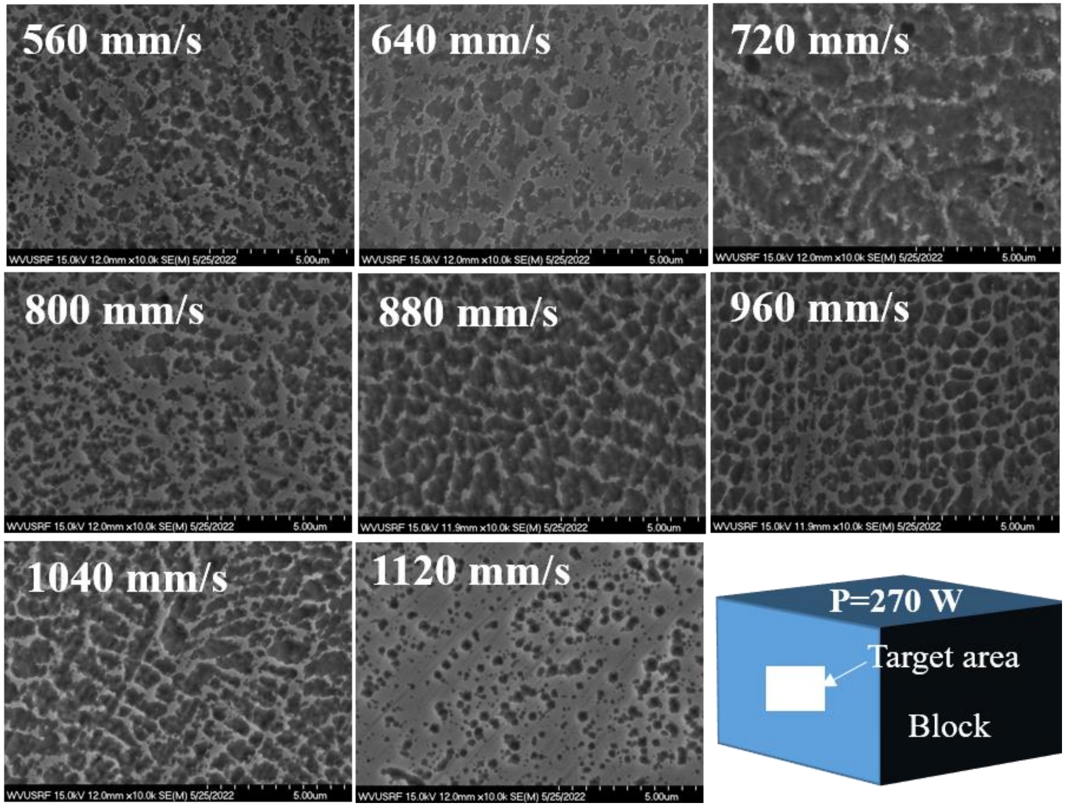
Microstructure of IN718/ODS IN718 (0.5 wt% Y_2O_3)

The dark area shows γ' (Ni_3 (Al, Ti)) in ODS IN718

Increasing scan speed favors lower density of γ' owing to the decrease of volumetric energy density (VED)

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

P:laser power (W)
V:scan speed (mm/s),
H: hatch spacing (mm)
t : layer thickness (mm)



Scan speed effects on phase formation of EOS printed ODS IN718 at 270 W.

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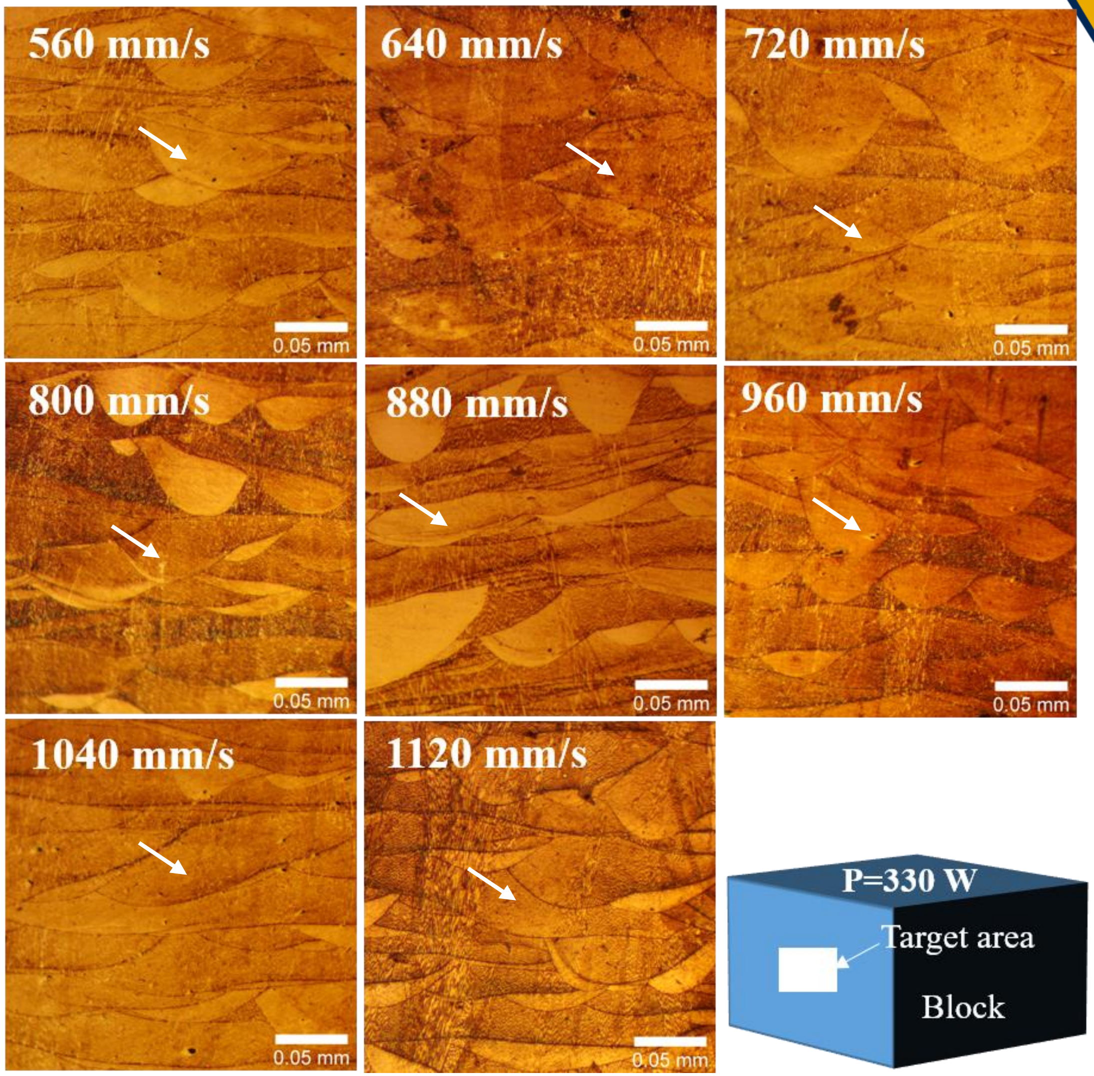
Microstructure of Pitt's EOS-printed ODS IN718 (0.5 wt% Y_2O_3)

Highest Hardness:
330 W and 560 mm/s

Increasing scan speed favors smaller melt pool (White arrows) in EOS printed ODS IN718 owing to the decrease of volumetric energy density (VED)

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

P:laser power (W)
V:scan speed (mm/s),
H: hatch spacing (mm)
t : layer thickness (mm)



Scan speed effects on melt pool of EOS printed ODS IN718 at 330 W.

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Microstructure of IN718/ODS IN718 (0.5 wt% Y_2O_3)

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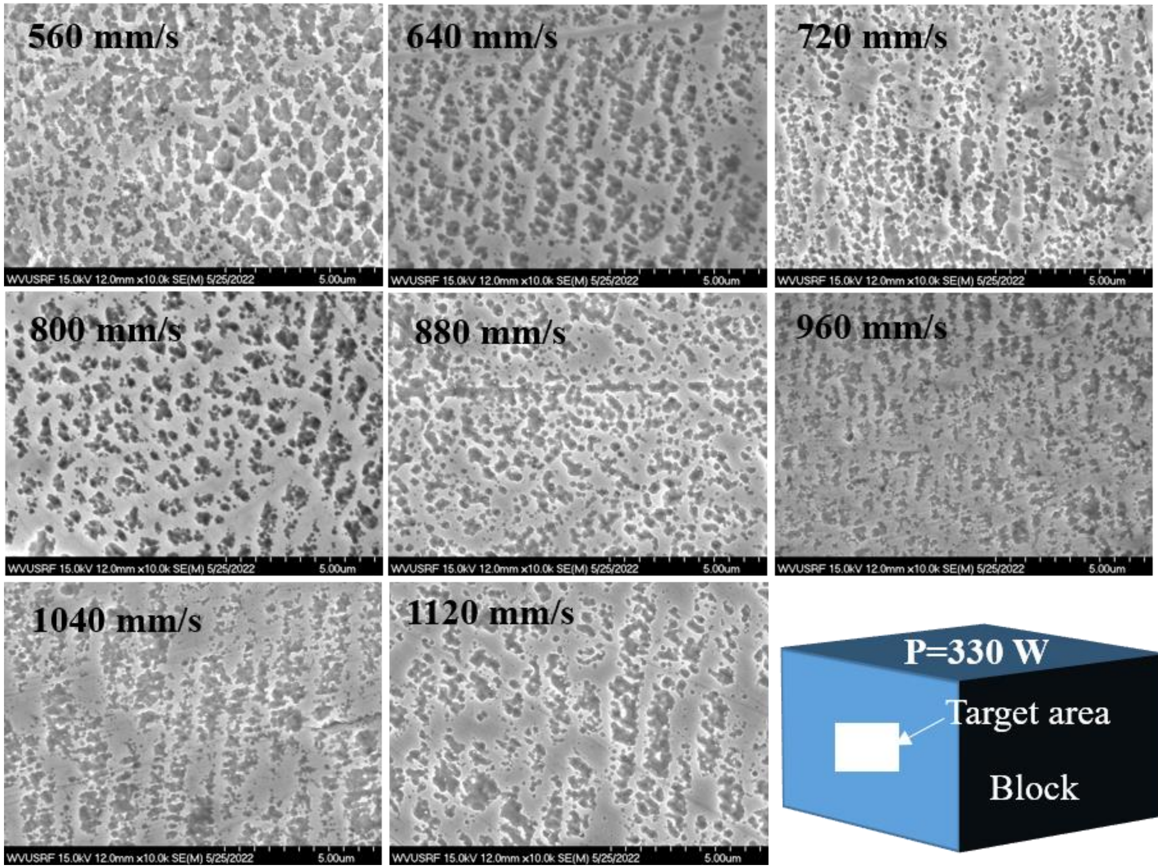


Scan speed effects on phase formation of EOS printed ODS IN718 at 330 W.

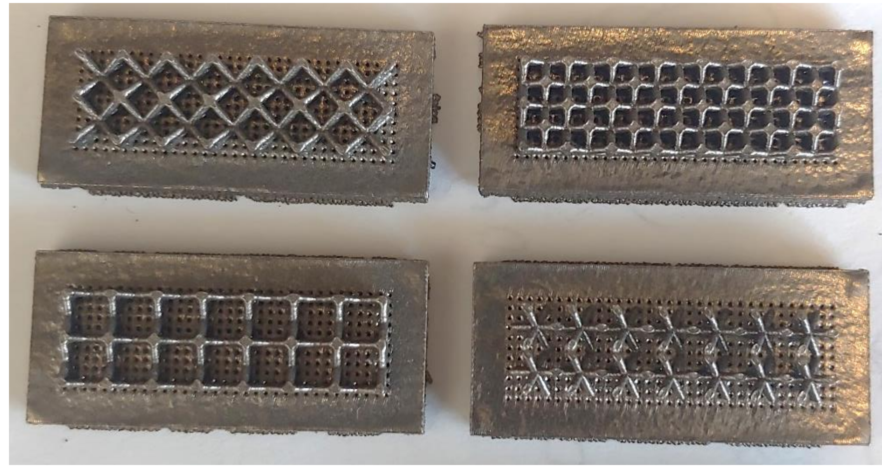
Parts using ODS IN718

Sample unit cells

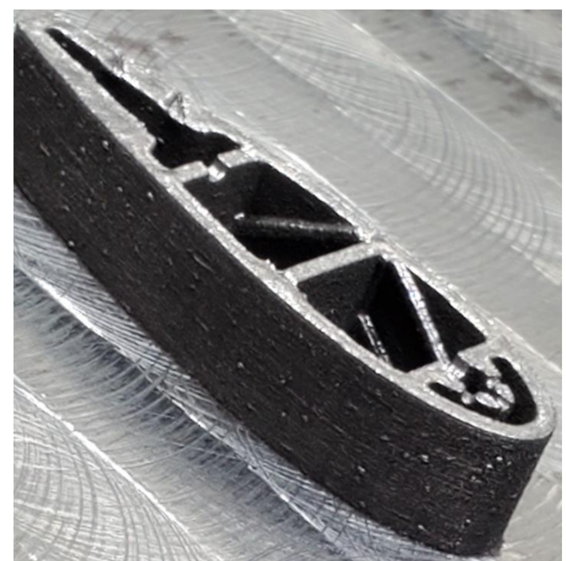
0.5 mm 0.75 mm 1 mm
Ligament diameter

Baseline Transpiration (0.3 mm holes, 3d pitch)

Sample integrated transpiration-lattice coupons



Sample blade with internal cooling features



Summary

❑ Transpiration cooling

- The micro-lithography technique was employed to fabricate the surface heater on transpiration cooling target surface
- The adiabatic cooling effectiveness and HTC for the transpiration cooling structures were investigated for the first time
- Transpiration cooling with low blowing ratio (0.125) has higher adiabatic cooling effectiveness than multi-row film cooling and HTC ratio close to 1
- Although higher blowing ratio increases HTC significantly, the adiabatic cooling effectiveness of transpiration cooling is still higher than film cooling

❑ Lattice cooling

- Conjugate heat transfer study was performed for true-scale lattices, showing high heat transfer
- Both heat transfer and pressure drop depended on the ligament diameter, unit cell topology, as well as the lattice orientation

❑ Integrated cooling

- Two possible integrated design based on coolant flow direction being investigated
- For a fixed total coolant flow, decreasing transpiration flow has low impact on the overall cooling effectiveness, showing potential to mitigate blockage effects

Summary

❑ ODS development and DMLS

- A novel ODS powder fabrication using MCB method (WVU Generation 3) has been developed. This novel MCB method enables embedded ultrafine Y2O3 in spherical metallic powders suitable of additive manufacturing turbine airfoils designs and fabrication.

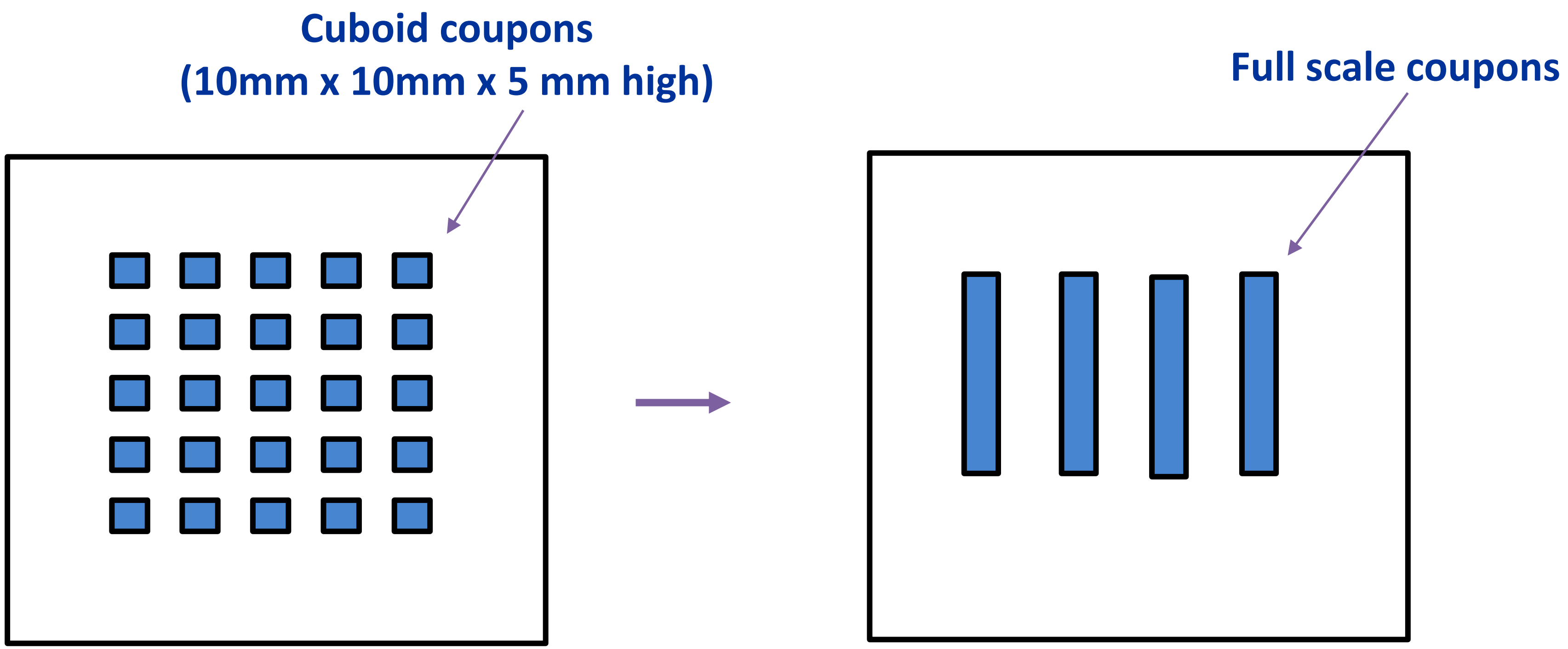
- Optimized printing processing parameters for MCB-processed ODS IN718 powder were obtained for EOS M290 AM machine. True-scale lattice and transpiration coupons were successfully fabricated.

- Preliminary TEM analyses showed clear evidence of uniform nano-sized yttrium distribution of the AM-printed ODS IN718 alloy.

Thank you!

Two-Staged Printing

- **First stage**: 48 cuboid samples using P and V pair from VED table
- Cross-section analysis for porosity and micro-hardness → optimal P and V
- **Second stage**: printing of full-scale test coupons

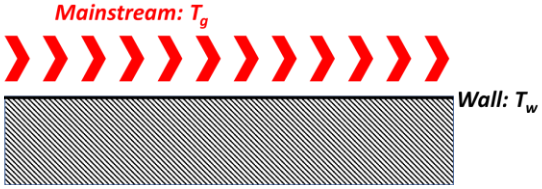


First-stage build to estimate optimal **P** and **V**

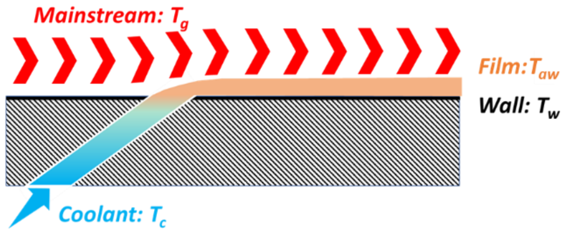
Second-stage build using the down-selected **P** and **V** value

➢ Thermo-fluid investigation – film cooling

- Flat surface without coolant protection: $q_0 = h_0(T_{ref} - T_w), \quad T_{ref} = T_g$



- Film covered surface: $q = h_f(T_{ref} - T_w), \quad T_{ref} = T_{aw}$



$$Net\ heat\ flux\ reduction\ (NHFR) = 1 - \frac{q}{q_0} = 1 - \frac{h_f}{h_0}\frac{(T_{aw} - T_w)}{(T_g - T_w)}$$
$$= 1 - \frac{h_f}{h_0}(1 - \eta/\varphi)$$

- Unknowns: $T_w, T_{aw}, \frac{h_f}{h_0}$

$\eta = \dfrac{T_g - T_{aw}}{T_g - T_c}$: Adiabatic cooling effectiveness

$\dfrac{h_f}{h_0}$: Heat transfer coefficient ratio

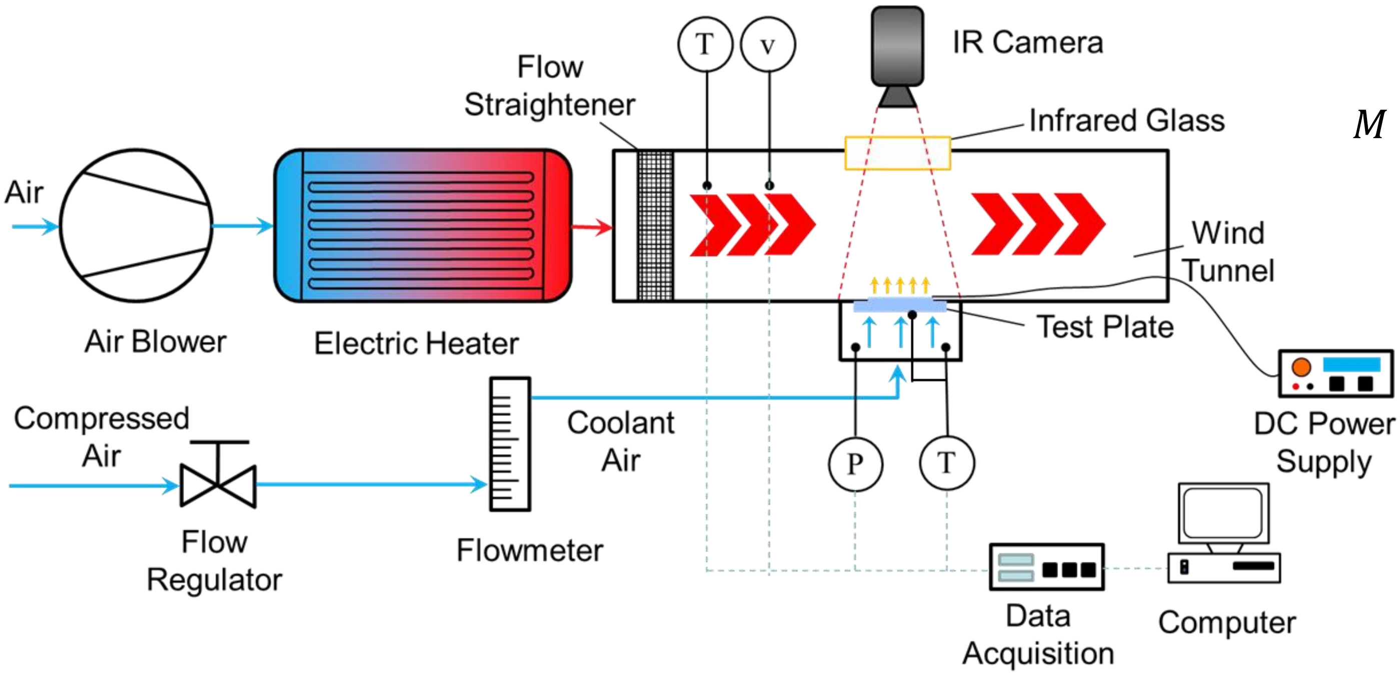
$\Rightarrow$ Obtained from polymer coupons with low thermal conductivity

Overall cooling effectiveness

$$\varphi = \frac{T_g - T_w}{T_g - T_c}$$

0.5 – 0.7 in real engine conditions

Wind Tunnel Test



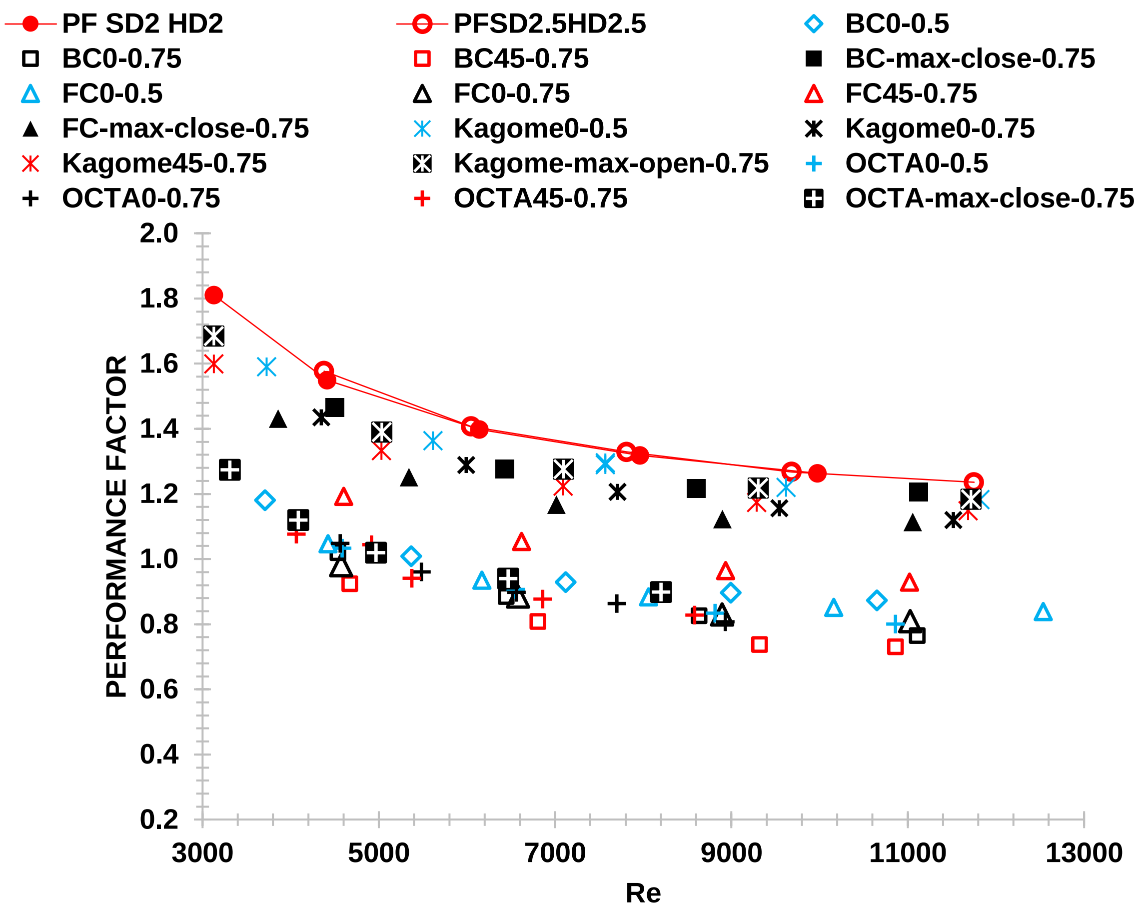
$$M = \frac{\rho_c u_c}{\rho_g v_g}$$

- **Heat transfer coefficient test:**

1. Blowing Ratio: M = 0.125, 0.25, 0.5
2. Coolant Temperature: T_c = 35 ℃
3. Mainstream Temperature: T_g = 35 ℃
4. Mainstream Velocity: v_g = 11m/s (Re_g=98,000)
5. Heater power on for h_f: 0.2W
6. No coolant injection to obtain h_0

- **Adiabatic cooling effectiveness test:**

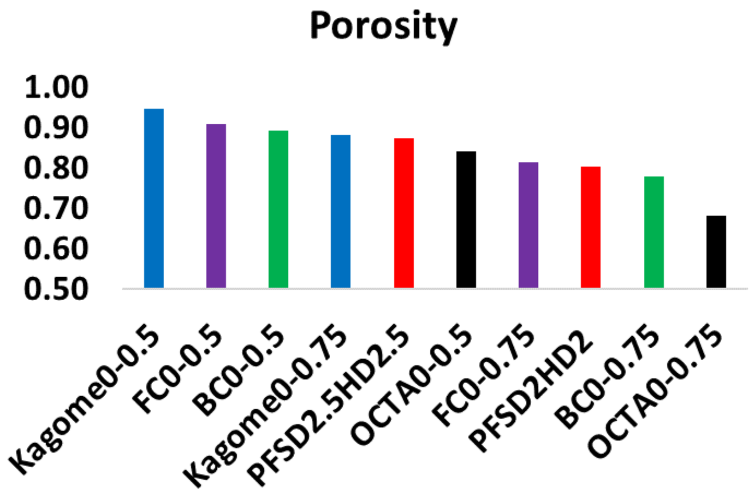
1. Blowing Ratio: M = 0.125, 0.25, 0.5
2. Coolant Temperature: T_c = 21 ℃
3. Mainstream Temperature: T_g = 50 ℃
4. Mainstream Velocity: v_g = 11m/s (Re_g=98,000)
5. Heater power off for T_{aw}

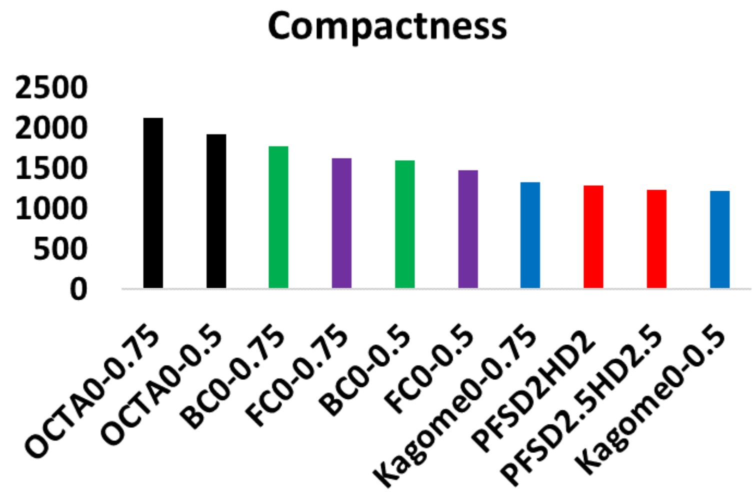


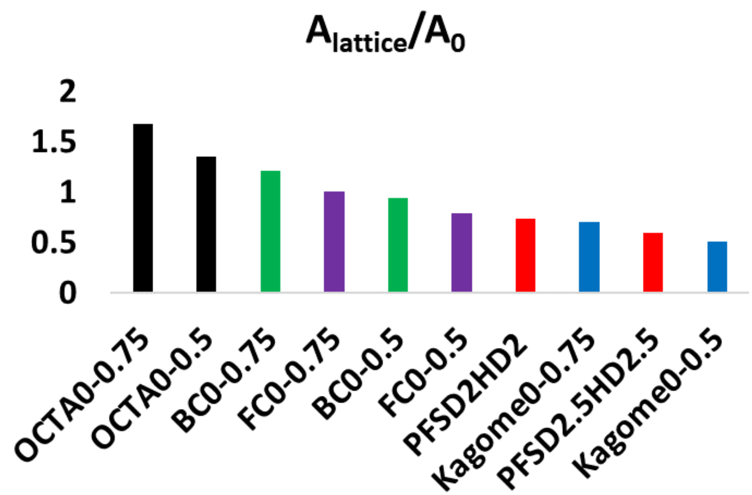
$$\text{Performance factor} = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_0}\right)^{1/3}}$$

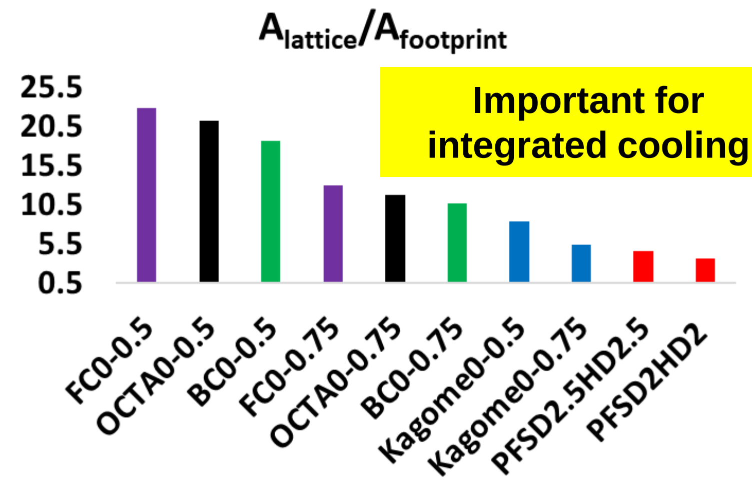
$$Porosity = 1 - \frac{V_{solid}}{V_0}$$

$$Compactness = \frac{A_{wetted}}{V_0}$$





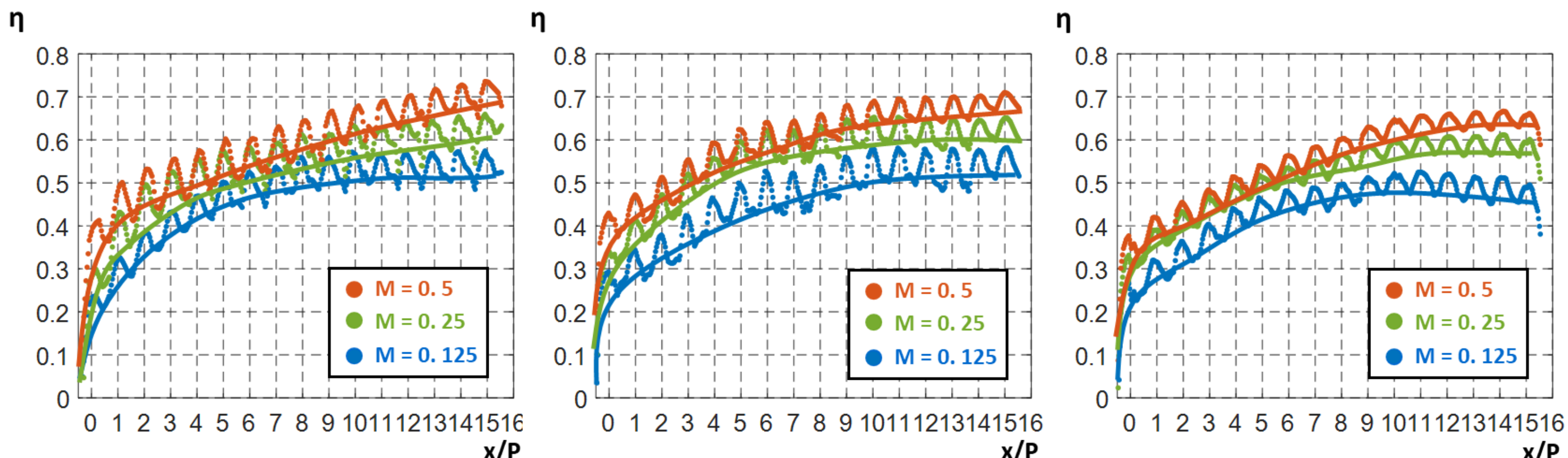




Important for integrated cooling

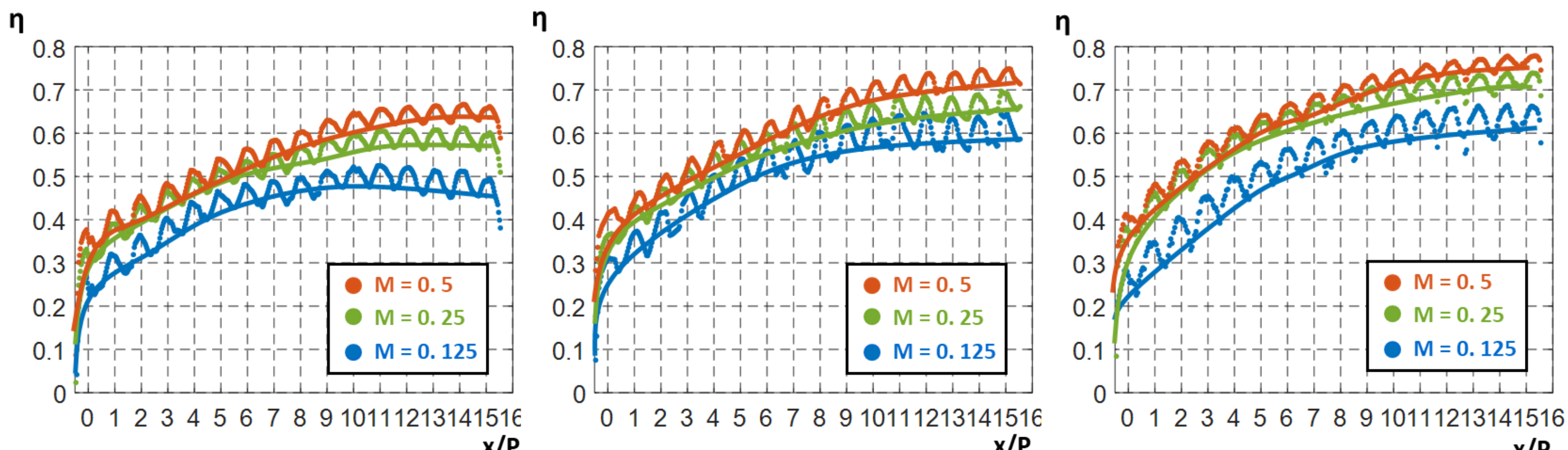
Adiabatic Cooling Effectiveness

Hole size variation:



(a) D = 0.4mm, P = 3D
(b) D = 0.45mm, P = 3D
(c) D = 0.5mm, P = 3D

Hole pitch variation:



(a) D = 0.5mm, P = 3D
(b) D = 0.5mm, P = 2.5D
(c) D = 0.5mm, P = 2D

- Smaller hole size or smaller hole pitch present better performance
- The impact of increasing blowing ratio from 0.25 to 0.5 is not as significant as the increase from 0.125 to 0.25

University of Pittsburgh

HTC

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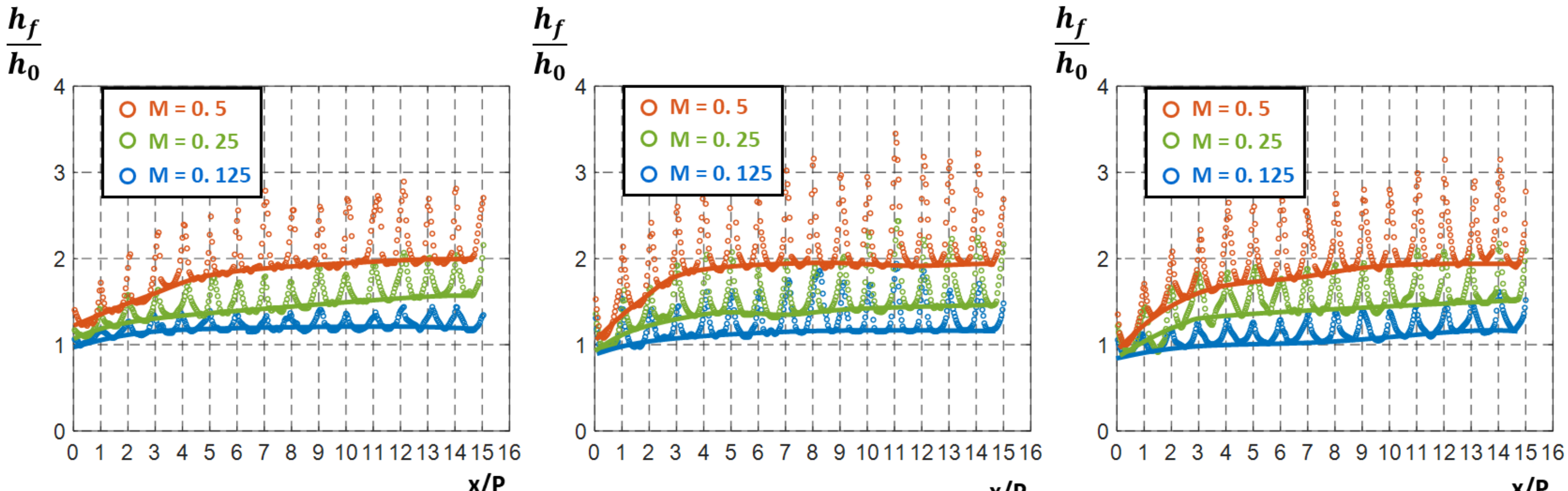
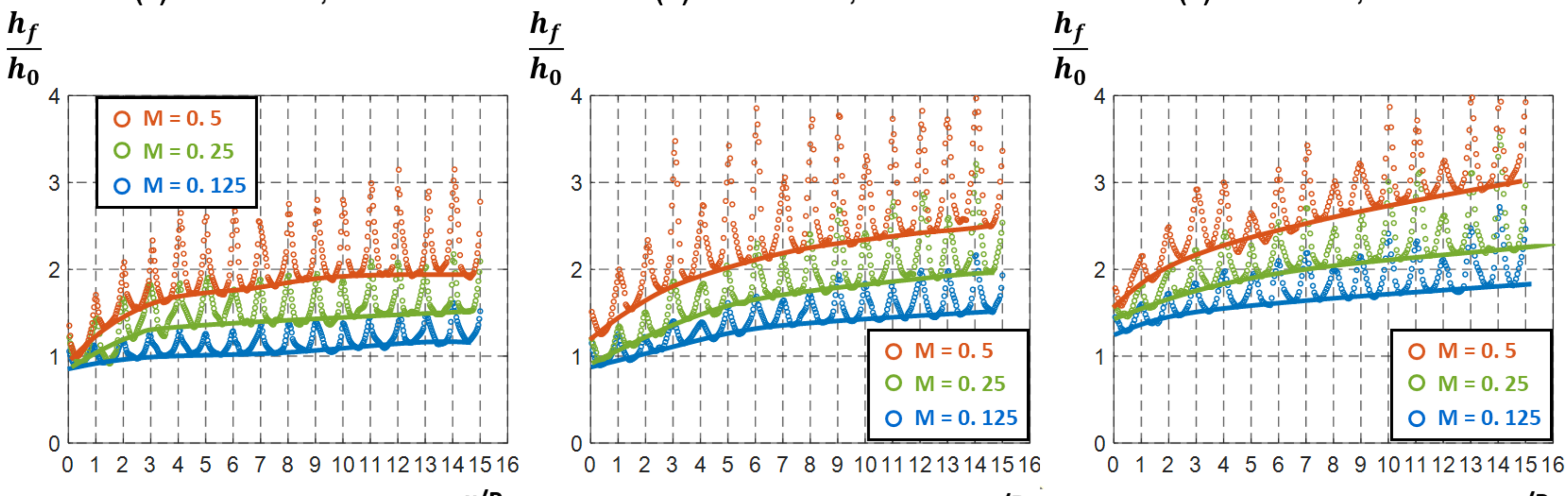
Hole size variation:



(a) D = 0.4mm, P = 3D (b) D = 0.45mm, P = 3D (c) D = 0.5mm, P = 3D

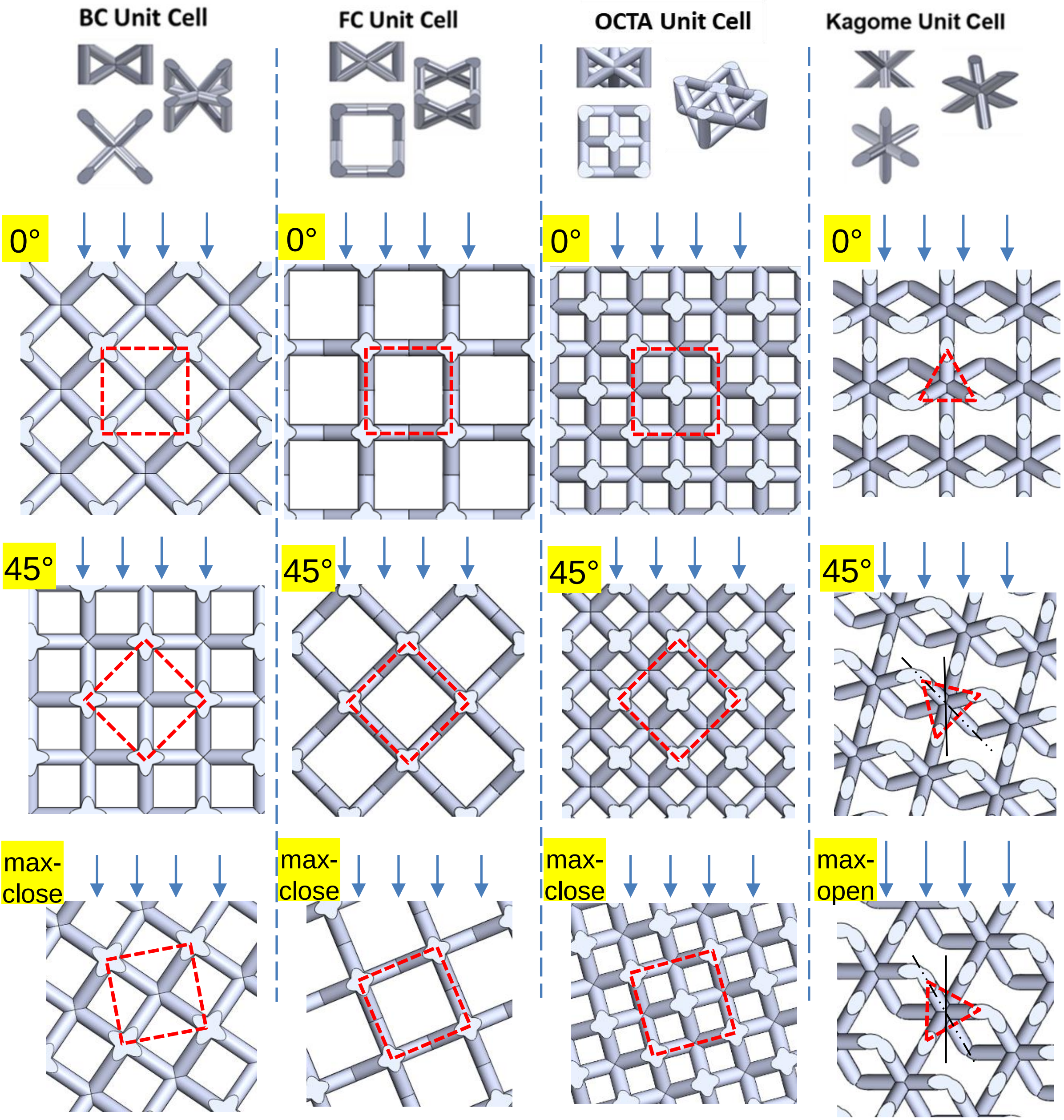
Hole pitch variation:

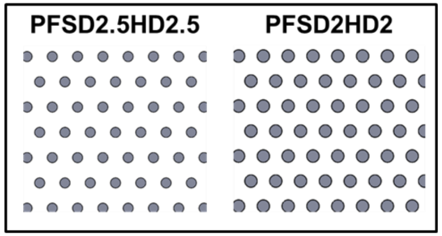


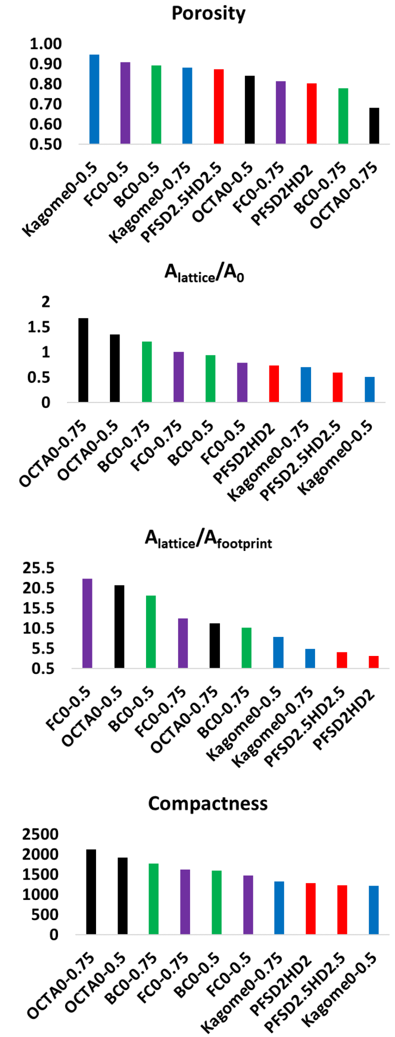
(a) D = 0.5mm, P = 3D (b) D = 0.5mm, P = 2.5D (c) D = 0.5mm, P = 2D

- HTC sensitive to blowing ratio and pitch-to-diameter ratio; but less sensitive to hole size
- Smaller pitch leads to higher HTC, due possibly to interactions between closely adjacent coolant discharge

Lattices from Unit Cells





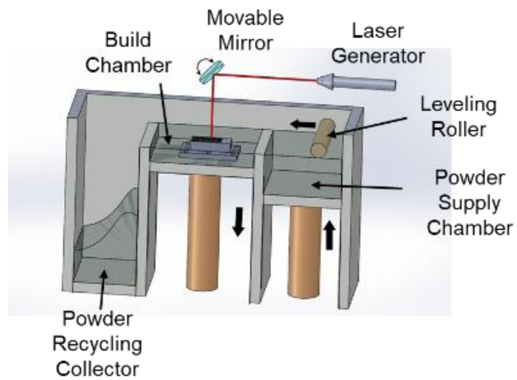


$$Porosity = 1 - \frac{V_{solid}}{V_0}$$

$$Compactness = \frac{A_{wetted}}{V_0}$$

DMLS for ODS

- ➢ Powder bed fusion process using laser
- ➢ Well developed process parameters for Inconel superalloys
- ➢ Challenges regarding ODS powder process development to be mitigated by systematic study



EOS M290

- **Laser Power**: 400W
- **Laser Focal Diameter**: 100μm
- **Scan Speed:** up to 7m/s
- **Printing Material:** Inconel 718 （similar composition to ODS)

- ➢ Fabricated coupons (In718)