NATIONAL ENERGY TECHNOLOGY LABORATORY

University Turbine Systems Research

Integrated Transpiration and Lattice Cooling Systems Developed by Additive Manufacturing with Oxide-Dispersion Strengthened Alloys

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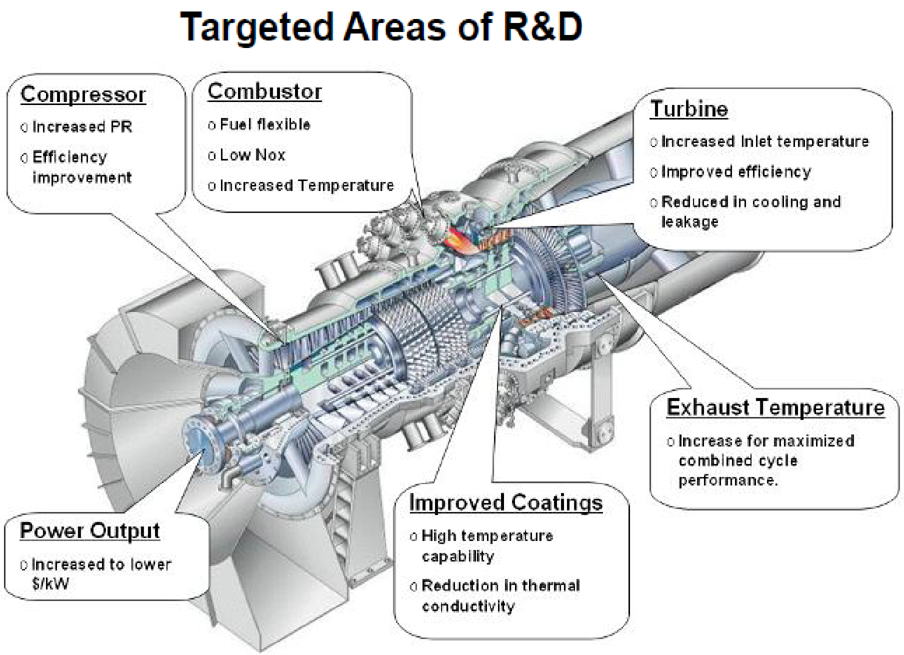
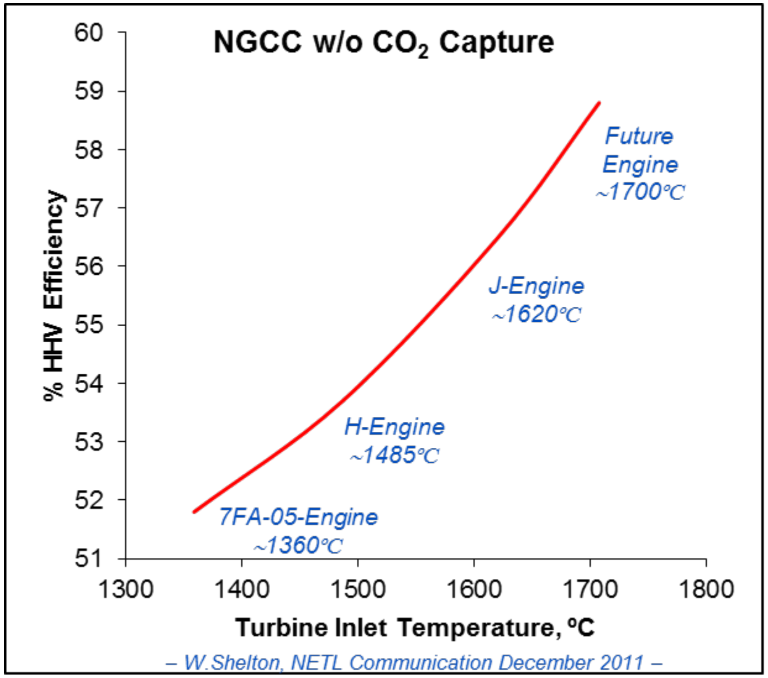
Outlines

- ***Introduction and Background***
- *Challenges, Objectives, Benefits of Technology, Research Task Plan*
- *Tasks*
  1. *Project Management*
  2. *Heat Transfer Characterization*
  3. *Multi-Objective Topology Optimization for Support Structure Design*
  4. *Process Optimization to Fabricate ODS Lattice Structures*
  5. *High Temperature Heat Transfer Characterization*
  6. *Production Process for ODS Powder*
  7. *Thermal Cycling Experiments*

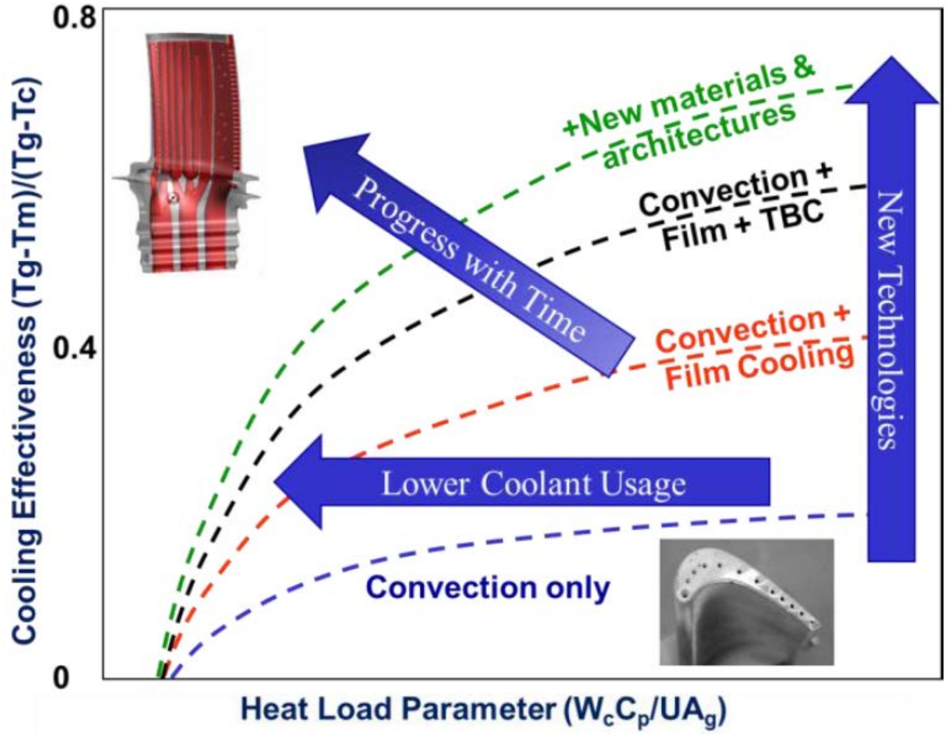
Technical Background



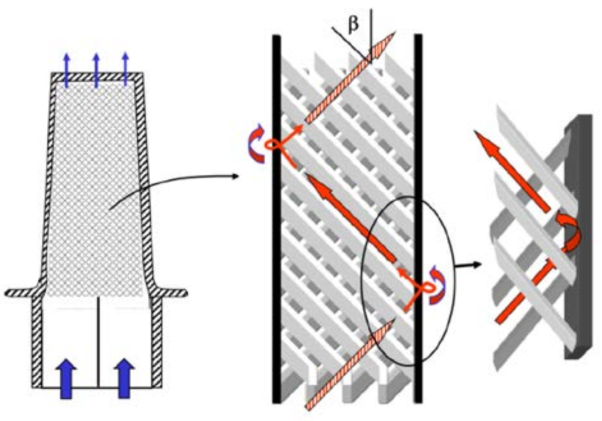


Advanced turbine development calls for higher efficiency with higher turbine inlet temperature

Turbine Thermal Management
– Advanced Cooling via Lattice Structures and Transpiration Cooling

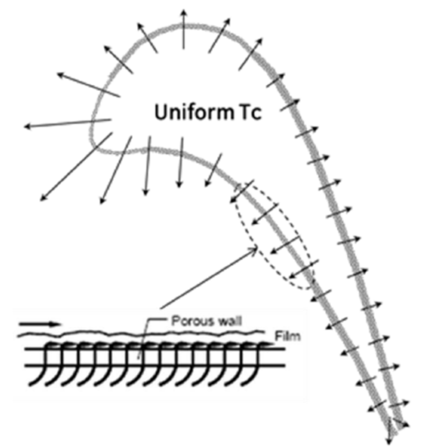


Bunker RS. Evolution of Turbine Cooling. ASME. Turbo Expo: Power for Land, Sea, and Air, Volume 1: Aircraft Engine; Fans and Blowers; Marine; Honors and Awards ():V001T51A001. doi:10.1115/GT2017-63205.



Lattice Cooling

Bunker, R.S., "Latticework (Vortex) Cooling Effectiveness Part 1: Stationary Channel Experiments", Paper No. GT-2004-54157, IGTI Turbo Expo, Vienna, Austria, 2004.



Transpiration Cooling

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.

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Integrated Lattice and Transpiration Cooling

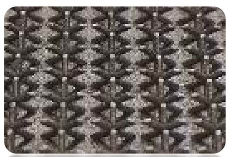
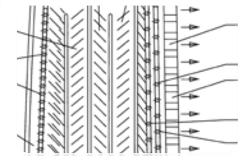
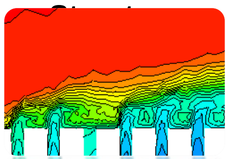
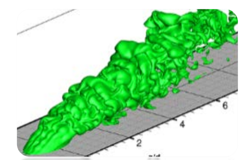
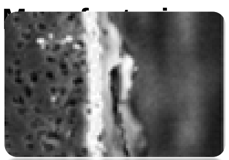
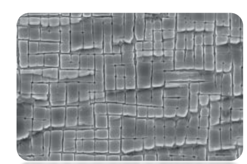
Technical Challenges

- *Enhance the cooling efficiency dramatically*
- *Achieve feasible mechanical properties for lattice-transpiration structure*
- *Manufacture complex geometry with ODS*

Project Objectives

- **1. To design highly efficient and manufacturable cellular lattice structure for the integrated transpiration and internal cooling which has an overall averaged cooling efficiency of more than 0.6.**
- **2. To produce ODS particles with proper sphericity and spreadability, which will be used in additive manufacturing (AM) processes to build lattice test modules.**
- **3. To develop multi-objective topology optimization algorithm for controlling residual stress induced cracking and distortion in lattice structure.**
- **4. To develop fabrication process through additive manufacturing for fabricating lattice structures for internal cooling, transpiration cooling and their integration.**
- **5. To characterize the thermal-mechanical material properties and cooling performance of the AM produced ODS integrated transpiration and internal cooling module under high-temperature conditions.**

Benefits of Technology to the DOE Turbine Program

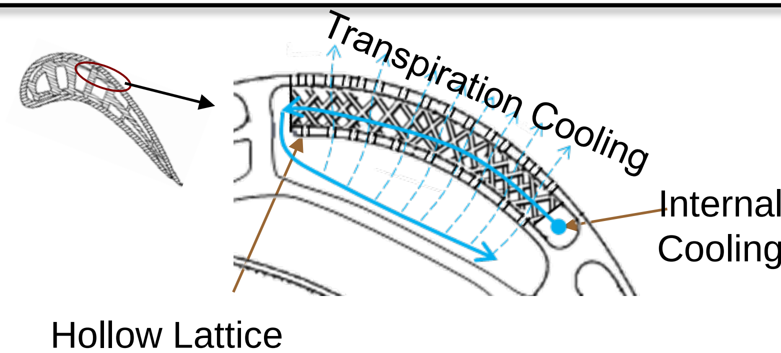
	Cooling Effectiveness	Mechanical Property	Oxidation Resistance	Anti-Blockage	
 Lattice	↑	↓		↓	 Serpentine Channels
 Transpiration Cooling	↑	↓	↓	↓	 Film Cooling
 Additive	↑	–		↑	 Investment Casting
 ODS		↑	↑	↑	 Supperalloy

- ❑ Scientific Advancement
- ❑ Turbine industry
- ❑ Additive manufacturing community

Project Work Breakdown Structure

Enhanced Thermal Protection

- *Lattice and transpiration combined conjugate cooling*
- *~2x of state-of-the-art film cooling.*



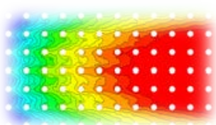
Integrated Transpiration and Lattice Cooling Systems

Novel Metallic ODS Lattice Structure

- *Ultra-High Temperature (1200 ℃) Strength*
- *Oxidation Resistance*
- *Additive-manufacturing assisted technology*

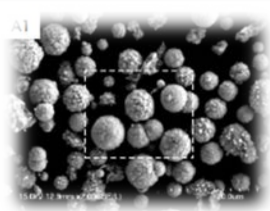
Task 2 – Heat Transfer Characterization

- *Design, CFD modeling & scaled testing*
- *Mini/micro scale cellular units*



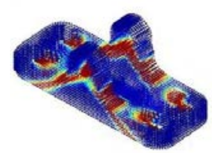
Task 6 – ODS Powder Fabrication and Characterization

- *ODS powders fabrication*
- *Characterization*



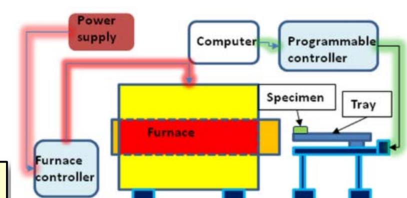
Task 3 – Multi-Objective Topology Optimization

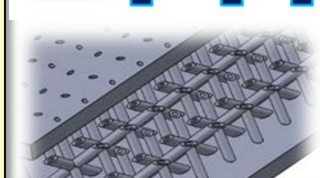
- *Geometry development and optimization*



Task 7 – Thermal Cyclic Testing

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

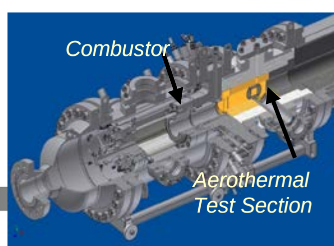




Task 5 – High Temperature Heat Transfer Characterization

High Temperature, Pressurized Testing (NETL)

- *High Temperature Testing Facilities (Solar Turbines, Inc.)*



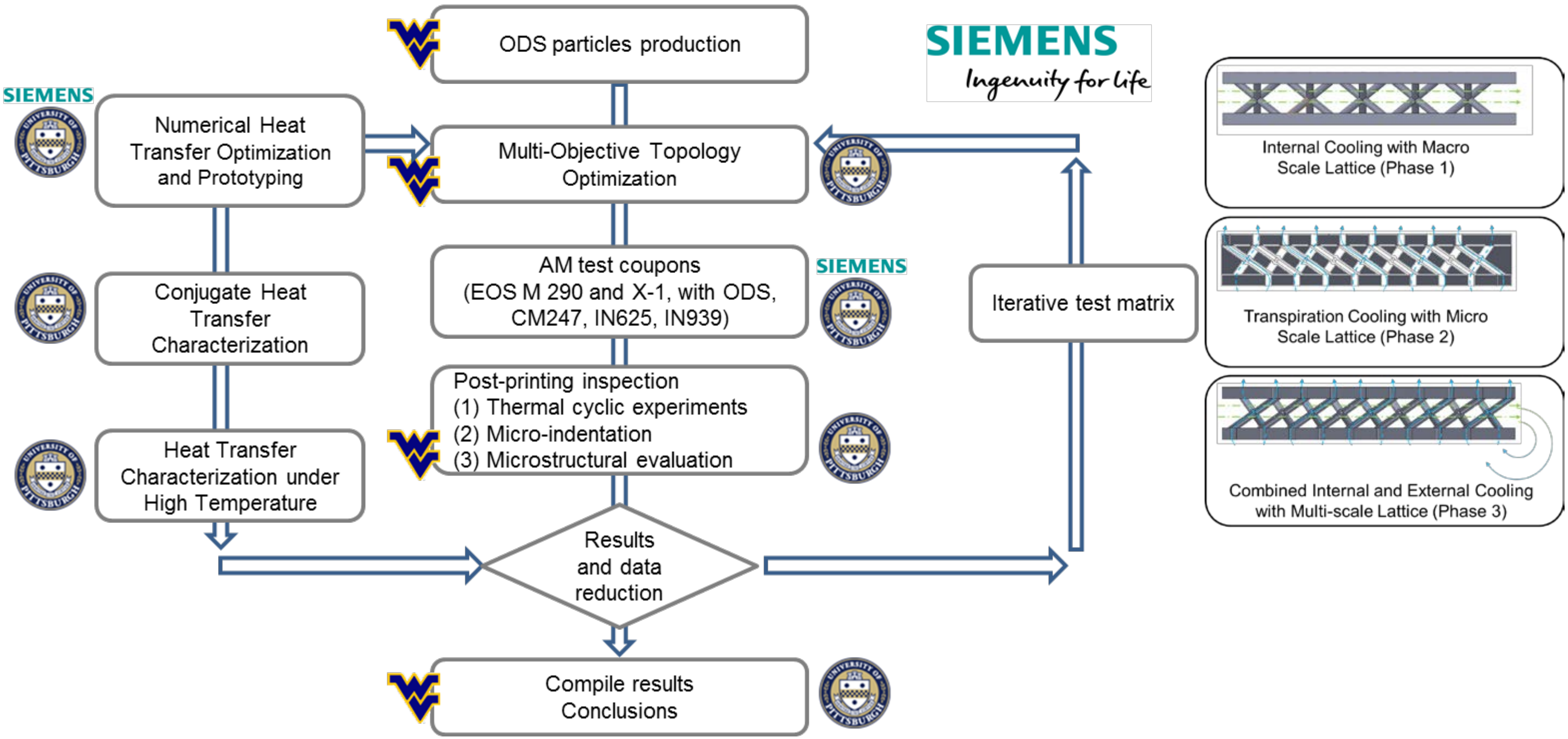
Task 4 – Process Optimization to Fabricate ODS Lattice Structures

- *Printing parameters*
- *Posting printing characterization*
- *OM, SEM,*

Research Task Plan

Integrated Transpiration and Lattice Cooling Systems developed by Additive Manufacturing with Oxide-Dispersion-Strengthened (ODS) Alloys

Research Task Plan (3 years)



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Task 2: Heat Transfer Characterization

Objective: Design highly efficient and manufacturable cellular lattice structure for the integrated transpiration and internal cooling which has an overall averaged cooling efficiency of more than 0.6.

- Integrated lattice and transpiration cooling

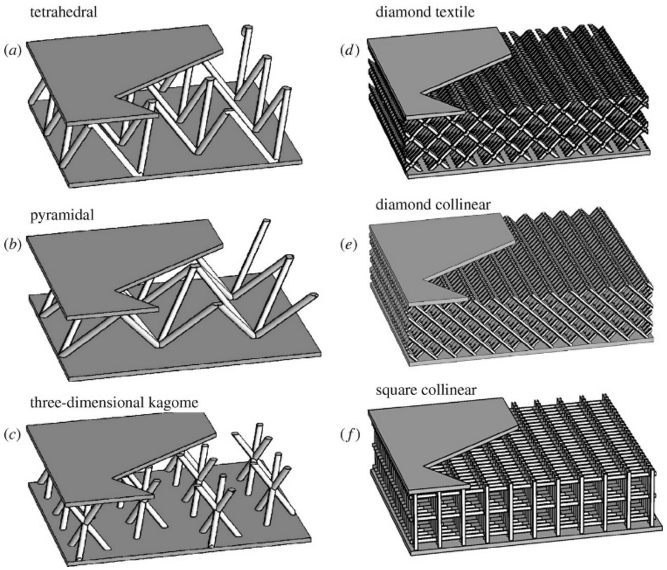
Challenges:

- Manufacturability :consider constrains of additive manufacturability.
- Cell Unit: identify optimal unit geometry for lattice structure.
- Topology: obtain optimal topology to achieve high cooling efficiency.

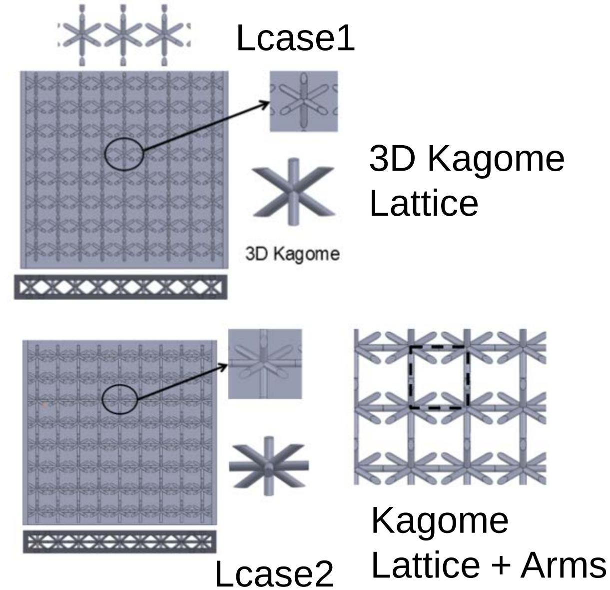
Approach:

- Basic measurement for unit cell.
- Topology optimization to fabricate prototypes. (part of Task 4)
- Iterative heat transfer characterization and modification, numerically.
- Experimental characterization and iteration.

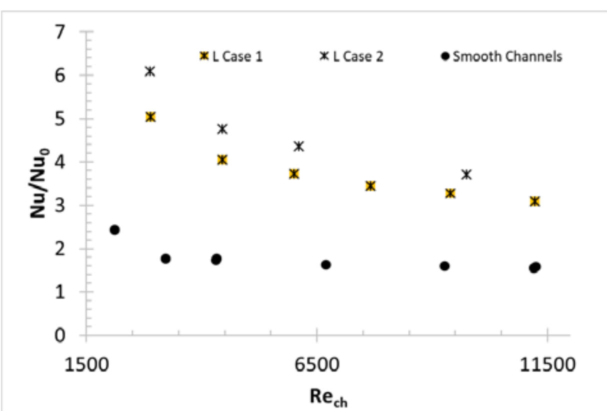
Cellular Unit for Lattice Structure

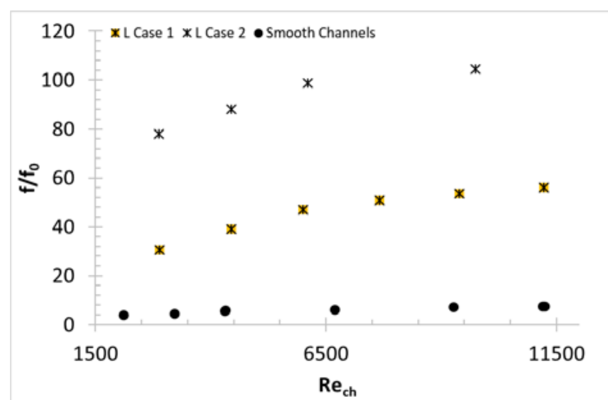


Lu, T. J., Xu, F., Wen, T.,2013 , "Thermo-Fluid Behaviour of Periodic Cellular Metals", Science Press Beijing, Springer.



Kagome Lattices





Preliminary tests:

- Nu and f increases with number of arms.
- Lcase2 **~13%** higher Nu and 90% high f than Lcase1

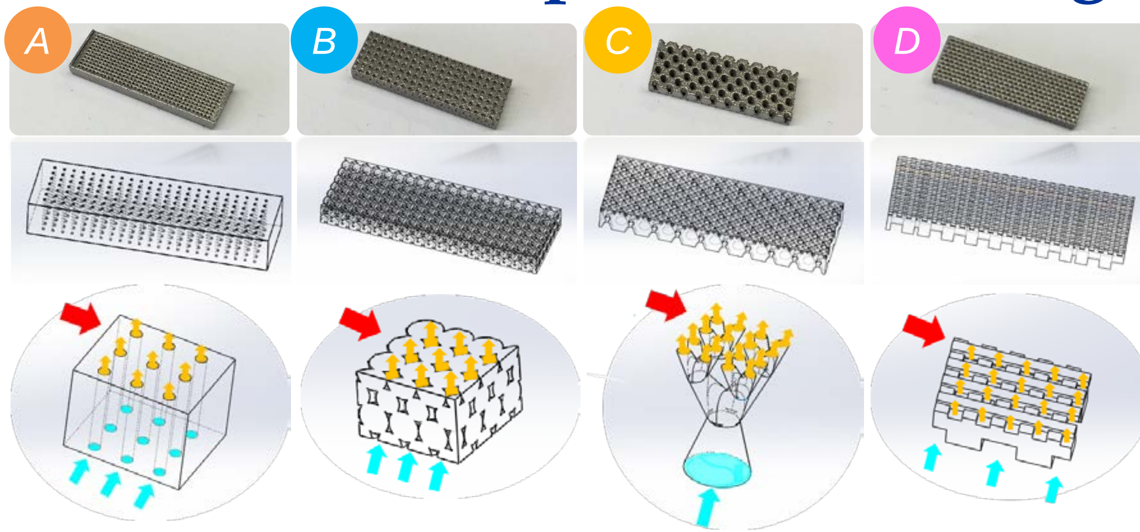
Additive Manufactured Transpiration Cooling

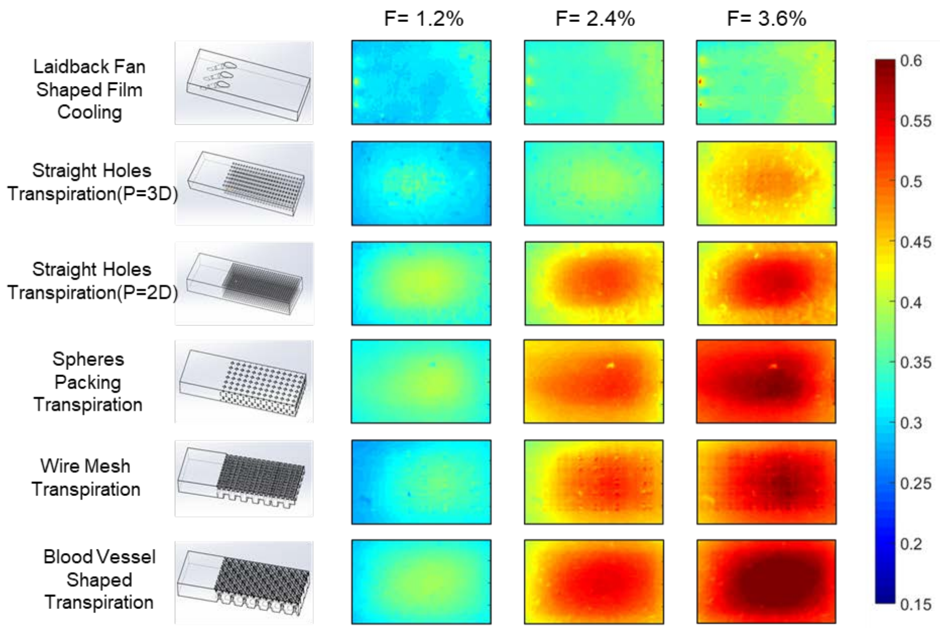
Type A: *Straight Holes*

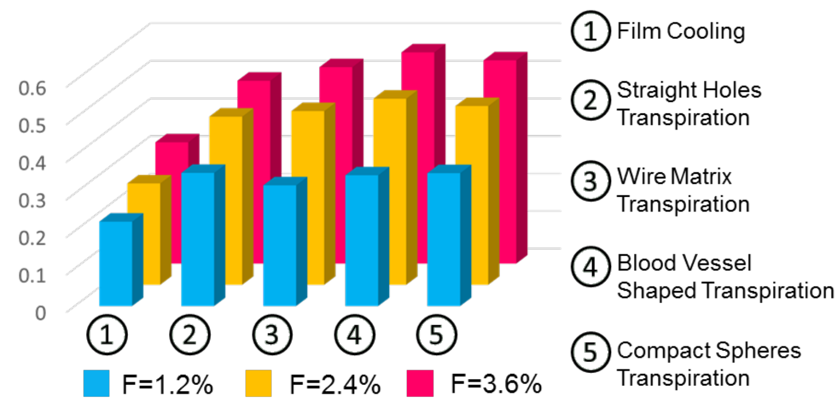
Type B: *Compact Spheres*

Type C: *Blood Vessel Shaped*

Type D: *Wire Matrix*





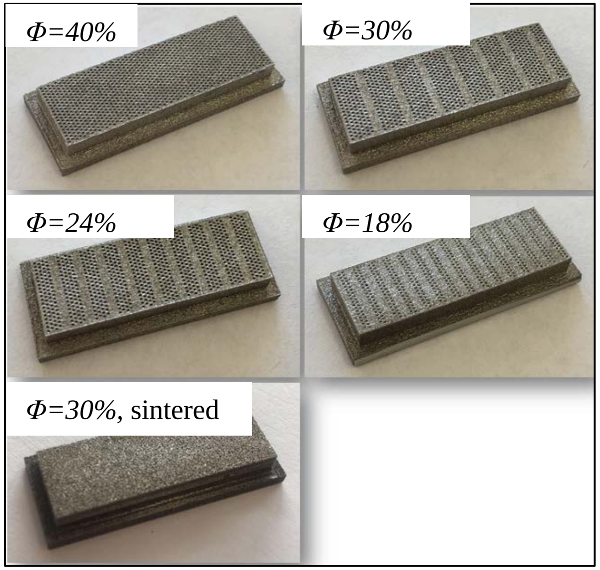


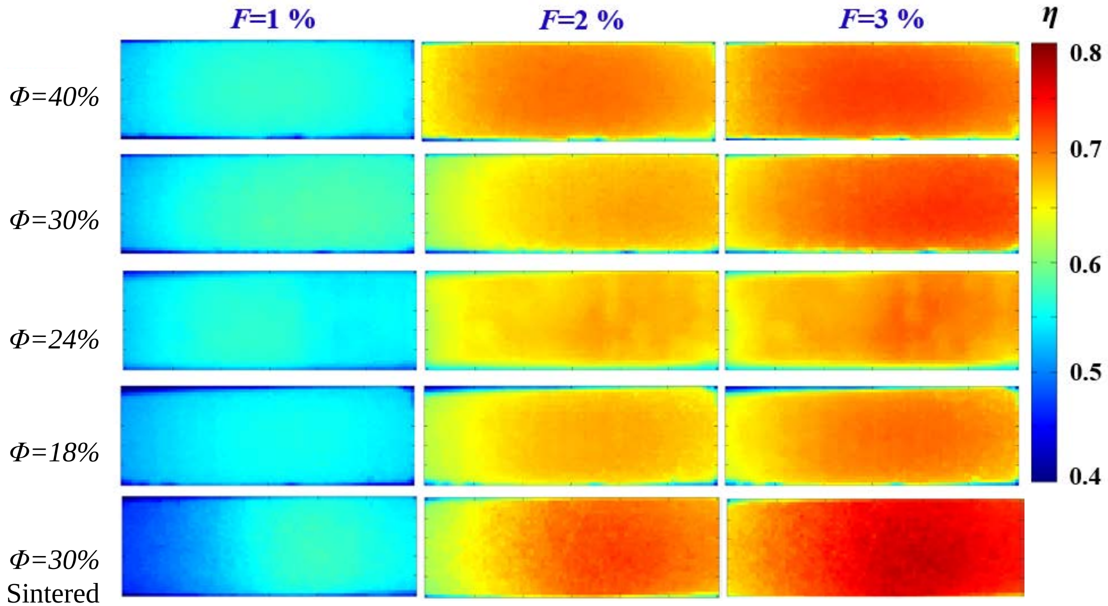
Cooling Efficiency Comparison against Film Cooling

Preliminary tests:

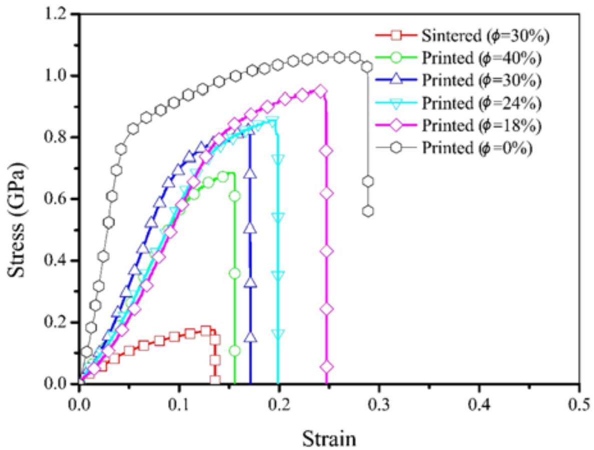
- Transpiration cooling could further enhance the conjugate cooling efficiency by 0.3 on top of film cooling.
- The "Blood Vessel" type with the largest internal surface area had the highest cooling efficiency among the test coupons.

Enhance Mechanical Strength for Transpiration Cooling with Partition Wall





Cooling Efficiency Comparison against Sintered Porous Media



Tensile Strength Comparison against Sintered Porous Media

Preliminary tests:

- Ultimate tensile strength increased by 440% comparing additive manufactured porous media and traditional sintered porous media.
- Partition wall could reinforce the porous media while causing minimal influence on cooling efficiency.

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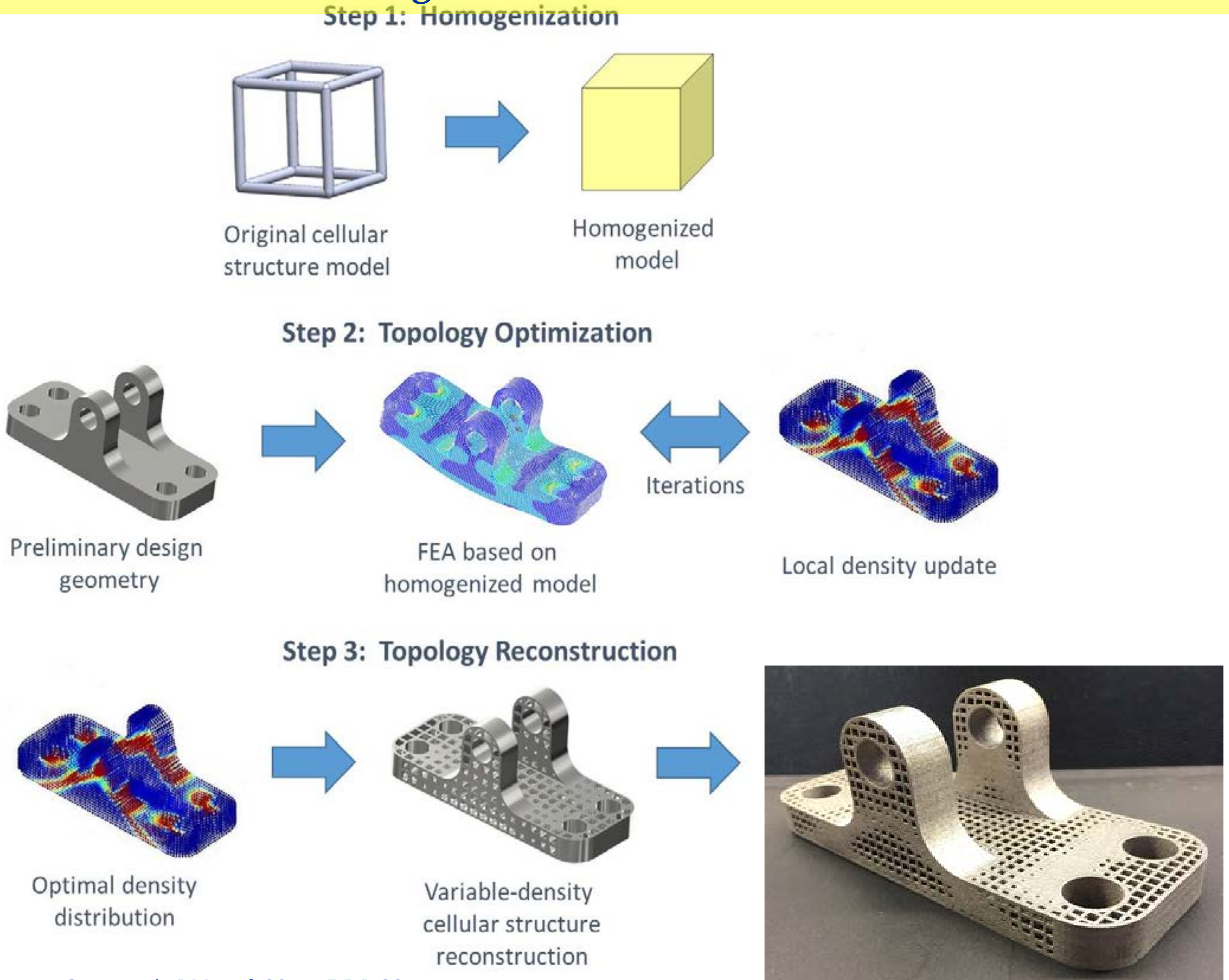
Task 3: Multi-Objective Topology Optimization for ODS Lattice Structure

Objective: Develop multi-objective topology optimization algorithm for controlling residual stress induced cracking and distortion in lattice structure.



- Eliminate the need to use very fine mesh to resolve the cellular structures

AC To et al, *J Manuf,* 2015; *RPJ*, 2017

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Task 4: Fabrication of ODS lattice Structures

Objective: Develop fabrication process through additive manufacturing for fabricating lattice structures for internal cooling, transpiration cooling and their integration.

Approach

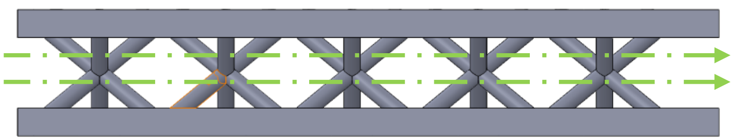
- *Produce a series of cellular lattice structures with ODS.*
- *Three phases: from macro to micro scale lattices, and eventually achieve combined multi-scale geometries.*

EOS M290

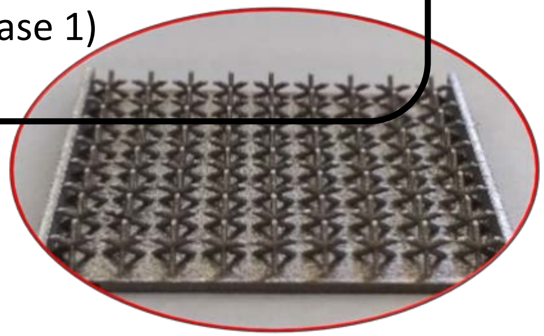
LENS 450

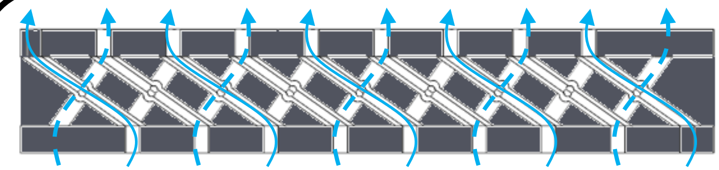
X1-Lab

Approaches to Fabricate ODS Lattice Structures

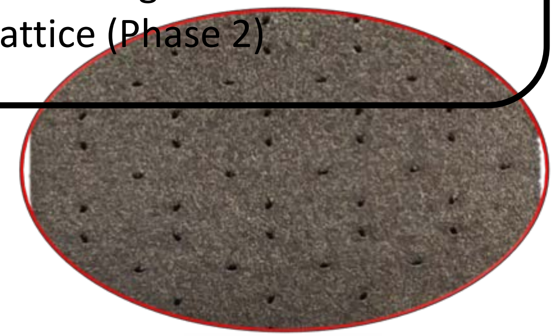


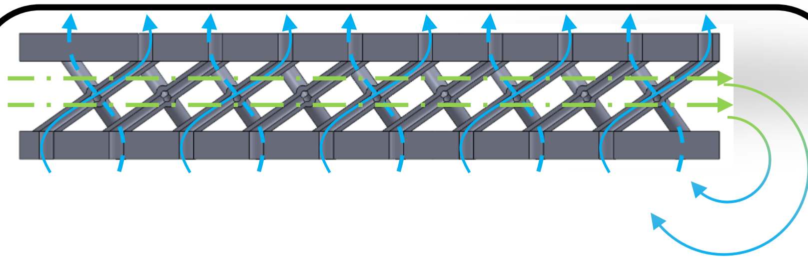
Internal Cooling with Macro Scale Lattice (Phase 1)



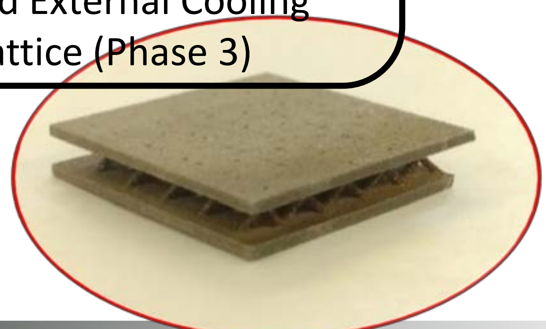


Transpiration Cooling with Micro Scale Lattice (Phase 2)





Combined Internal and External Cooling with Multi-scale Lattice (Phase 3)



Challenges:

- AM process parameters for ODS.
- Control dimensions and deformation.
- Identify minimum limitation of pore diameters.

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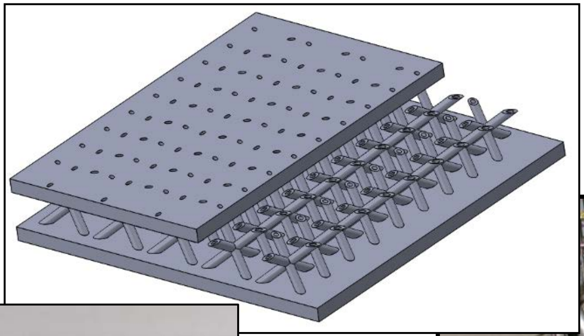
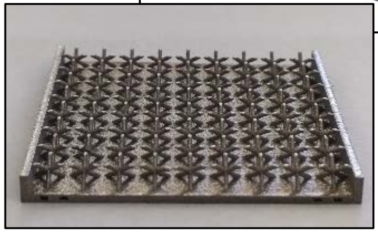
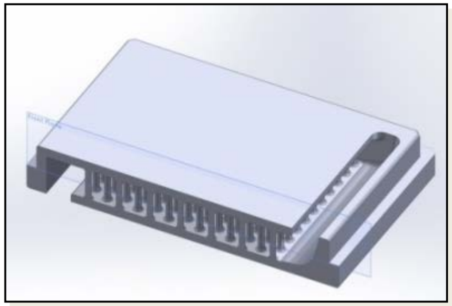
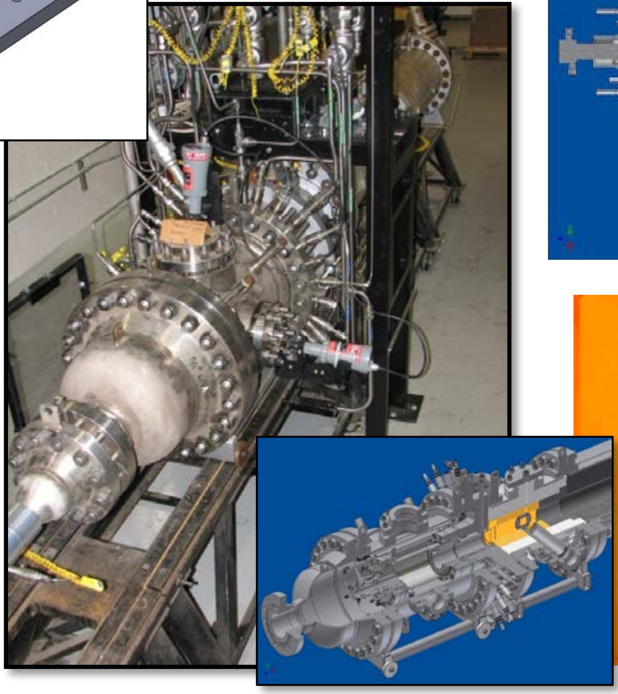
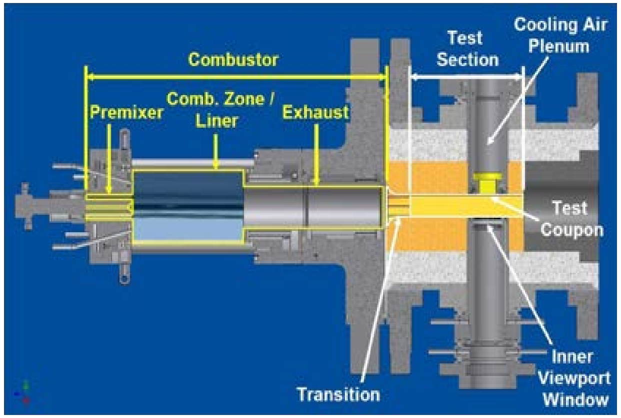
Task 5: High Temperature Experimental Measurements and Validation

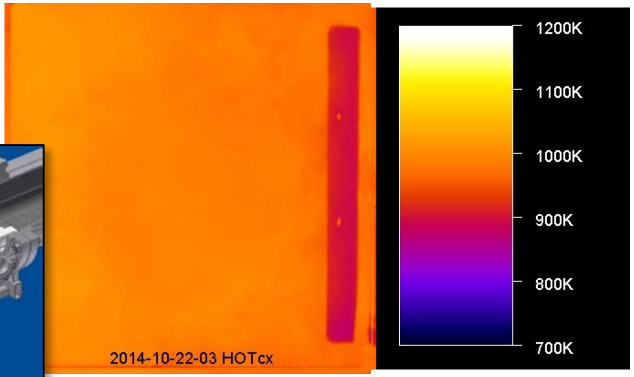












- ➢ Conduct HT/P testing at 1100°C for integrated lattice and transpiration cooling
- ➢ Further optimization of the lattice structures for enhanced cooling performance
- ➢ Address additive manufacturing capabilities for production of parts

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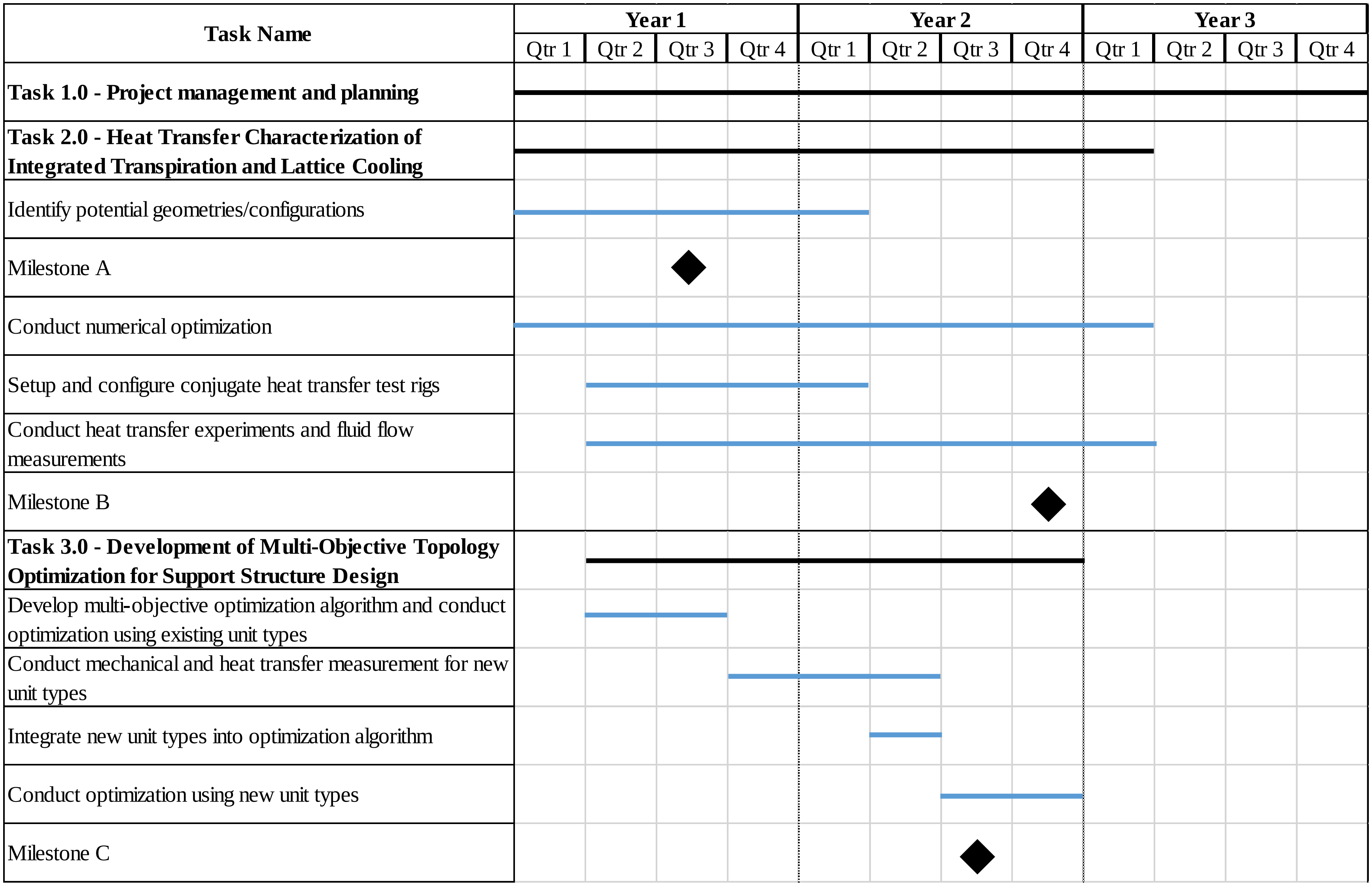
Project Timeline

SIEMENS
Ingenuity for life



Project Timeline

Task Name	Year 1				Year 2				Year 3			
	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Task 4.0 - Development and Process Optimization to Fabricate ODS Lattice Structures	—	—	—	—	—	—	—	—	—			
Identify the AM process parameters for ODS			—	—	—	—						
Explore capabilities of additive manufacturing to make lattice structures using Nickel based superalloy powders and ODS	—	—	—	—								
Milestone D				◆								
Development and process optimization for ODS Lattice Structure					—	—	—	—	—	—		
Milestone E										◆		
Task 5.0 - High Temperature Heat Transfer Characterization									—	—	—	—
Milestone F												◆
Task 6.0 - Develop Production Process for ODS Powder	—	—	—	—	—	—	—	—	—	—		
Develop optimal process parameter to produce ODS powder	—	—	—	—	—	—	—	—	—	—		
Characterize the powder particle size distribution, sphericity and spreadablity		—	—	—	—	—	—	—				
Milestone G								◆				
Task 7.0 - Conduct Thermal Cycling Experiments on ODS Alloy Specimens					—	—	—	—	—	—	—	
Thermo-fluid characterization on ODS Lattice Structure after thermal cyclic tests					—	—	—	—	—	—		
Mechanical characterization on ODS Lattice Structure after thermal cyclic tests					—	—	—	—	—	—		
Milestone H										◆		

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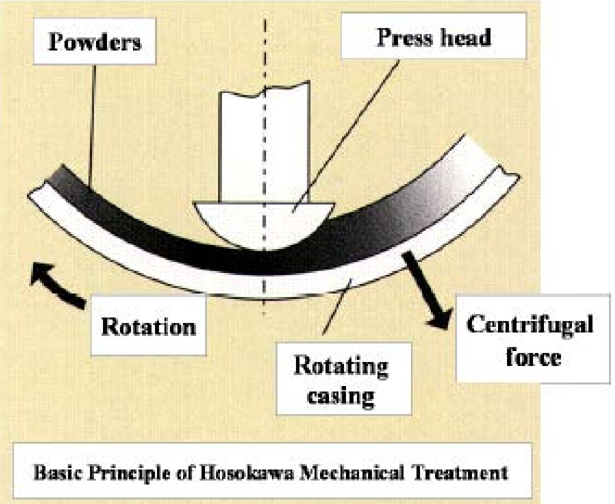
Task 6: ODS Powders Fabrication and Characterization

Objective: Produce ODS particles with proper sphericity and spreadability, which will be used in additive manufacturing (AM) processes to build lattice test modules.

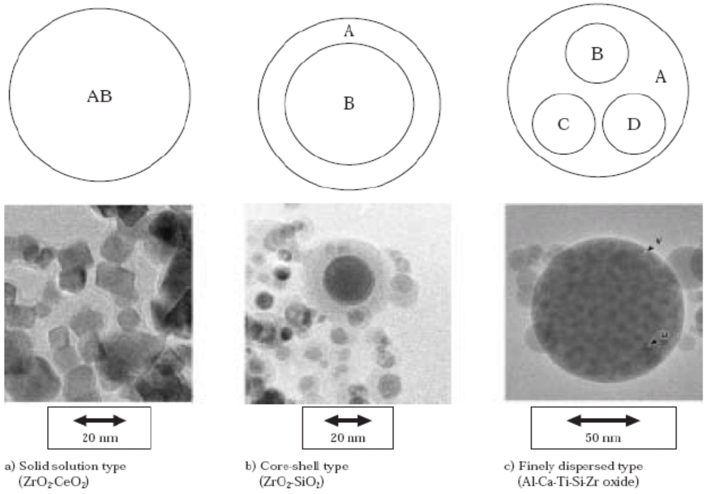
Approach

- Powder mechanical alloying using **Hosokawa Mechano-Chemical Bonding (MCB)** followed by **Ball Milling (BM)**
  - For MCB, powders are subjected to substantial compression, shear, mechanical forces under high rotating condition (~**4000 rpm**), through a gap between chamber and press head
  - Enable smaller particles to be dispersed uniformly and bonded onto base(host) particles without using binders.
  - Improved particle sphericity, ideal for precision mixing of nano and submicron powders.
  - Grain boundaries of host particles are pinned by nai
  - minimized grain growth during sintering.

Why MCB + BM?



Basic Principle of Hosokawa Mechanical Treatment

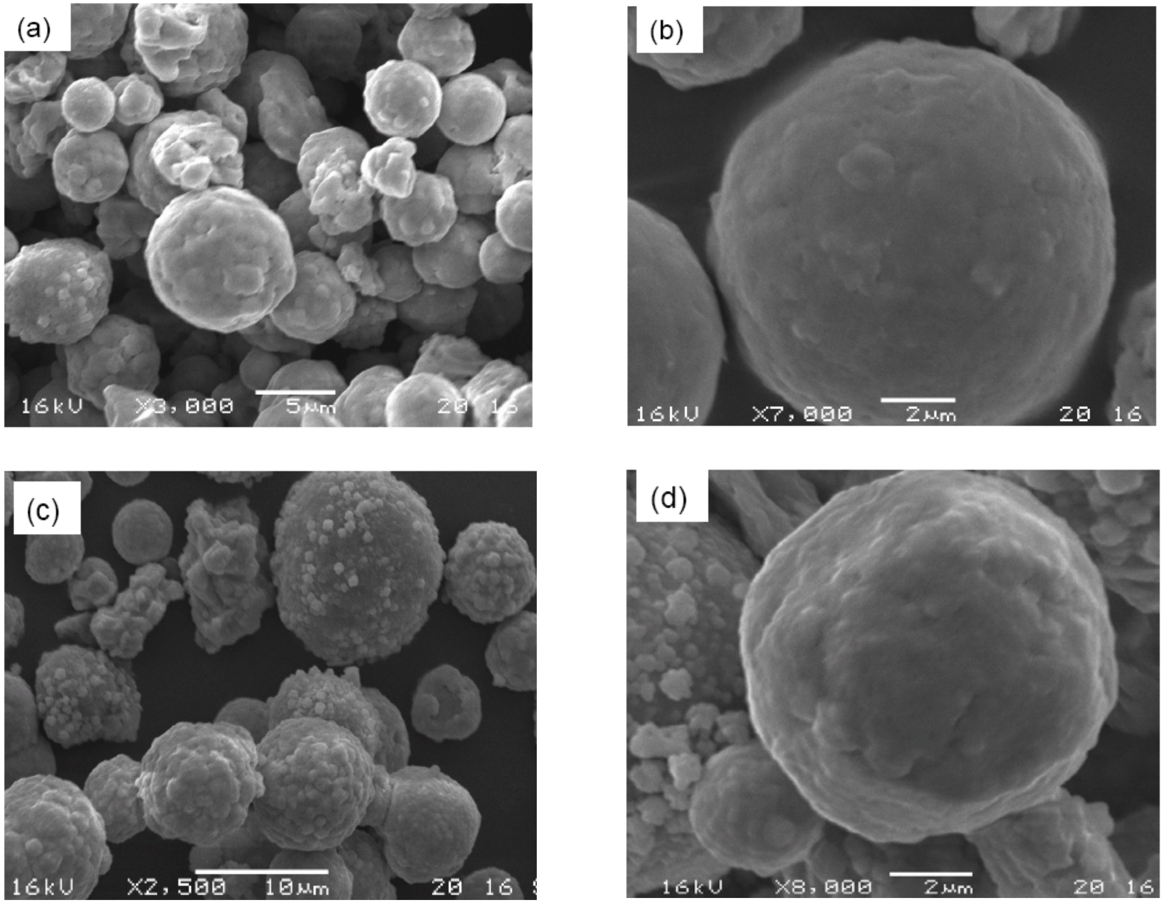


Structural patterns of nanocomposite particles
[T. Yokoyama and C. C. Huang, KONA No.23 (2005)]

Kang, B.S., Chyu, M.K., Alvin, M.A., and Gleeson, B.M, "Method of Producing an Oxide Dispersion Strengthened Coating and Micro-Channels," US Patent 8609187 B1, 17, 2013

ODS Powder Compositions (in weight %)

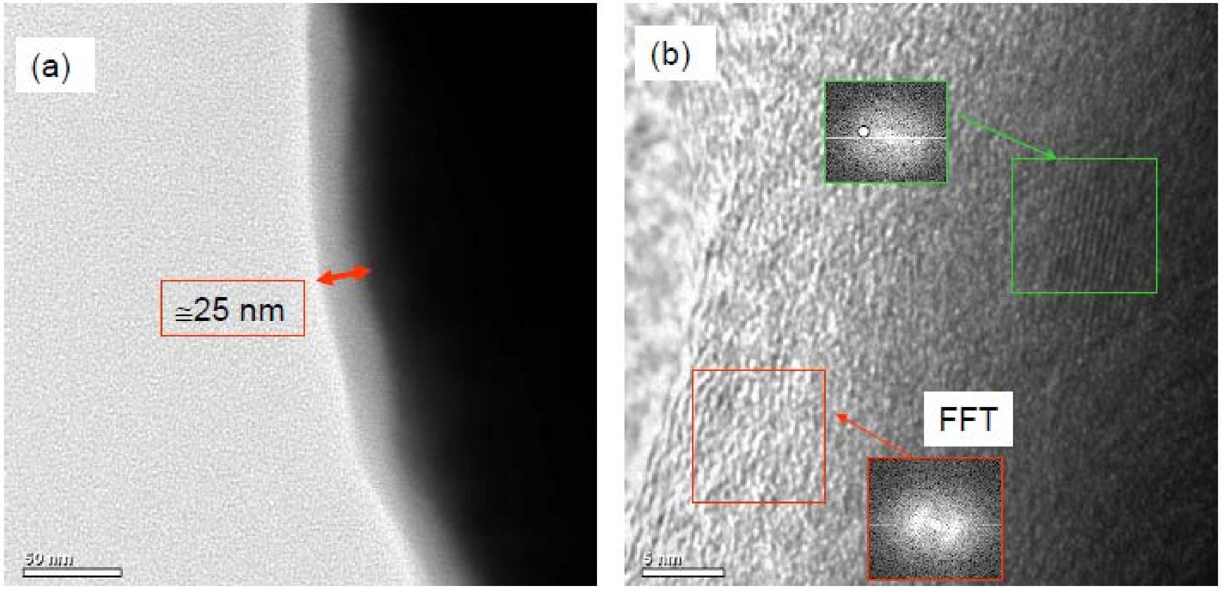
	Cr (7.5~10 μm)	Al (4.5 ~ 7 μm)	Y_2O_3 < 50nm	W (~1 μm)	Ni (4 ~ 8 μm)
A1	20	5	1.5	0	73.5
A2	20	5	1.5	3	70.5



SEM micrographs of MCB processed powder sample A1 and A2
(a). Sample A1; (b) close view of (a); (c) sample A2; (d). close view of (c)

ODS Powder Characterization

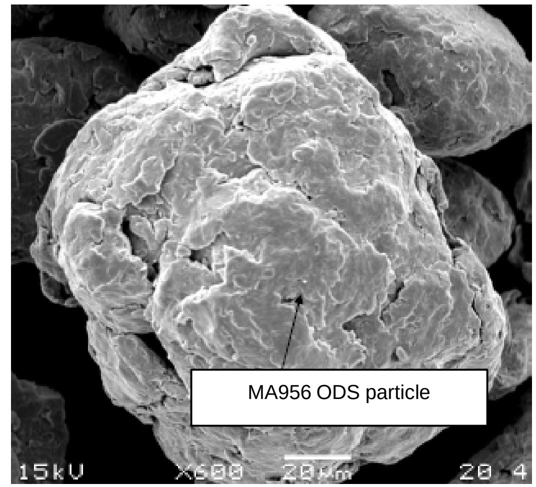
TEM BF and HREM imaging – A1 Sample

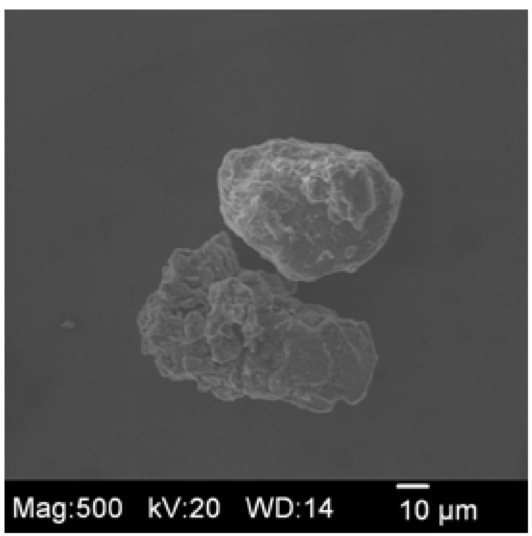


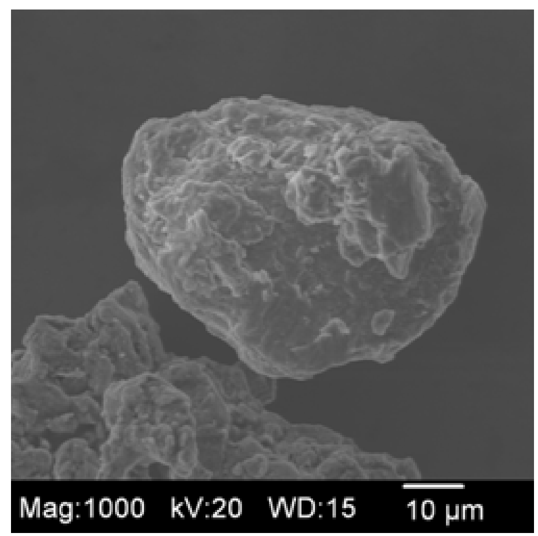
- TEM BF image (a) shows a layer of Y_2O_3 thin film with thickness about 25nm around the edge of particle. The film thickness is relatively homogeneous.
- HREM image (b) shows the fine structure of the thin film. Most area of the film is amorphous and the corresponding FFT (Fast Fourier Transform) image show the diffusive feature.
- There is crystal structure within film as FFT indicated. The embedded FFT shows the spots and image shows the orientation fringe. The growth of film may involve crystallization of Y_2O_3.

Comparison between MA956 and ODS Powder

MA 956 ODS sample ***(Special Metals Inc.)***

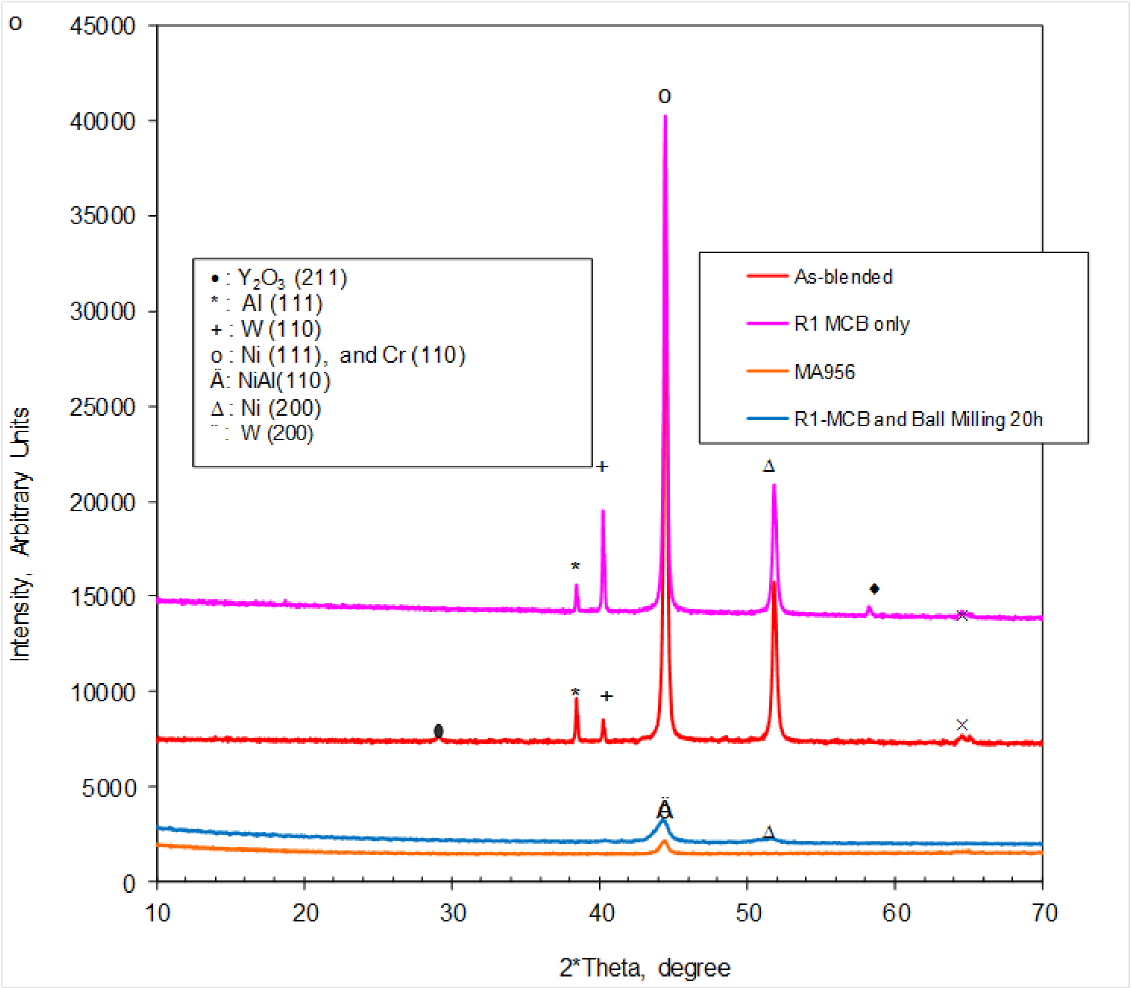




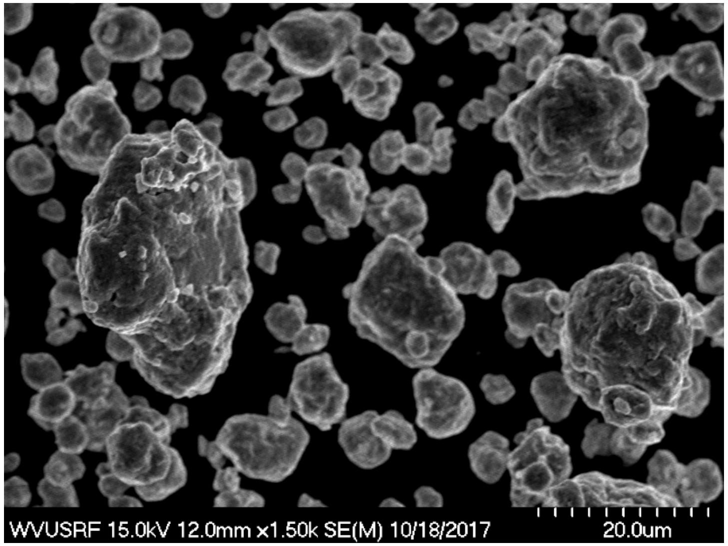


R1 sample with 15 hrs ball milling

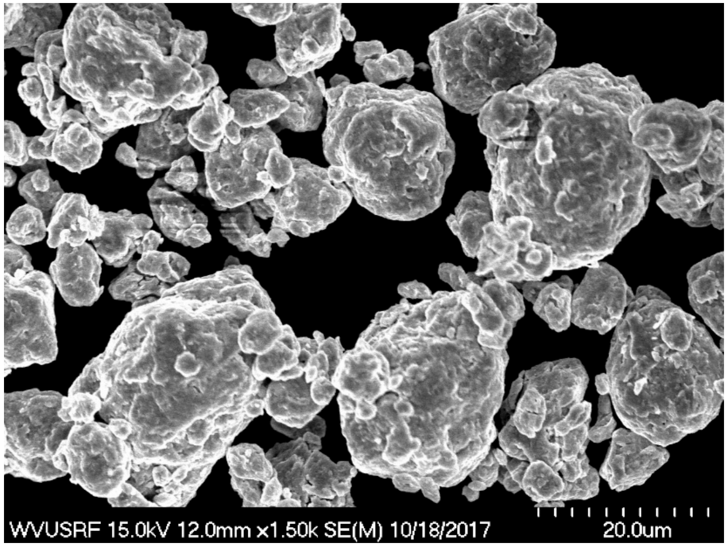
XRD Characterization of ODS Powder



Ball Milled ODS Powders after MCB processing at 400 rpm for 15 and 25 hours

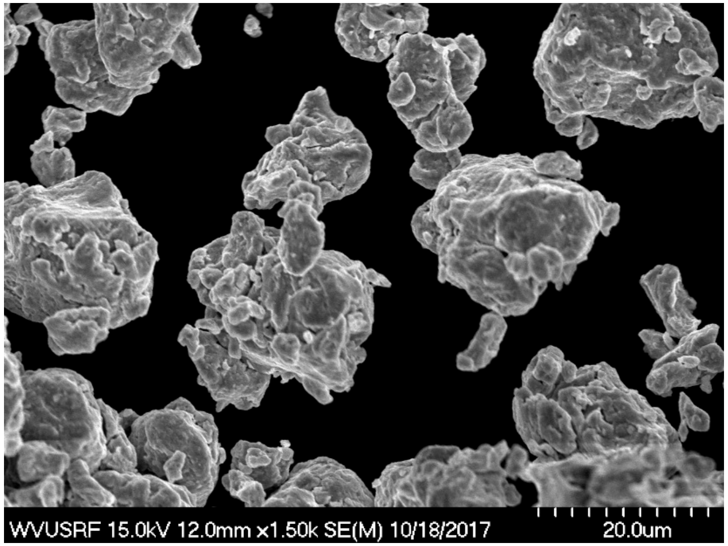


15 hours

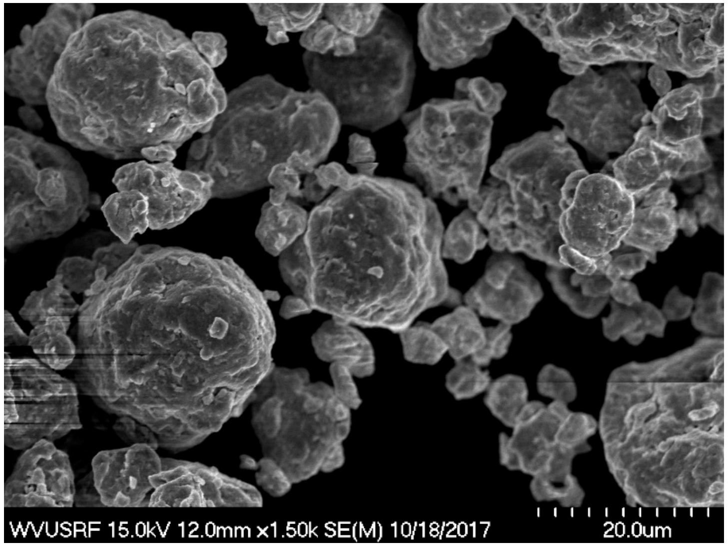


25 hours

Ball Milled ODS Powders after MCB processing at 400 rpm for 30 and 40 hours

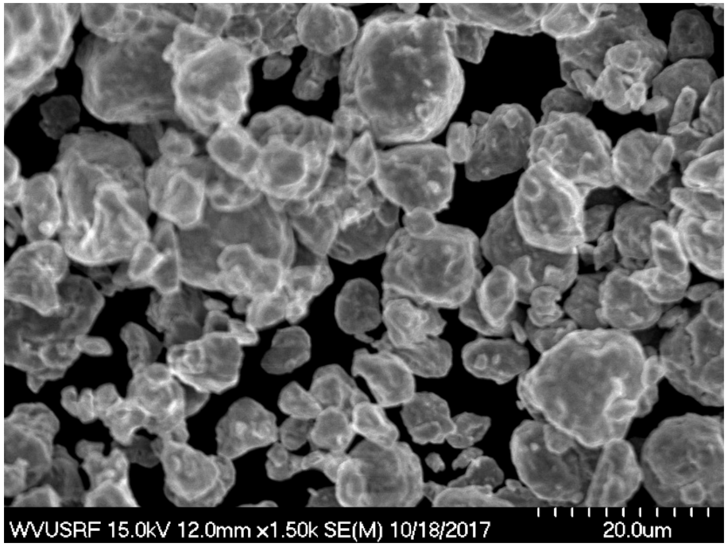


30 hours



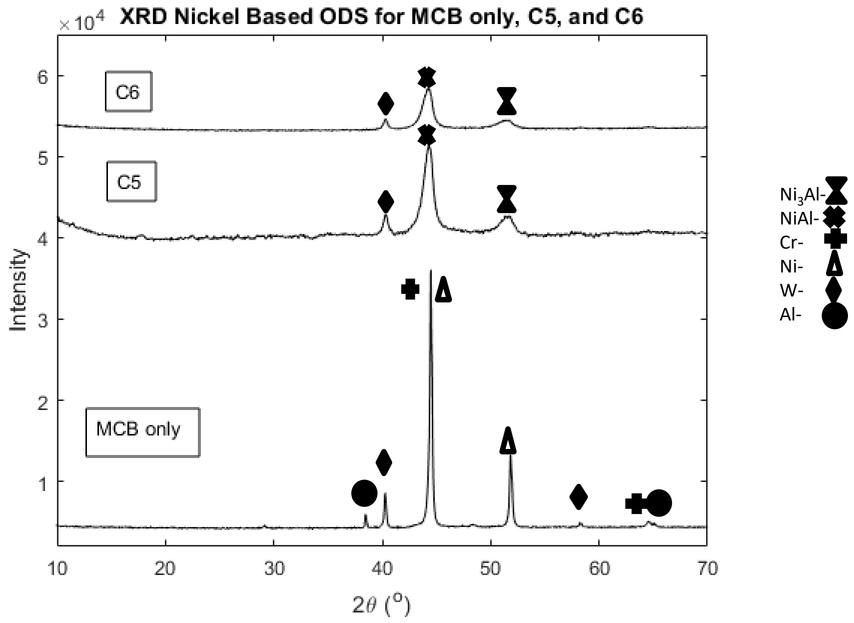
40 hours

Ball Milled ODS Powders after MCB processing at 400 rpm for 50 hours



50 hours

XRD of ODS Powders MCB only, MCB + Ball Mill for 20 hours, and MCB + Ball Mill for 40 hours.



- C5 depicts MCB plus ball milling process for 20 hours at 400 rpm, with a BPR of 15:1.
- C6 depicts MCB plus ball milling process for 40 hours at 400 rpm, with a BPR of 15:1.

Outlines

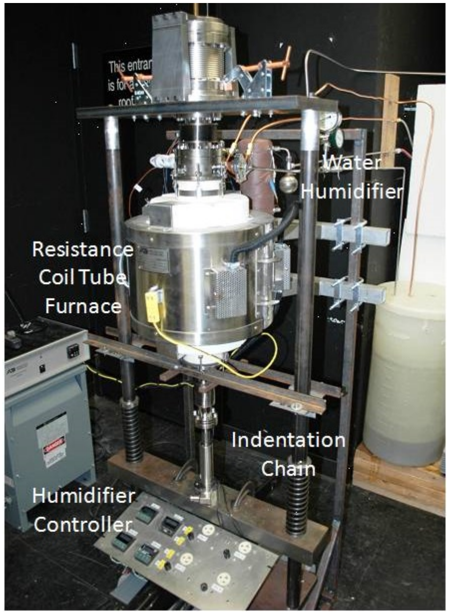
- *Introduction and Background*
- *Challenges, Objectives, Benefits of Technology, Research Task Plan*
- *Tasks*
  1. *Project Management*
  2. *Heat Transfer Characterization*
  3. *Multi-Objective Topology Optimization for Support Structure Design*
  4. *Process Optimization to Fabricate ODS Lattice Structures*
  5. *High Temperature Heat Transfer Characterization*
  6. *Production Process for ODS Powder*
  7. ***Thermal Cycling Experiments***

Task 7: Microstructural and Mechanical Properties Evaluations

Objective: Characterize the thermal-mechanical material properties and cooling performance of the AM produced ODS integrated transpiration and internal cooling module under high-temperature conditions.

Approach

- Advanced microstructural characterization - OM, EDX, XRD, SEM, TEM
- *Micro-indentation using in-house test rig*
- *Thermal cyclic tests*

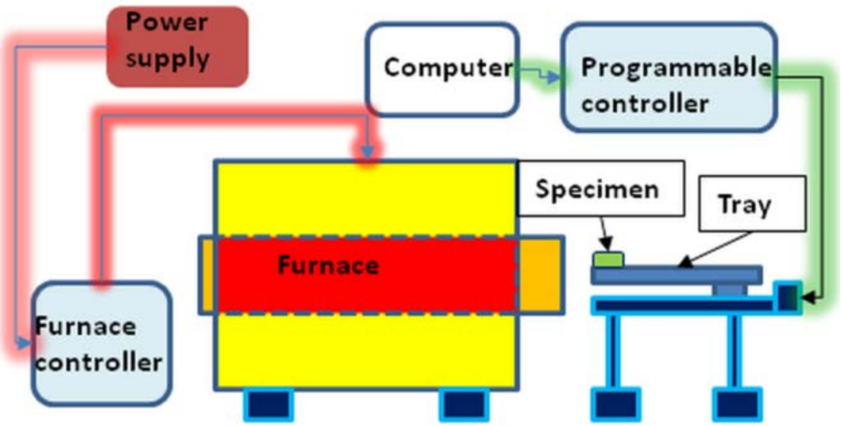


Controlled environment high temperature micro-indentation system (WVU)

Sample

- ODS Coating layers on flat plate substrates

Gridding and Cutting of ODS Coated Coupons



Schematic of the cyclic thermal exposure apparatus setup (WVU)

Thank you!

UTSR Kick-off Meeting, Oct 27, 2017