NATIONAL ENERGY TECHNOLOGY LABORATORY

REVIEW MEETING

Design, Fabrication and Performance Characterization of Near-Surface Embedded Cooling Channels with an Oxide Dispersion Strengthened (ODS) Coating Layer

Award Number: DE-FE0025793
Period of Performance :10/1/15 to 9/30/18

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University of Pittsburgh

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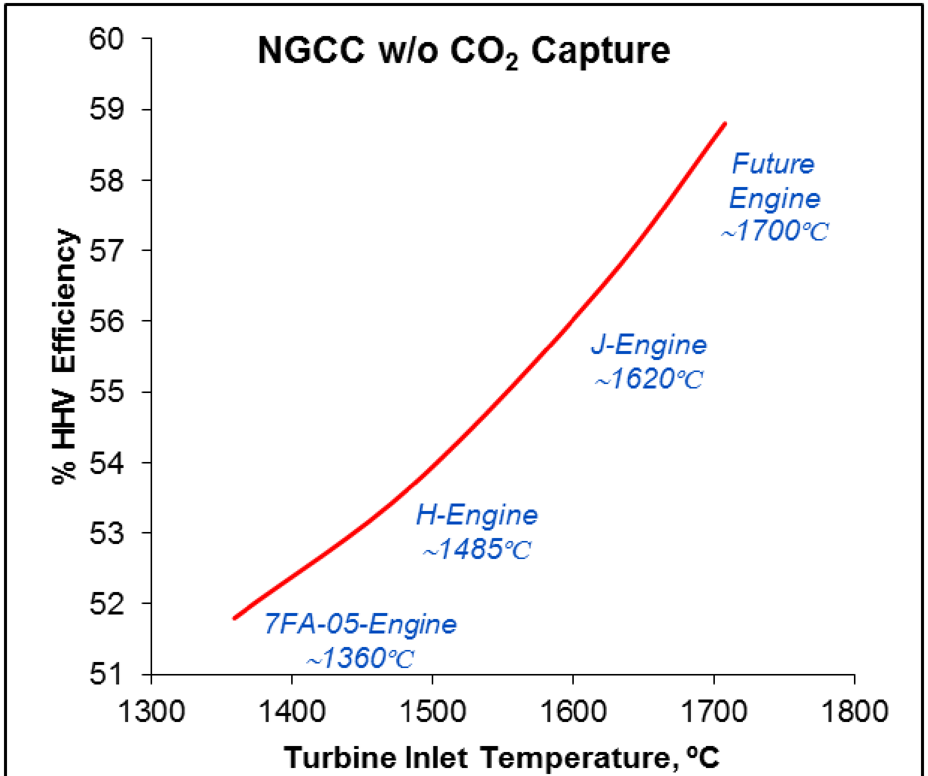
West Virginia University

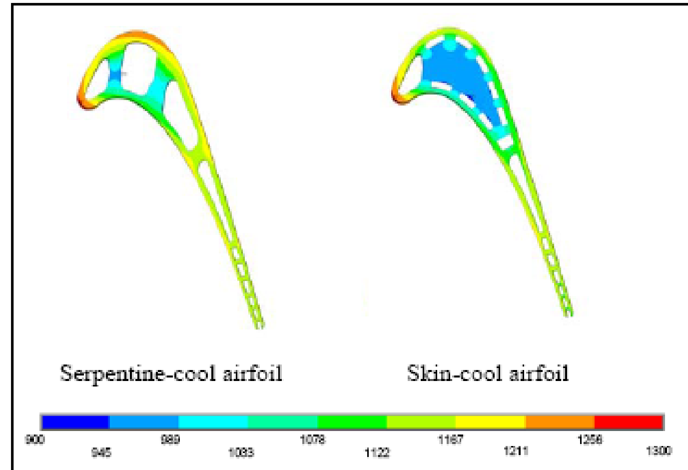
Outlines

- ***Introduction and Background***
- ***Challenges, Objectives, Benefits of Technology, Research Task Plan***
- *Tasks*
  1. *Advanced Impingement*
  2. *ODS Coating (AM Assisted)*
  3. *ODS Powders Fabrication and Characterization*
  4. *Microstructural and Mechanical Properties Characterization*
  5. *Detailed Experimental Measurement and Validation*

Technical Background/Approach



– W.Shelton, NETL Communication December 2011 –



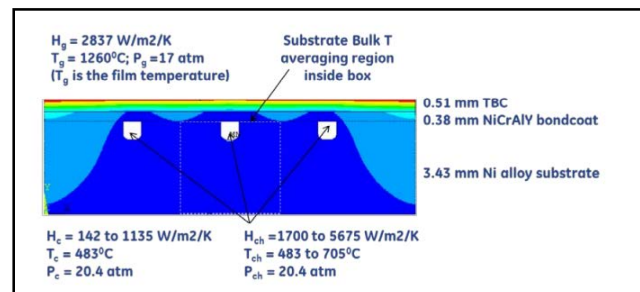
(a) Hydrogen-fired turbine

Siw, S.C., Chyu, M.K., Karaivanov, V.G., Slaughter, W.S., and Alvin, M.A., 2009, "Influence of Internal Coolinjg Configuration on Metal Temperature Distributions of Future Coal-Fuel Based Turbine Airfoils," ASME Turbo Expo 2009, Paper No. GT2009-59829.

Airfoil metal temperature distributions (in K) h_c=3000W/m^2-K

- ***Gas temperature: Hydrogen-fired turbine (~1430^{o}C)***

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



Skin Cooled Bulk Substrate Metal Temperature as a Function of Channel Heat transfer Coefficient and Coolant Temperature

Bunker, R.S., 2013, "Gas Turbine Cooling: Moving from Macro to Micro Cooling," ASME Turbo Expo 2013, Paper No. GT2013-94277

Near Surface Embedded Channel Cooling

Technical Challenges

- *Design optimal aero-thermal configuration*
- *ODS powder fabrication, ODS layer deposition processing*
- *Scale-up and commercial manufacturing of test articles*

Objectives

- **To design highly-heat-transfer augmented and manufacturable internal cooling channels for the development of NSECC.**

- **To produce ODS particles within 45-105 microns which will be used in an additive manufacturing (AM) process based on laser deposition to build NSECC test modules**

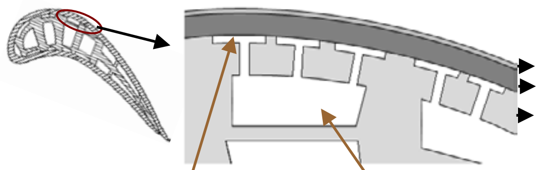
- **To develop fabrication process through additive manufacturing for coating either a densified ODS layer over a grooved single crystal superalloy substrate to form an enclosed NSECC, or an ODS layer with cooling channels embedded within the ODS layer atop a single crystal superalloy metal substrate**

- **To characterize the thermal-mechanical material properties and cooling performance of the AM produced ODS-NSECC protective module under high-temperature conditions. Comparison with the state-of-the-art cooling technology will be made and the performance improvements over the standards will be assessed**

Project Work Breakdown Structure

Enhanced Heat Removal Capability

Current NSECC design leads to 50-70% over existing internal cooling technologies.
Additional improvement is projected.



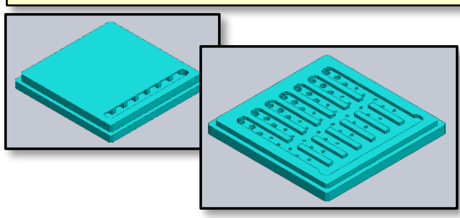
Near Surface Embedded Cooling Channel (NSECC)

Novel Metallic ODS Surface Coating

- *Ultra-High Temperature (1200 ℃) Strength*
- *Oxidation Resistance*
- *Significant challenges in traditional manufacturing*

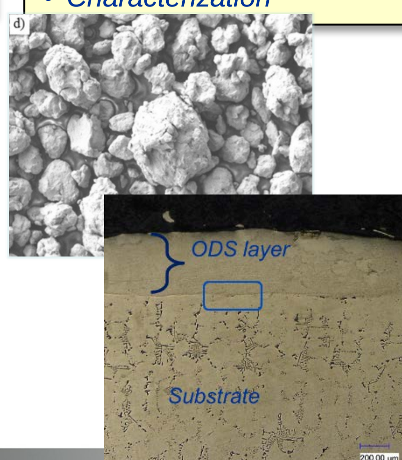
Task 1 – Advanced Impingement

- *Design, CFD modeling & scaled testing*
- *Advanced impingement*



Task 2 – ODS Powder Fabrication and Characterization

- *ODS powders fabrication*
- *Characterization*



Task 3 – ODS Coating (AM Assisted)

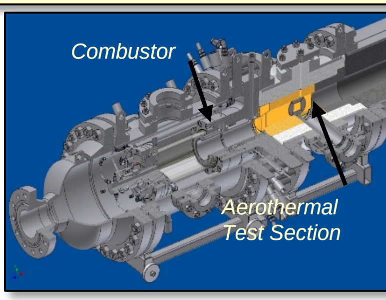
- *Process development and optimization*

Task 4 – Microstructural and Mechanical Properties Evaluation

- *Thermal Cyclic Tests, Micro-Indentation Tests*
- *OM, EDX, SEM, XRD,TEM*

Task 5 – Design Integration & Testing

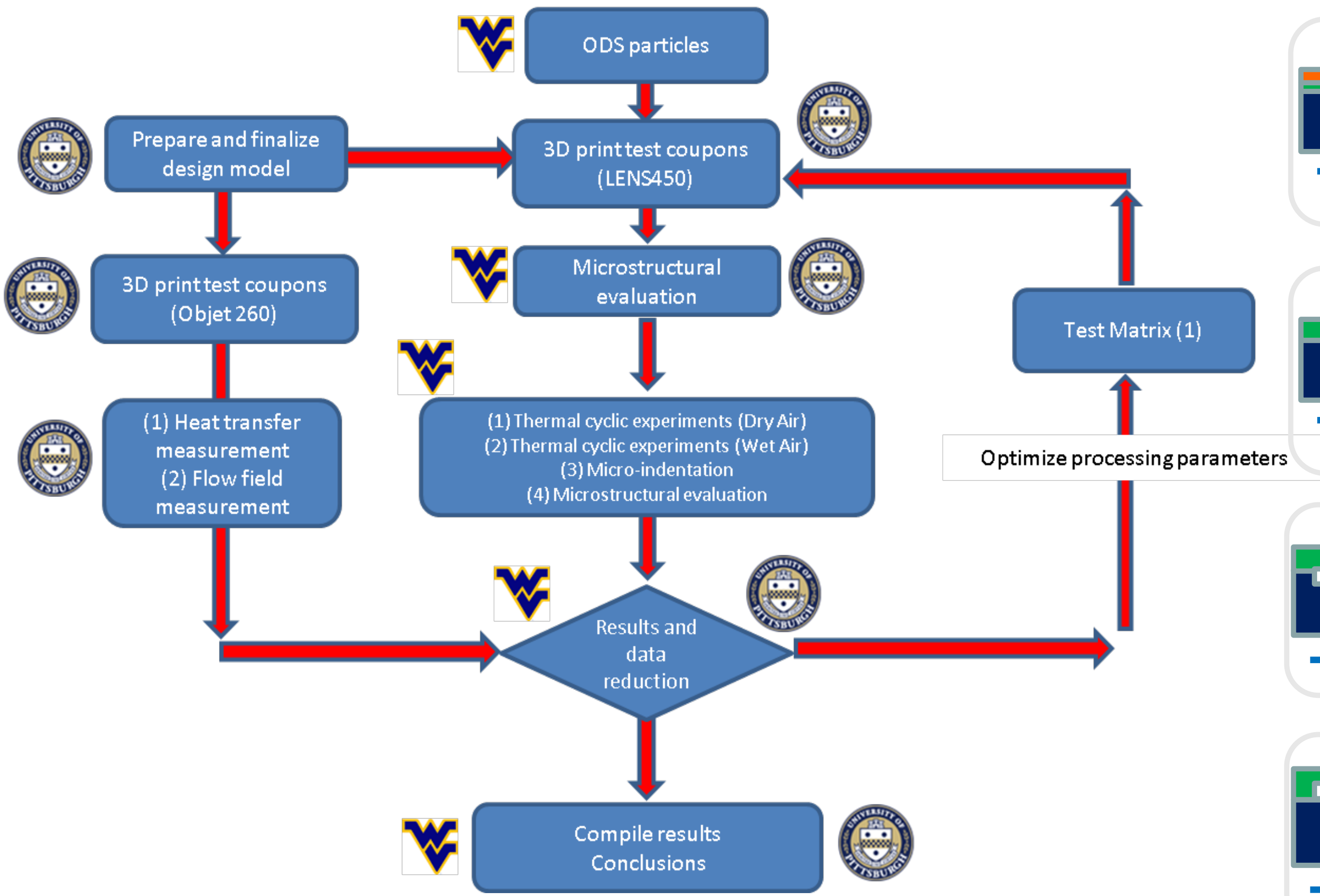
- *High Temperature, Pressurized Testing (NETL)*
- *High Temperature Testing Facilities (Solar Turbines, Inc.)*

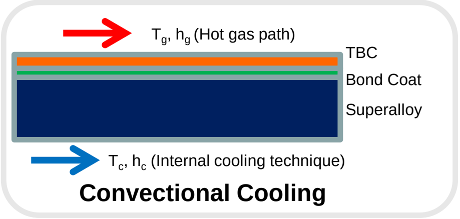


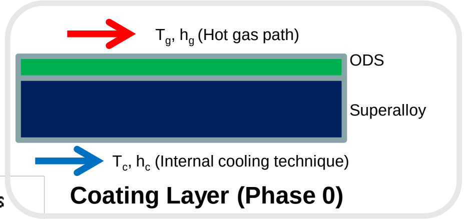
Research Task Plan

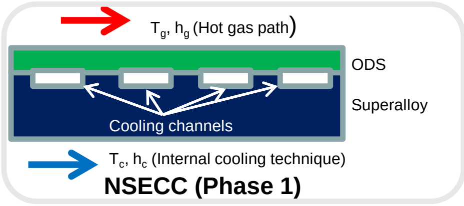
Design, Fabrication and Performance Characterization of Near-Surface Embedded Cooling Channels with an Oxide Dispersion Strengthened (ODS) Coating Layer

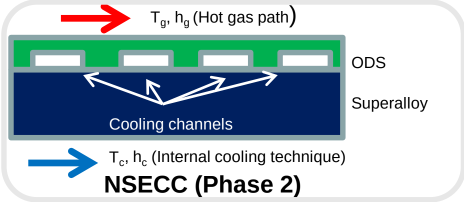
Research Task Plan (3 years)











Milestones

Solar Turbines
A Caterpillar Company

HOSOKAWA MICRON

Design, Fabrication and Performance Characterization of Near-Surface Embedded Cooling Channels with an Oxide Dispersion Strengthened (ODS) Coating Layer

Research Task Plan (3 years)

University of Pittsburgh

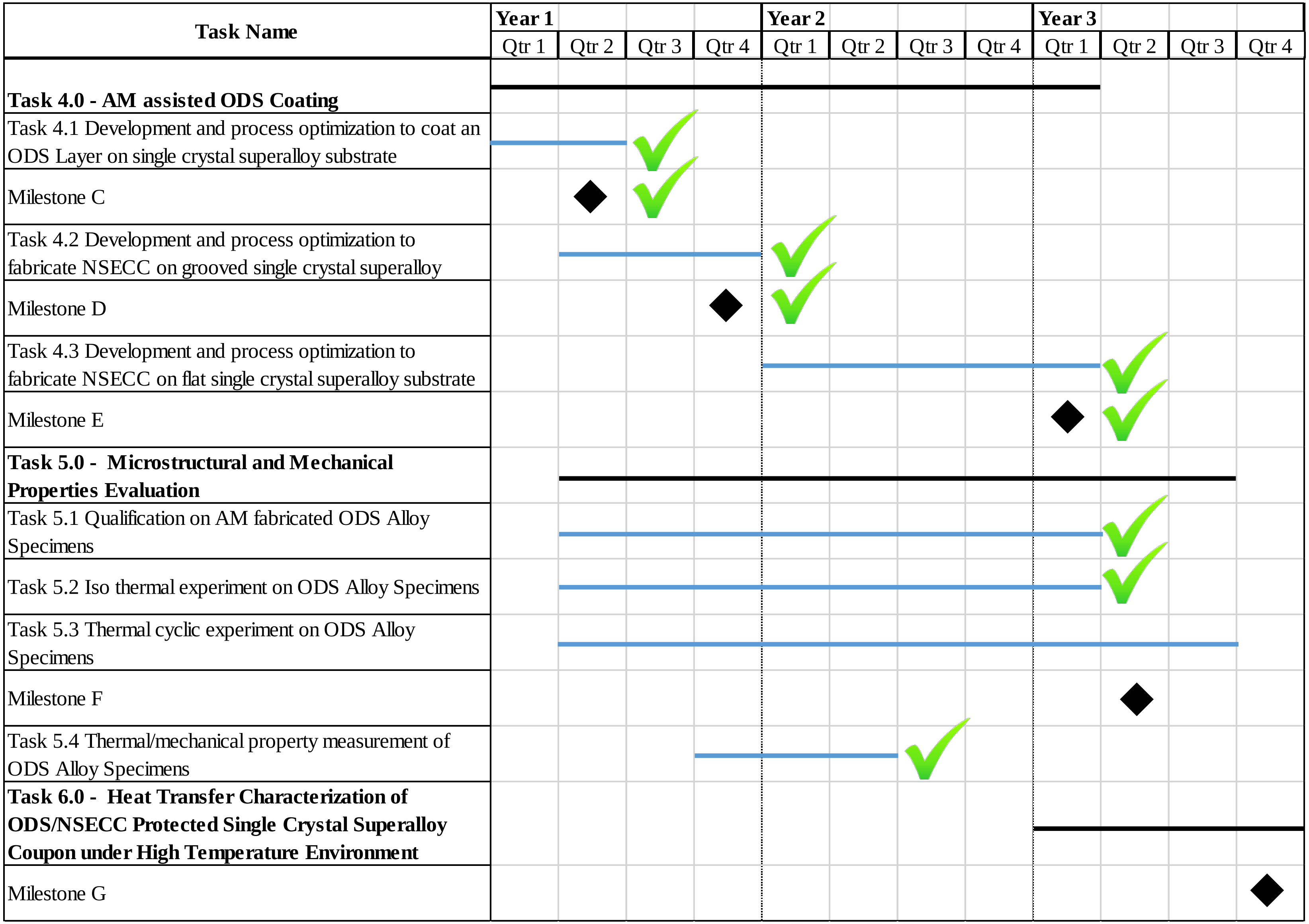
West Virginia University

Title	Planned Date	Verification Method
A - Heat transfer and fluid flow experiments of test sections and test modules	3/31/2017	Data analysis and comparison to bench data
B - Produce and characterize ODS powders	3/31/2017	XRD and SEM
C - ODS coating on substrate	3/31/2016	Optical micrographs, SEM
D - Fabrication of NSECC on grooved single crystal superalloy substrate	9/30/2016	Optical micrographs, SEM
E - Fabrication of NSECC on flat single crystal superalloy substrate	12/31/2017	Optical micrographs, SEM
F - Thermal cyclic loading tests	3/31/2018	Optical micrographs, SEM
G - High temperature experiments (Validation)	9/30/2018	Data analysis and comparison to bench data (SOTA standards)

Project Timeline1

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 1.0 - Project management and planning												
Task 2.0 - Heat transfer characterization of advanced NSECC Concepts at low temperature												
Subtask 2.1 Identify potential geometries/configurations												
Subtask 2.2 Conduct numerical calculations (ANSYS CFX)												
Subtask 2.3 Fabricate test sections and test coupons												
Subtask 2.4 Conduct heat transfer experiments and fluid flow measurements												
Milestone A												
Task 3.0 - ODS Powders Fabrication and Characterization												
Subtask 3.1 Develop optimal process parameter to produce ODS powder												
Subtask 3.2 Installation, adjusting and training for powder fabracation equipments												
Subtask 3.3 Characterize the powder particle size distribution												
Milestone B												

Project Timeline2



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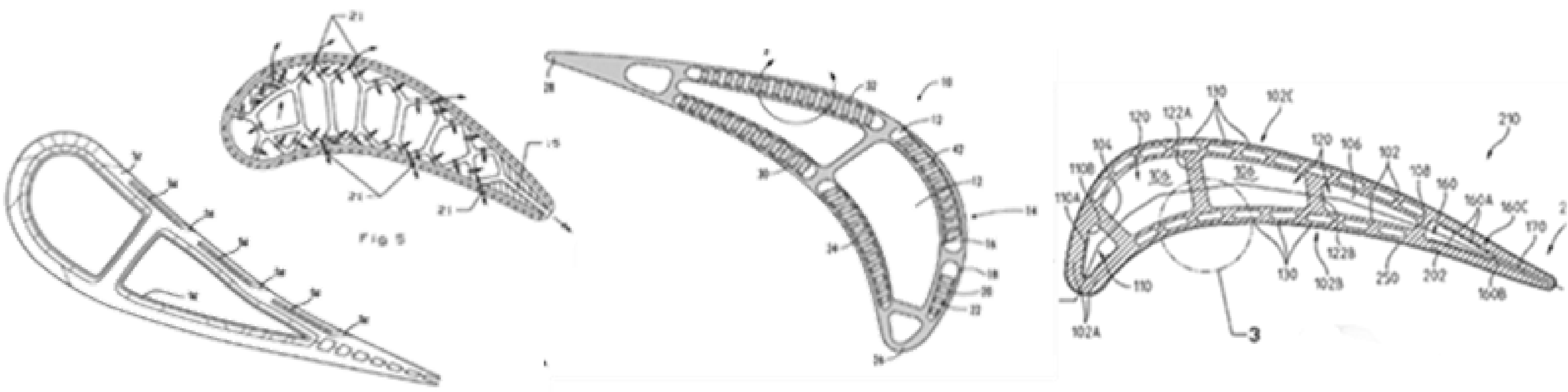
Task 1 Heat Transfer Characterization

Objective: Develop internal air foil cooling technologies capable of additive manufacturing and suitable for surface embedding, and seek for heat transfer enhancement in the meantime.

- Advanced Impingement

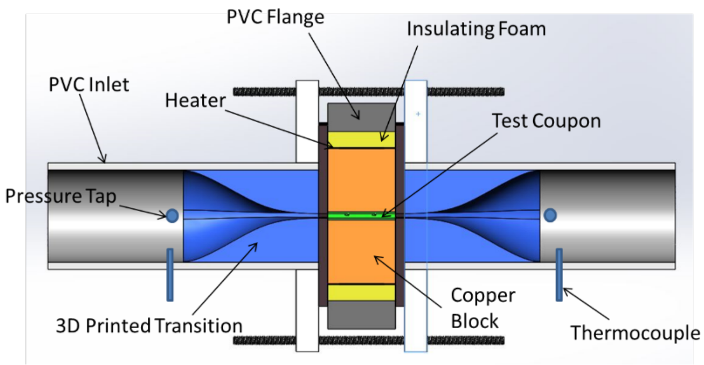
Challenge:

Cooling channels embedded near the outer surface have small sizes and irregular shapes. Distributing the coolant to feed the channels will be more difficult than traditional cooling concepts. In the meantime, this novel cooling concept still requires further enhancement of local heat transfer to achieve higher efficiency.

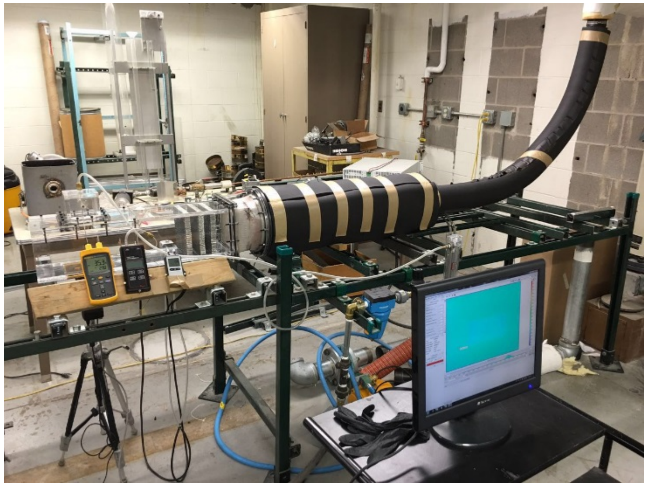


Different patents showing double wall cooling by UTC, Siemens and Florida Turbine Technologies

Heat Transfer Test Facilities

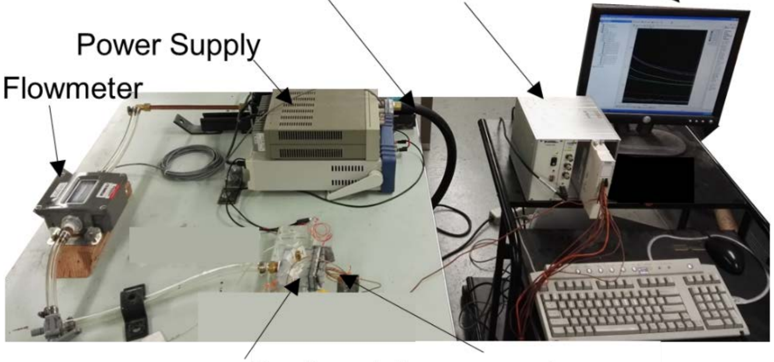


Test Rig for AM Parts
based on thermocouples



Test Rig for Conjugate Heat Transfer
based on IR

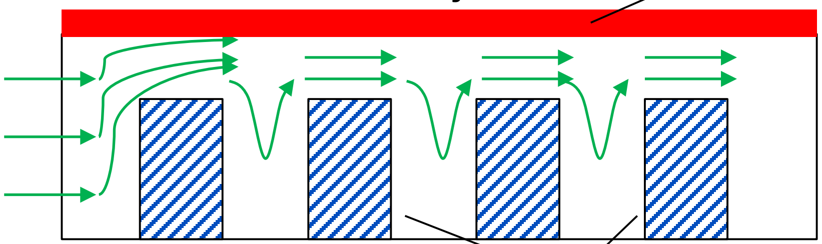
Test Rig for Scaled up Models
based on TLC

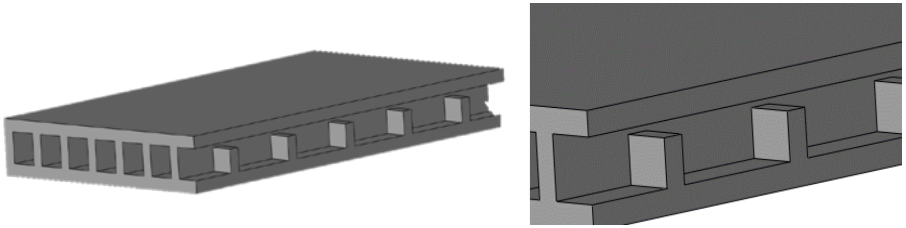


Test Rig for Steady State
based on thermocouples

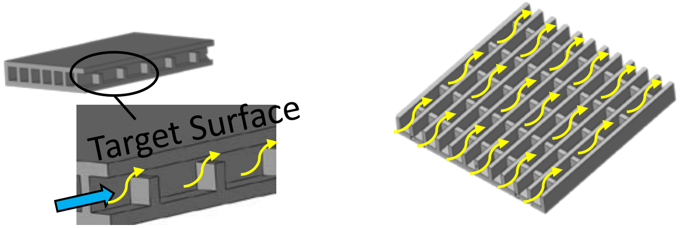
Wall Jets Cooling Channels

- **Concept:**
  - Confine the coolant to the most near surface areas to achieve high heat removal capability.
  - Enhanced heat transfer on the side of hot surface while lower heat transfer on the inner side.
- **Identified Geometry:**
  - Slot wall jet
  - Chevron wall jet

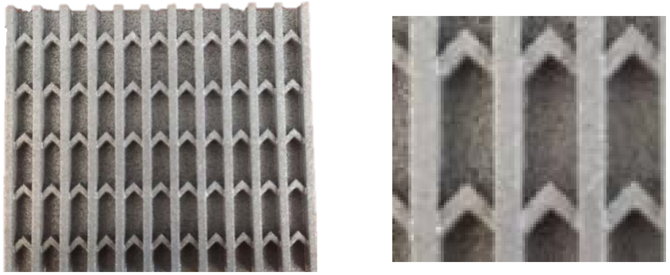




Slot Type Wall Jets

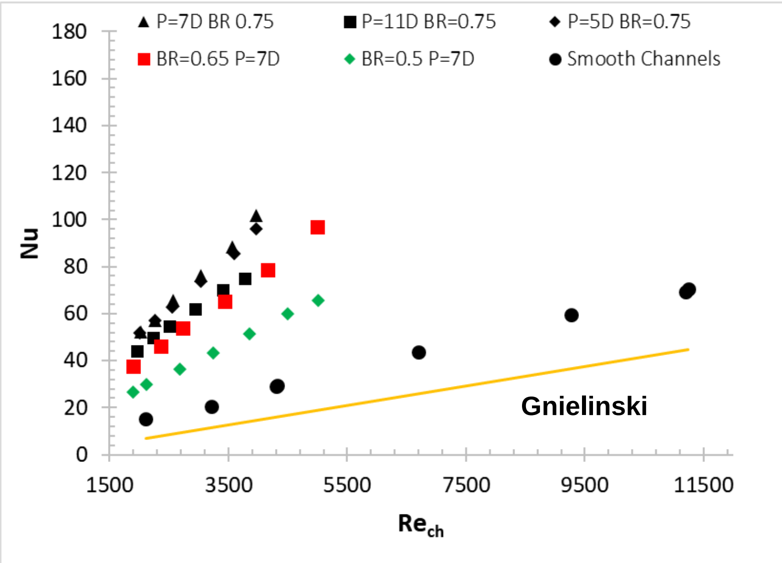


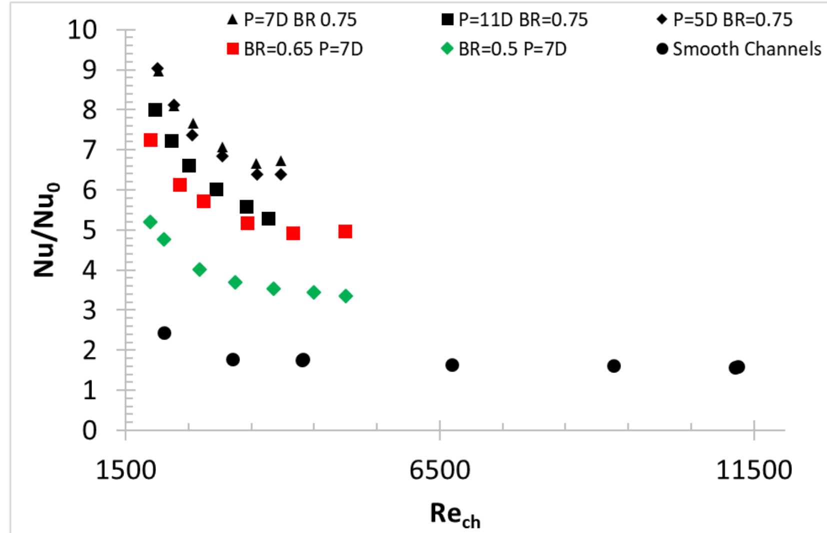
Wall Jet Coupons

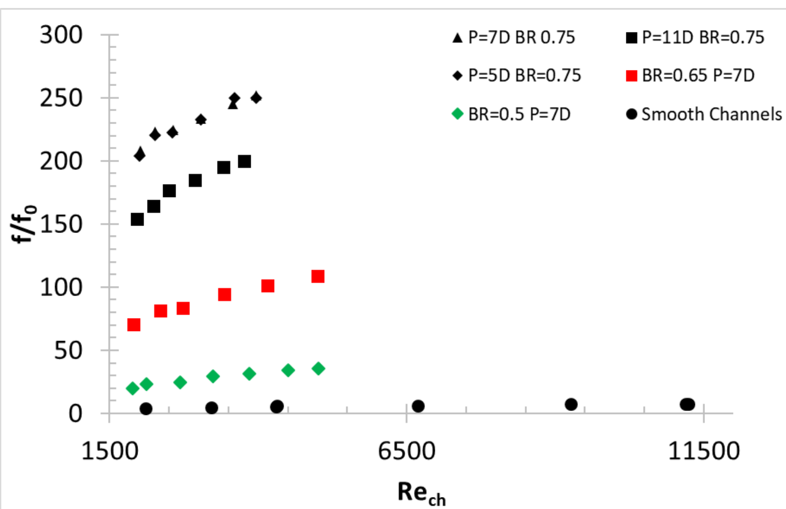


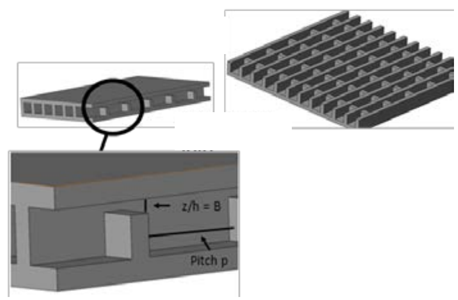
Chevron type jets

Slot Type Wall Jets



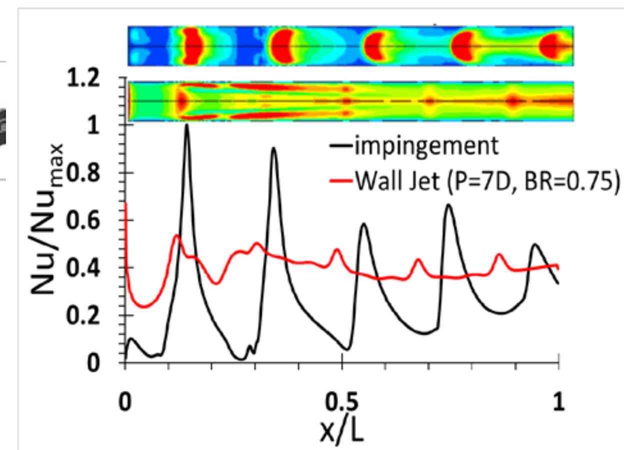


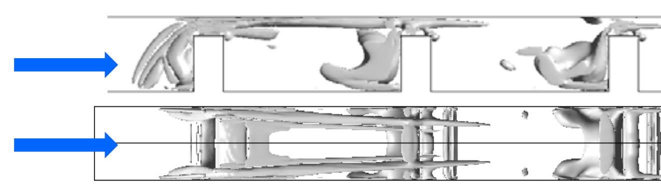




Important parameters

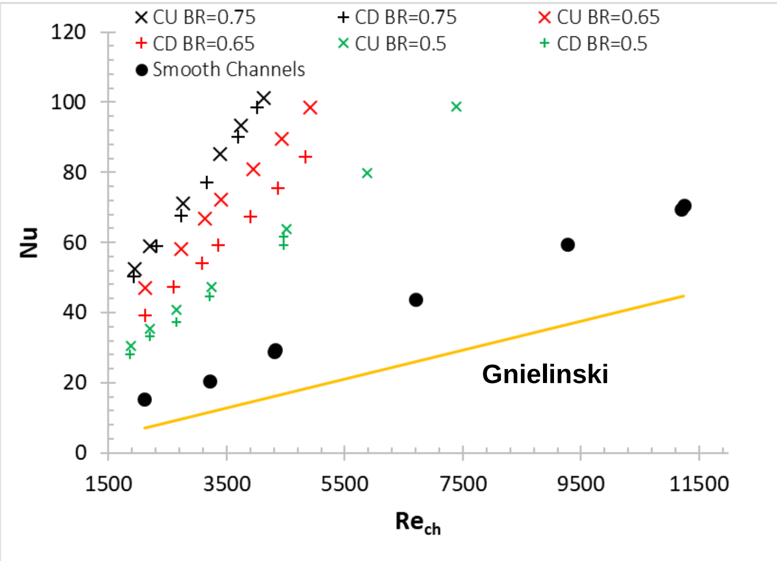
- Jet hydraulic diameter — D
- Channel hydraulic diameter — D_{ch}
- Jet pitch — P = 5D - 11D
- Number of jets — N = 4 - 6
- Channel diameter — D_{ch} = 2.5D
- Blockage ratio (h/Z) — BR = 0.5 – 0.75

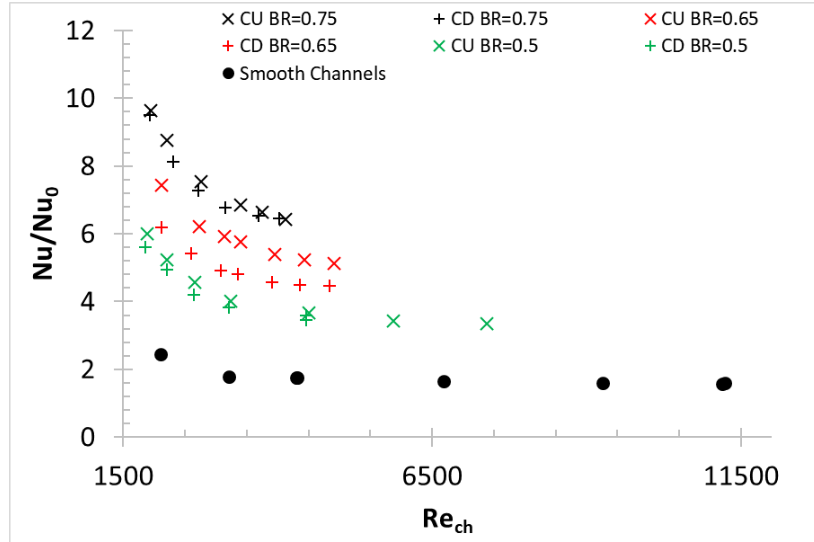


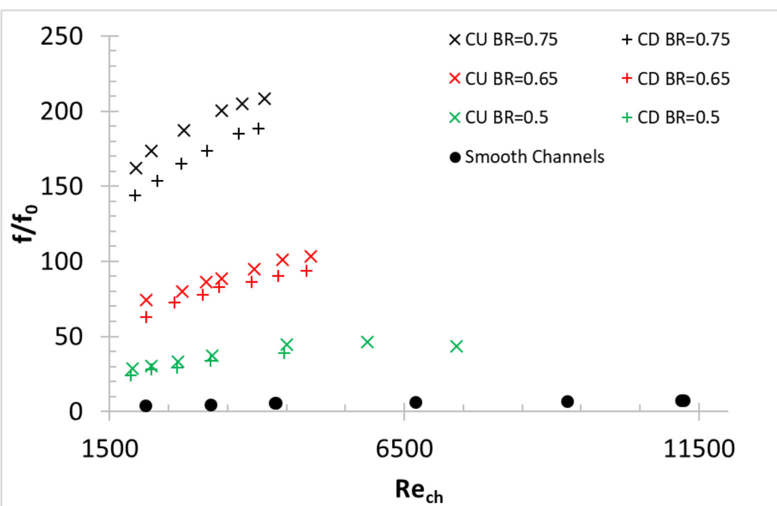


- BR=0.75 had the highest heat transfer
- More uniform heat transfer than jet impingement.

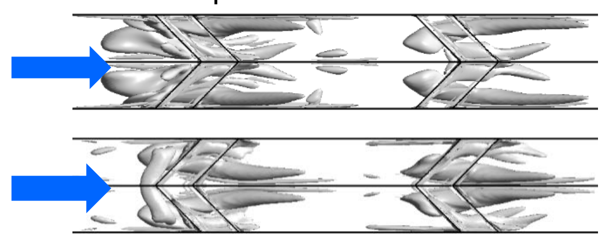
Chevron Type Wall Jets



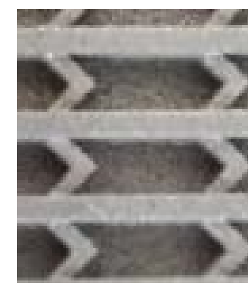




CU: upstream chevron

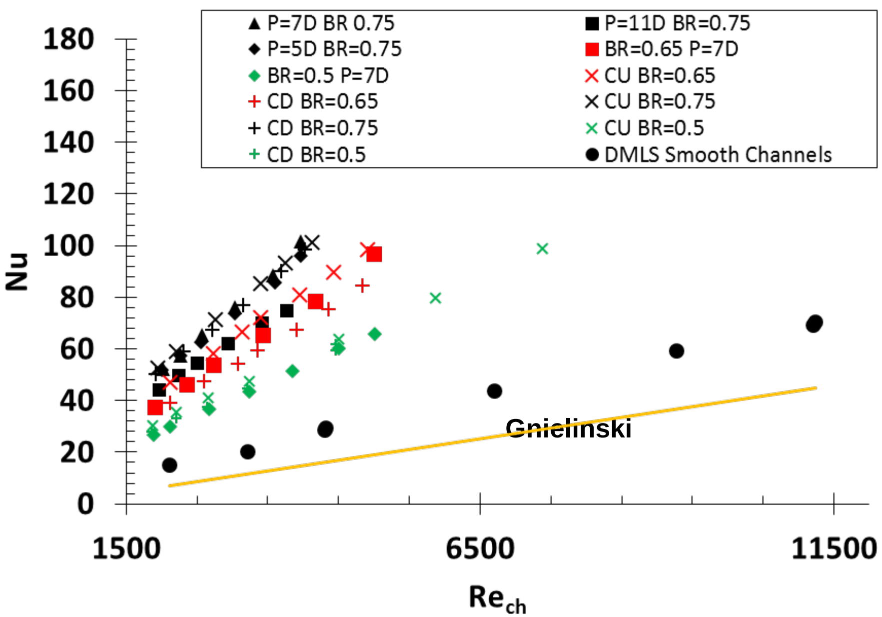


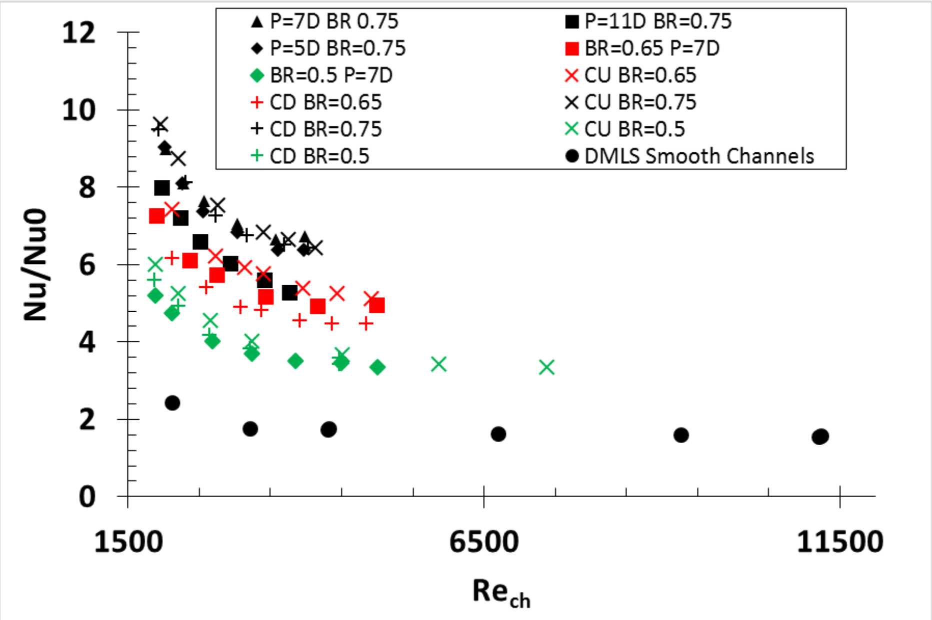
CD: downstream chevron

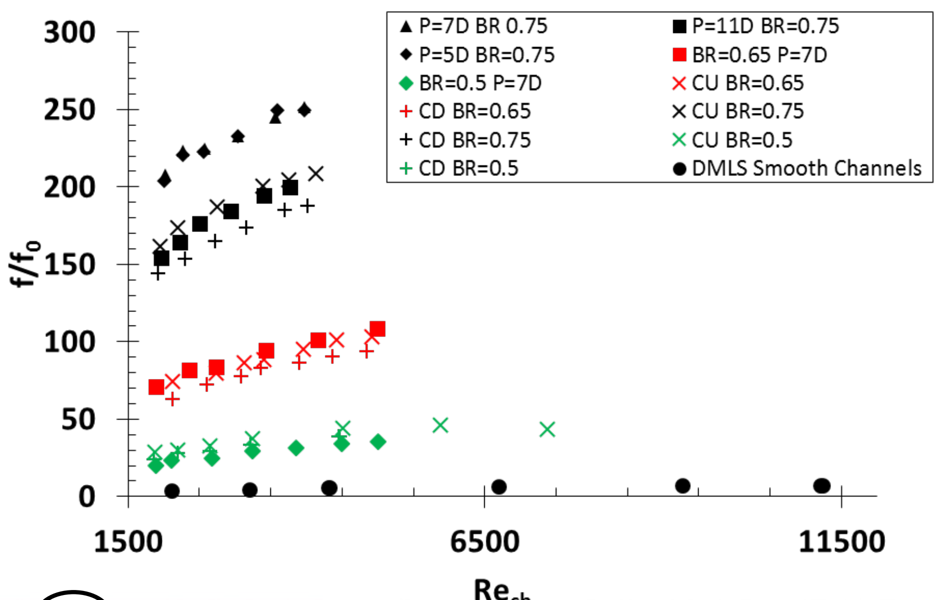


- BR was a dominating parameter.
- Downstream chevron had lower heat transfer enhancement and lower pressure drop.

All Geometries Comparison







- Compared with Gnielinski correlation for smooth channel, the wall jet geometries increased the heat transfer by 4~10 times.
- Chevron wall jets were the most efficient in this study, with similar heat transfer of slot wall jets by lower pressure drop.
- Blockage ratio was a dominating parameter for wall jets.

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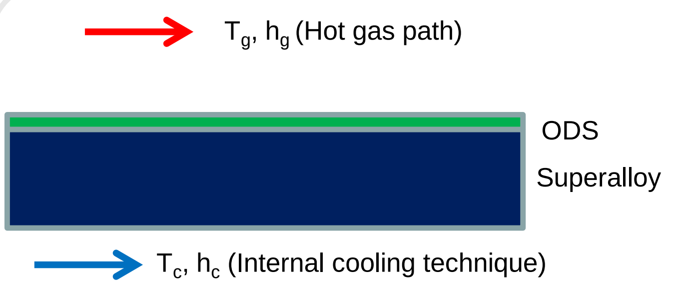
Task 3: ODS Coating with AM Assisted

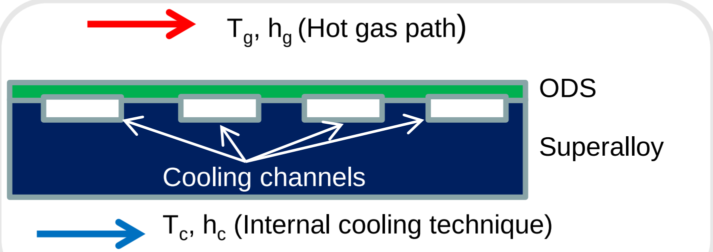
Objective: Develop and optimize processing parameters for fabricating an ODS layer atop of superalloy substrate of turbine airfoils

Approach

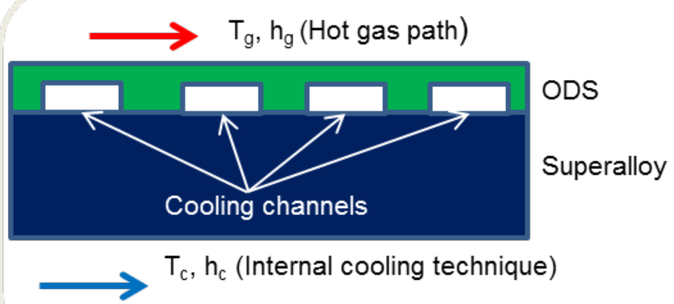
- *Produce a series of test coupon with densified ODS layer atop of single crystal nickel based superalloy substrate using varying major parameters.*
  - Laser power, powder feeding rate, deposition speed, hatch spacing, hatch pattern



Coating Layer (Phase 0)

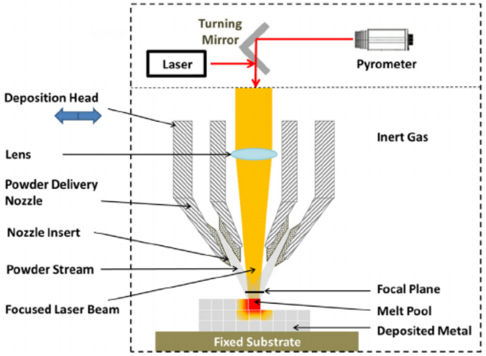


NSECC (Phase 1)



NSECC (Phase 2)

LENS 450 System at Pitt

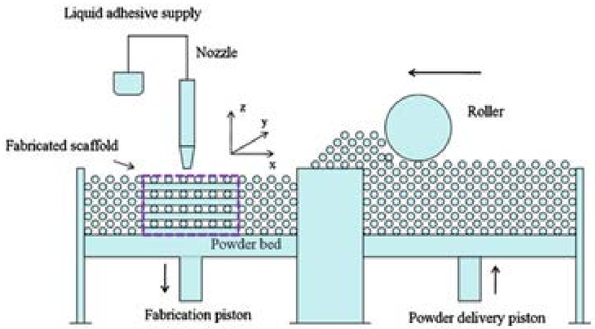


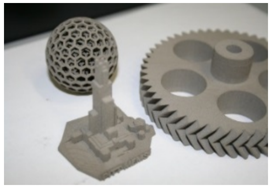
Scott M. Thompson et al.

Metallic Additive Manufacturing

Bind Jetting

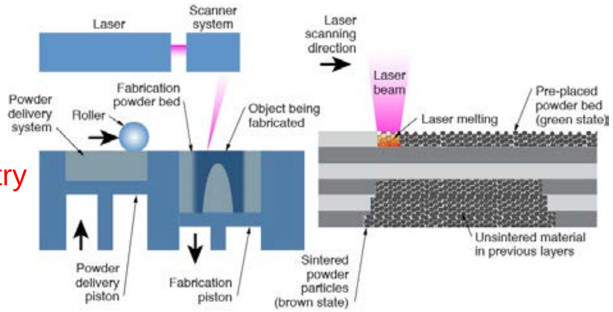
Pros: geometry free
cons: high porosity





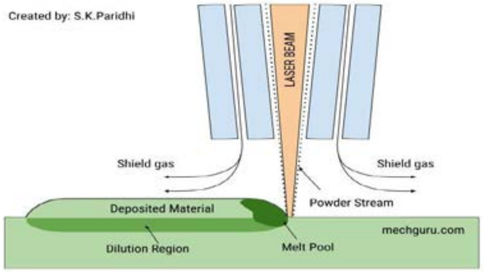
Powder Bed Fusion

Pros: complex geometry
cons: single material



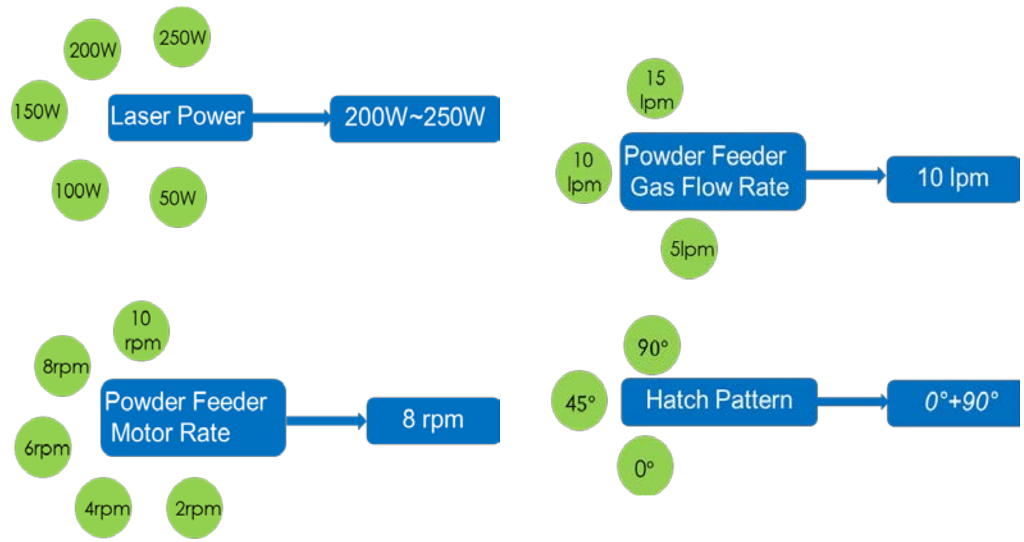
Direct Energy Deposition

Pros: multiple materials
cons: no overhangs or unsupported structure

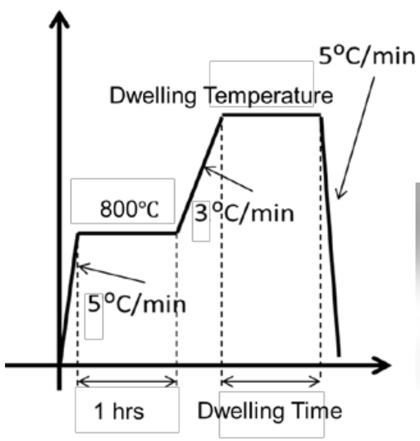


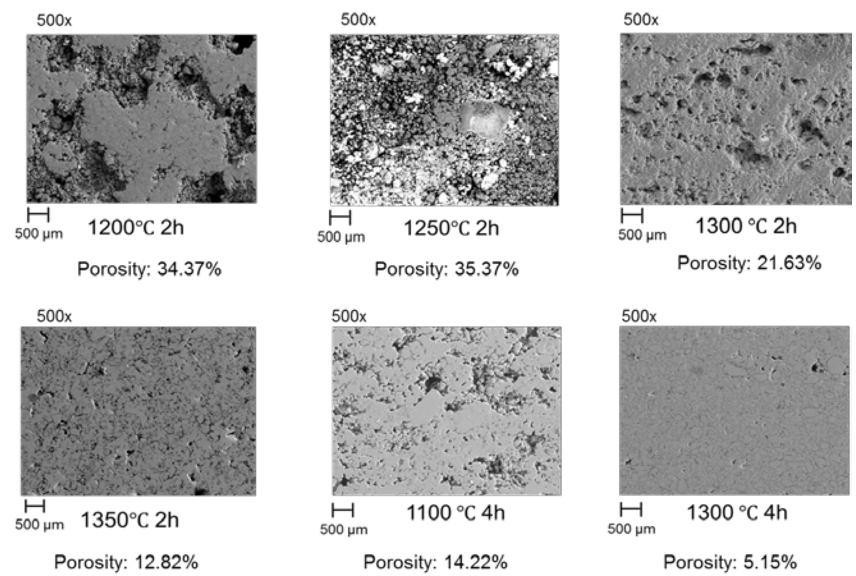
As metallic additive manufacturing technologies matured, it became possible for complex metal product to be manufactured by this innovative technology, which also provides great capabilities to make complex geometries for turbine airfoil cooling channels.

AM Control Parameters



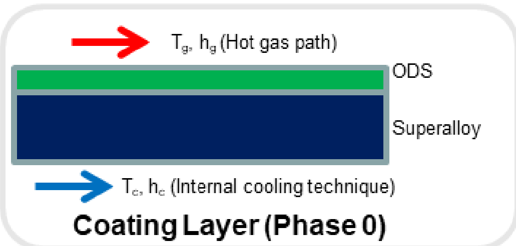
LENS Key Parameters:
laser power, motor rate,
gas flow rate, hatch pattern

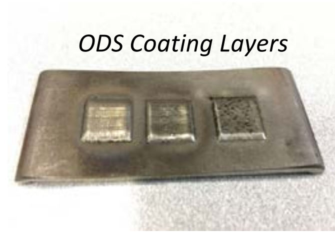


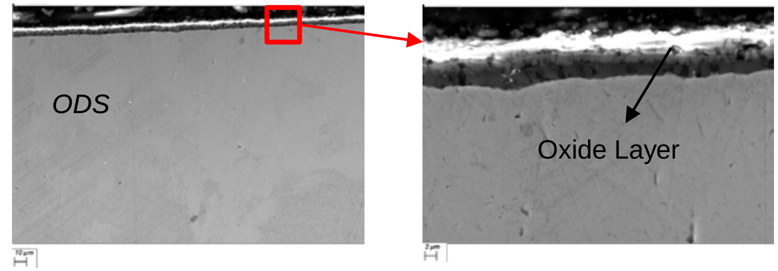


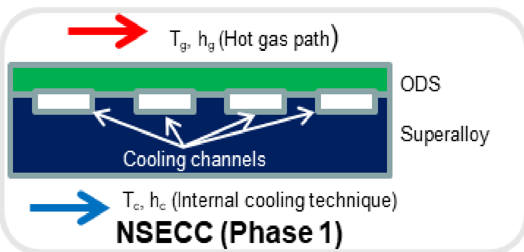
ExOne X1-Lab Key Parameters:
dwelling temperature, dwelling time

Additive Manufactured ODS Coating Layers and Cooling Channels

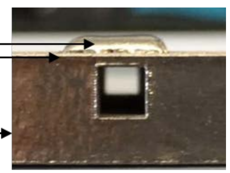




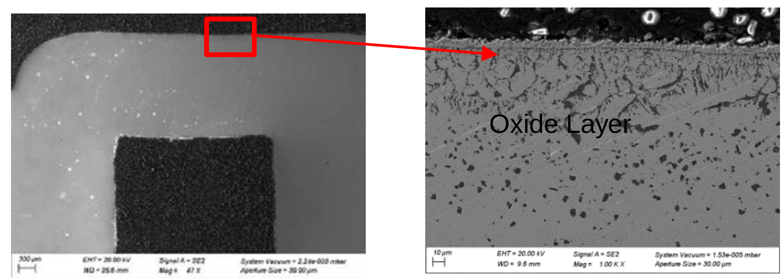


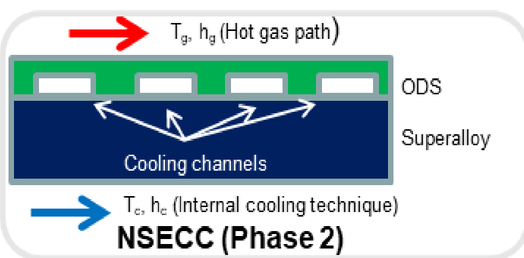


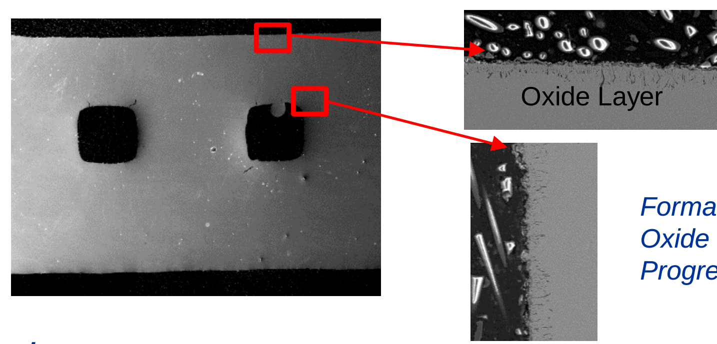
ODS
Interface
Substrate



ODS
Interface
Substrate





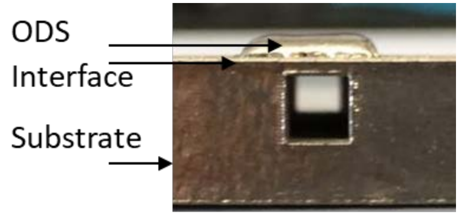


Formation of Oxide Layer in Progress

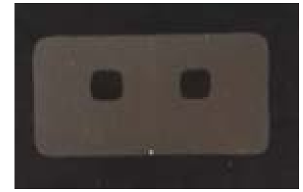
- *Phase 0: 1200℃, 2000h, 1100 ℃, 2480 cycles, Air Environment*
- *Phase 1: 1100℃, 900h, Air Environment, (ongoing)*
- *Phase 2: 1100℃, 400h, Air Environment, (ongoing)*

Hardness Tests of ODS material Produced by Different Additive Manufacturing technologies

LENS Coating



LENS Top Wall



LENS Full Channel

EOS IN718

2^{nd} generation supperalloy

X1 Full Channel

	Sample	Hardness
Phase 0	Coating layer made by 250W laser in LENS450	HV382.0
	Coating layer made by 200W laser in LENS450	HV390.3
Phase 1	ODS top wall made by LENS 450, 250W	HV357.0
Phase 2	Full ODS channel made by X1-Lab, sintered at 1300C for 4 hours	HV272.8
	Full ODS channel made by LENS 450, 250W	HV335.4
Reference	2^{nd} generation superalloy substrate, single crystal	HV410.3
	Inconel 718 coupons made by EOS	HV368.7

Outlines

- *Introduction and Background*
- *Challenges, Objectives, Benefits of Technology, Research Task Plan*
- *Tasks*
  1. *Heat Transfer Characterization*
  2. *ODS Coating (AM Assisted)*
  3. ***ODS Powders Fabrication and Characterization***
  4. *Microstructural and Mechanical Properties Characterization*
  5. *Detailed Experimental Measurement and Validation*

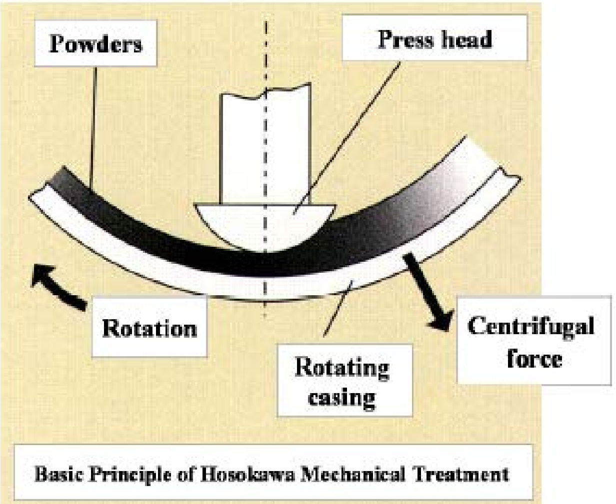
Task 6: ODS Powders Fabrication and Characterization

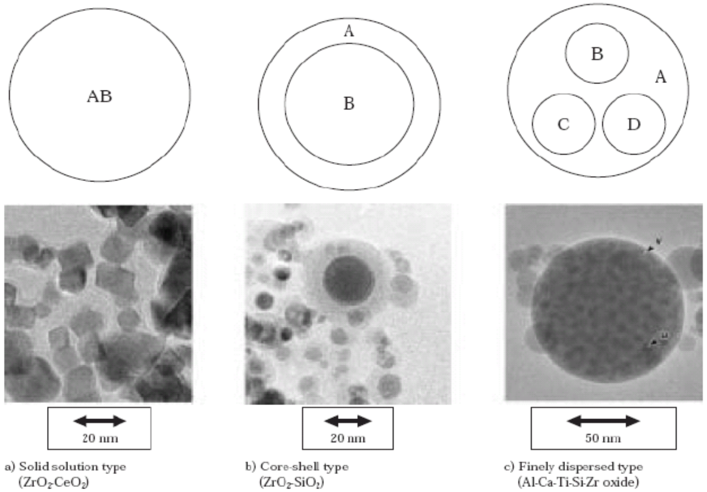
Objective: Produce ODS particles with proper sphericity and spreadability, which will be used in additive manufacturing (AM) processes to build lattice test modules.

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?



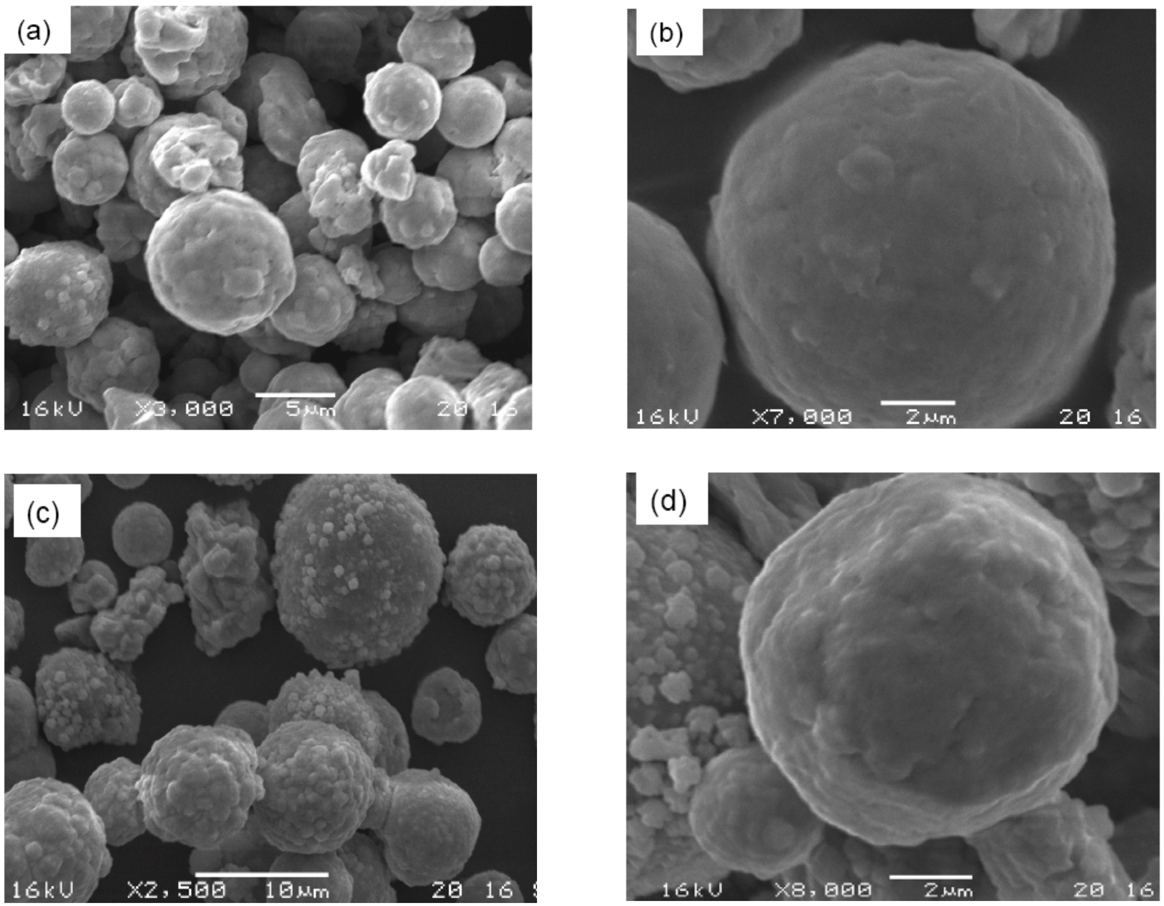


Structural patterns of nanocomposite particles
[T. Yokoyama and C. C. Huang, KONA No.23 (2005)]

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

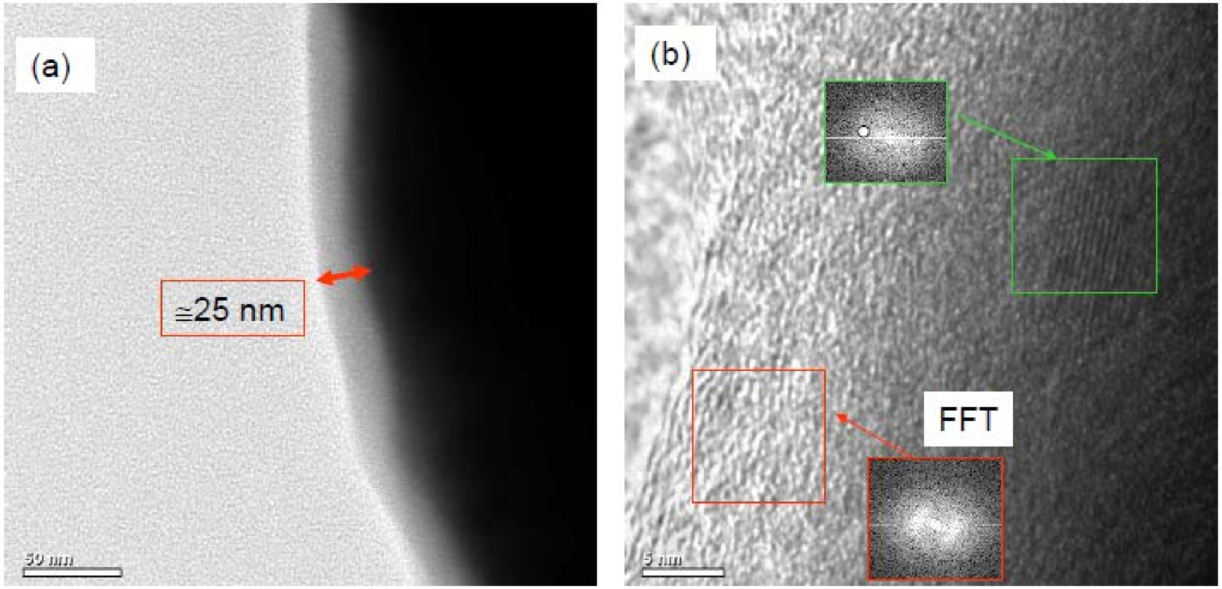


SEM micrographs of MCB processed powder sample A1 and A2

(a). Sample A1; (b) close view of (a); (c) sample A2; (d). close view of (c)

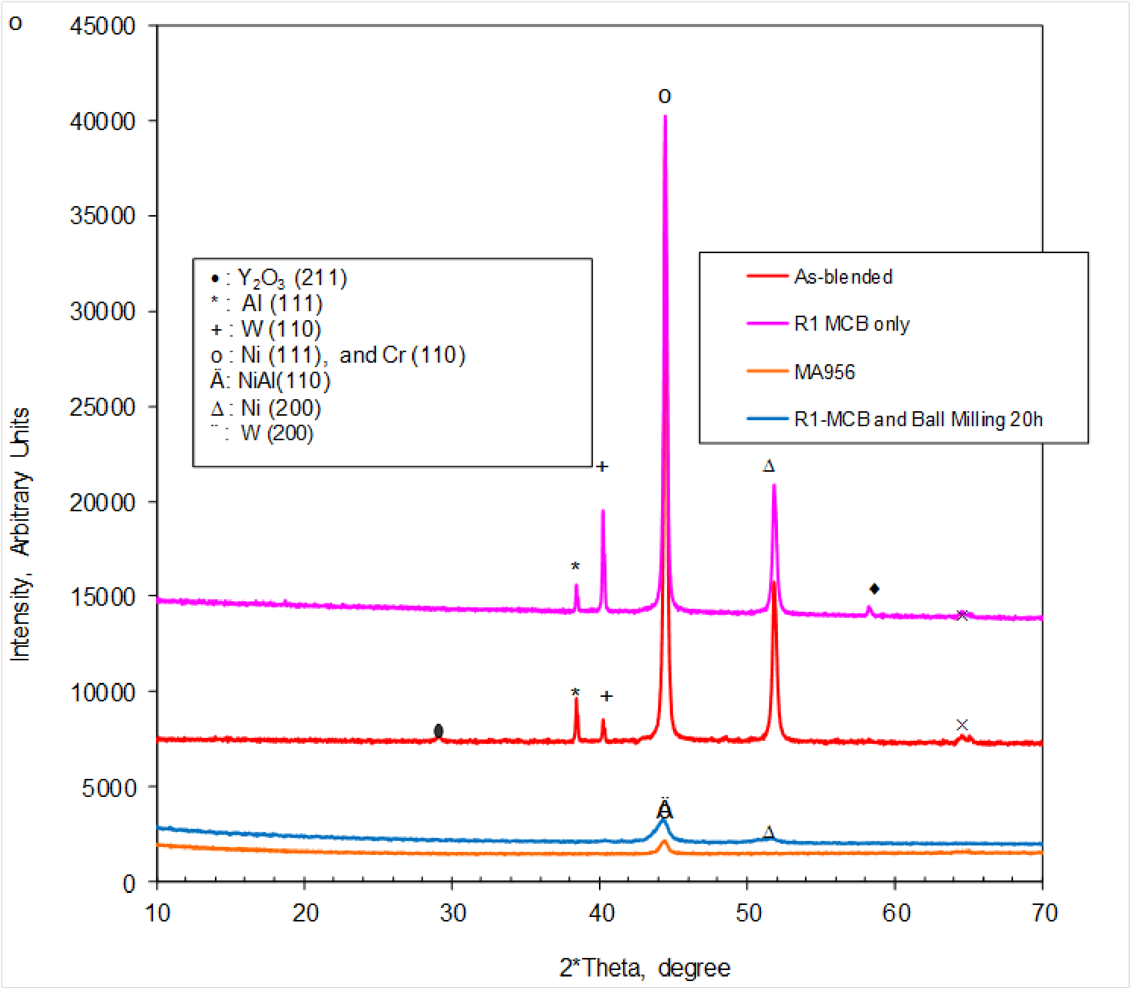
ODS Powder Characterization

TEM BF and HREM imaging – A1 Sample

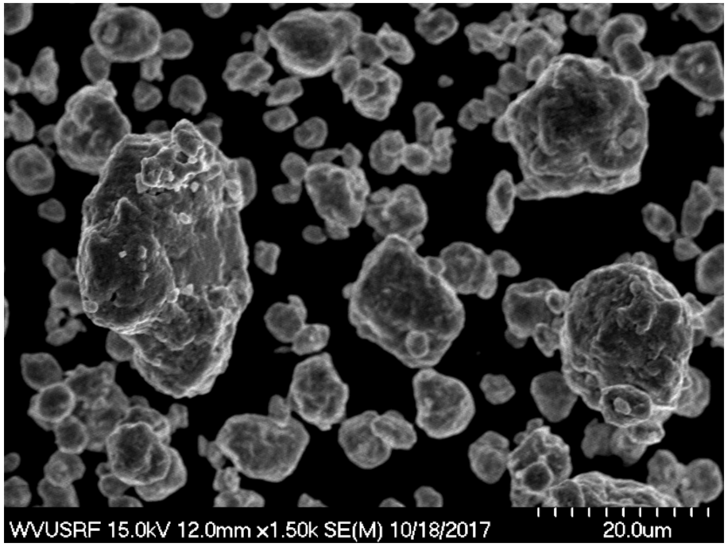


- TEM BF image (a) shows a layer of Y_2O_3 thin film with thickness about 25nm around the edge of particle. The film thickness is relatively homogeneous.
- HREM image (b) shows the fine structure of the thin film. Most area of the film is amorphous and the corresponding FFT (Fast Fourier Transform) image 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.

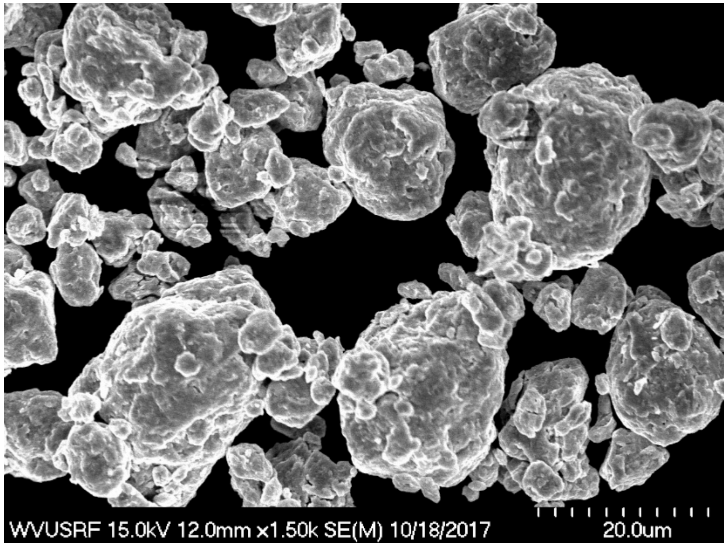
XRD Characterization of ODS Powder



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

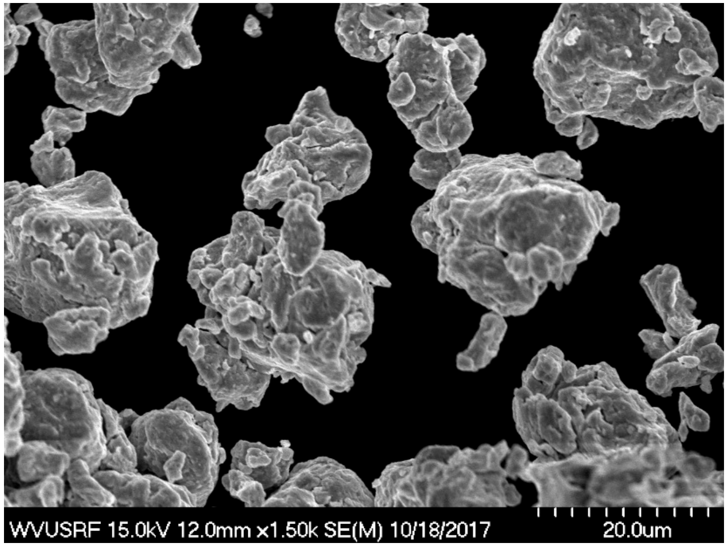


15 hours

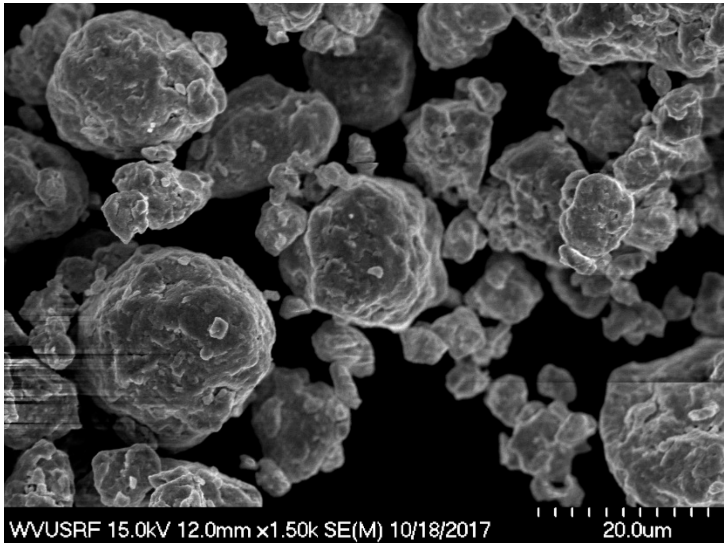


25 hours

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

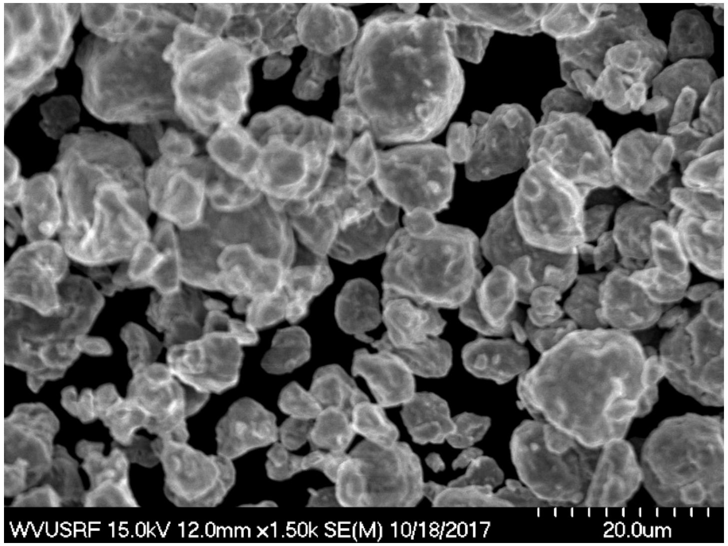


30 hours



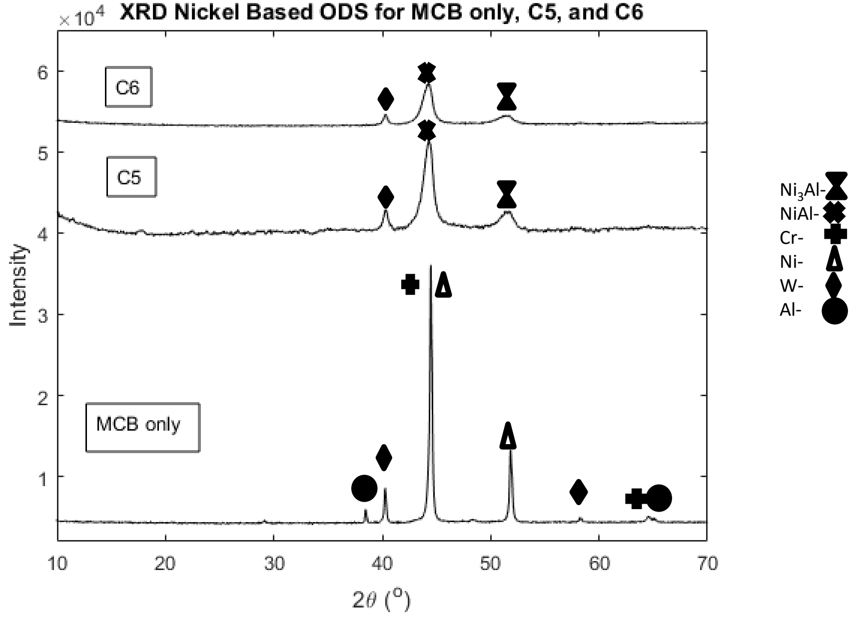
40 hours

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.

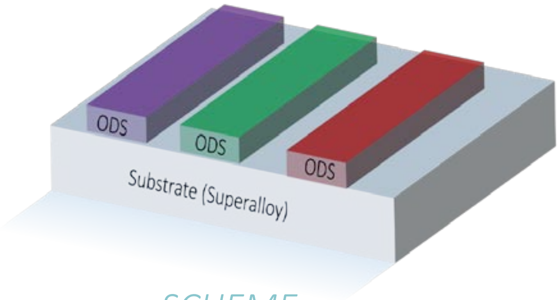


- C5 depicts MCB plus ball milling process for 20 hours at 400 rpm, with a BPR of 15:1.
- C6 depicts MCB plus ball milling process for 40 hours at 400 rpm, with a BPR of 15:1.

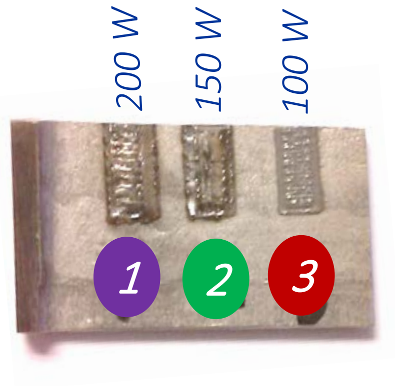
Outlines

- *Introduction and Background*
- *Challenges, Objectives, Benefits of Technology, Research Task Plan*
- *Tasks*
  1. *Advanced Impingement*
  2. *ODS Coating (AM Assisted)*
  3. *ODS Powders Fabrication and Characterization*
  4. ***Microstructural and Mechanical Properties Characterization***
  5. *Detailed Experimental Measurement and Validation*

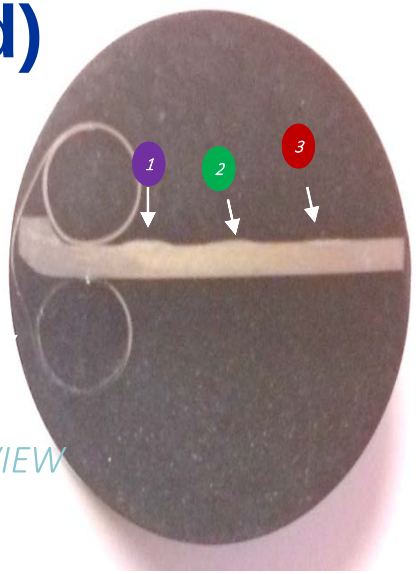
ODS Coating (AM Assisted)



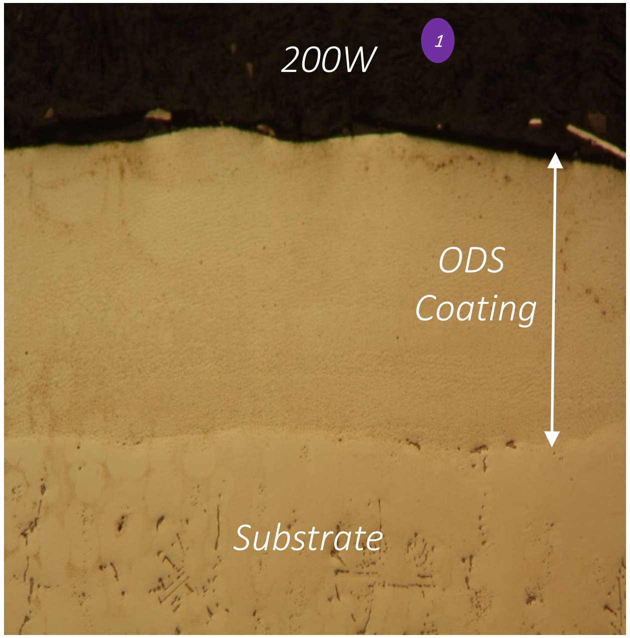
SCHEME

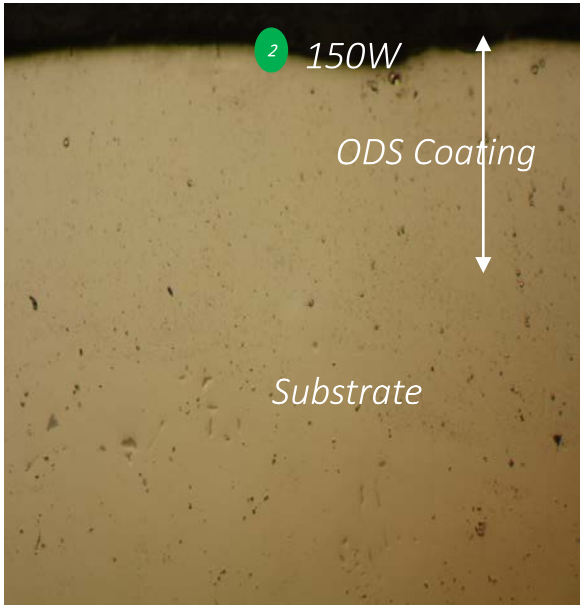


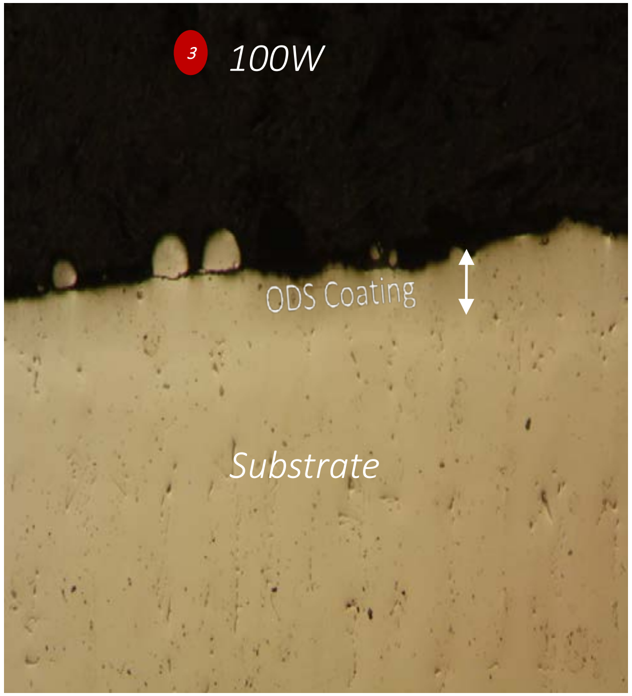
TOP VIEW

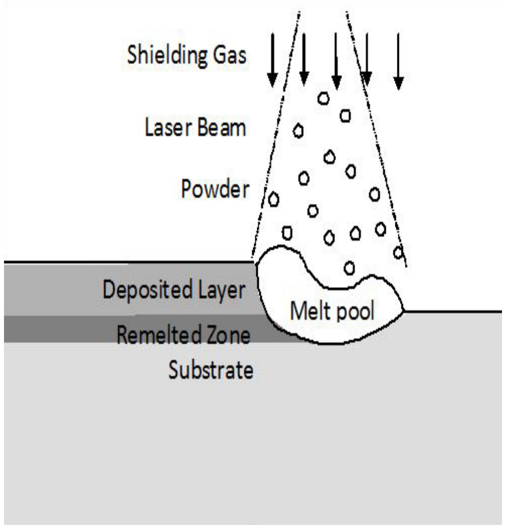


SIDE VIEW

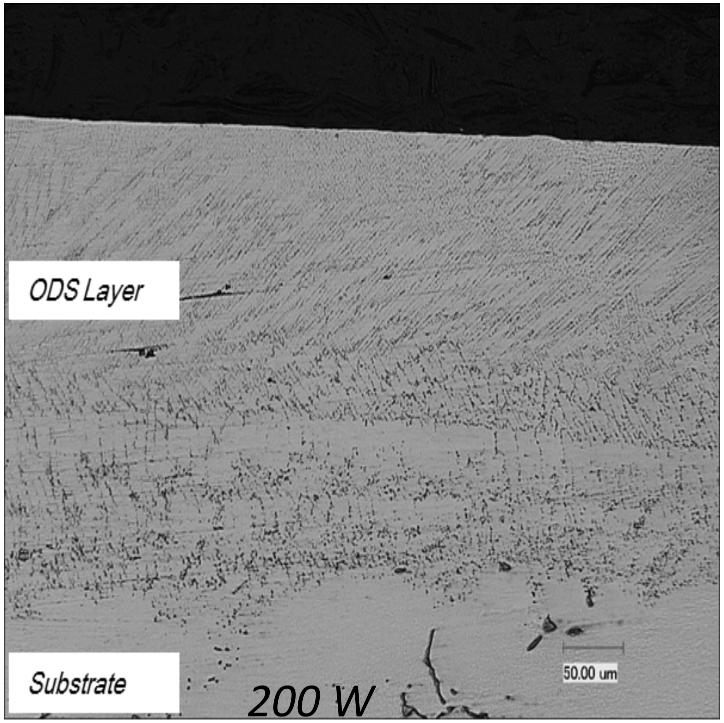


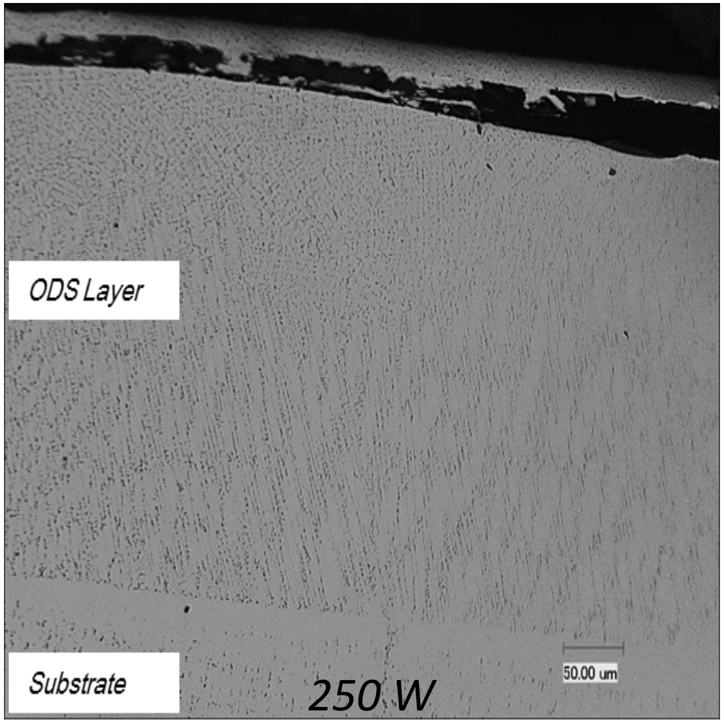






ODS Strip Deposition Samples





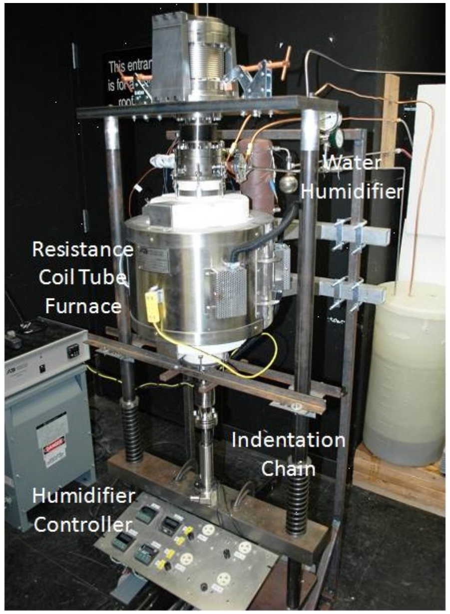
Cross Section of Laser Deposited

Task 4: 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*

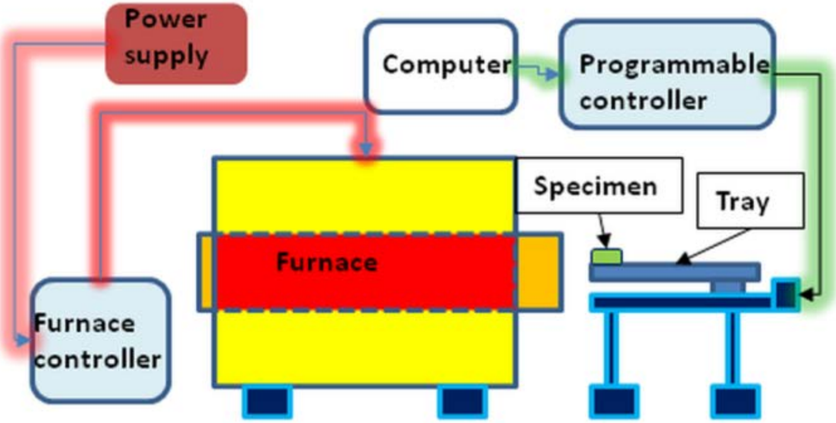


Controlled environment high temperature micro-indentation system (WVU)

Sample

- ODS Coating layers on flat plate substrates

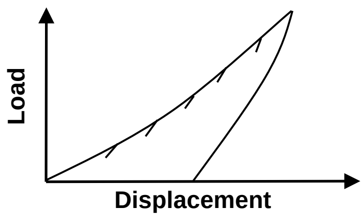
Gridding and Cutting of ODS Coated Coupons



Schematic of the cyclic thermal exposure apparatus setup (WVU)

Durability/Damage Assessment of Advanced Turbine Components

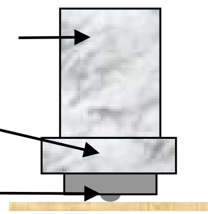
Multiple Loading/Partial Unloading Micro-Indentation



PZT Actuator

Load Cell

Indenter



Applications:

- Elastic Modulus
- Stress-Strain Curve
- Indentation Creep
- High Temperature Characterization

Potential:

- In Situ Material Characterization
- Portability
- Variable Influence Zone

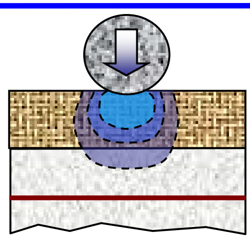
Load Based vs. Contact Area Based

$$P = \frac{4}{3} \cdot \frac{\sqrt{R}}{k_0} h^{3/2}$$ *Hertzian Spherical Contact Mechanics*

where, $$k_0 = \frac{1}{E_r} = \frac{1-\upsilon^2}{E_d} + \frac{1-\upsilon^2}{E_i}$$

$$\frac{dP}{dh} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A}$$ ***Area Based***

$$\frac{dP}{dh} = (6RE_r^{\ 2})^{1/3} \cdot P^{1/3}$$ ***Load Based (WVU)***



$$\frac{dP}{dh} = (6RE_r^{\ 2})^{1/3} \cdot P^{1/3}$$

$$\frac{dh}{dP} = C \times \frac{1}{P^{1/3}}$$

$$\left.\frac{dh}{dP}\right|_1 - \left.\frac{dh}{dP}\right|_2 = C \times \left(\frac{1}{p_1^{\ 1/3}} - \frac{1}{p_2^{\ 1/3}} \right)$$

$$\left(\frac{dh}{dP} \right) = C \times \left(\frac{1}{P^{1/3}} \right) + C_s$$

$$x = \frac{1}{p^{1/3}} \ , \ y = \frac{dh}{dp}$$

$$y = mx + b$$

where, $a = \left(6RE_r^{\ 2}\right)^{-1/3}, \ b = C_s$

Technique Benefits

- **Designed for TBC/Bond and ODS Coating specimen**
  - Measurement of surface stiffness responses as a means to correlate the evolution of the microstructural changes of the coating layer/substrate subjected to high temperature thermal cycles.
  - Can also be correlated to the damping effect
  - No surface preparation needed
- **Controllable Influence Zone**
  - The overall response obtained is a contribution form different regions of the multilayered thermal barrier coating structure.
  - As load increases, the influence zone increase as well.

ODS Mechanical Property Measurement

	200 W	150 W	100 W	Substrate
As-received	174.4	173.8	227.6	126.5
15 cycles	141.5	80.9		100.2
40 cycles	132.1	85.5		109.1
	143	86.8		
80 cycles	113.2	59.4	57.3	58.7
	113	58.4	57.4	61
				56.2
160 cycles	110.3	68.8	62.4	
	135.4	65.4	61.2	
	118.2			
240 cycles	210	72		
	213.5	88.8		
360 cycles	197.3	123.4		123
	181.5	136.1		125.7
480 cycles	250.5	100.5	63.8	124.9
	229.4	98.2	59	141.7
600 cycles	183	84.7	163.6	124.6
	225	96.5	139	140.2
720 cycles	201.5	176.5	116.1	155.8
	205.4	200.4		168.9
1040 cycles	194.6			99.3
	188.7			92.9
1080 cycles	343.0	168.2	174.8	123.6
	261.2	142.1		141.9

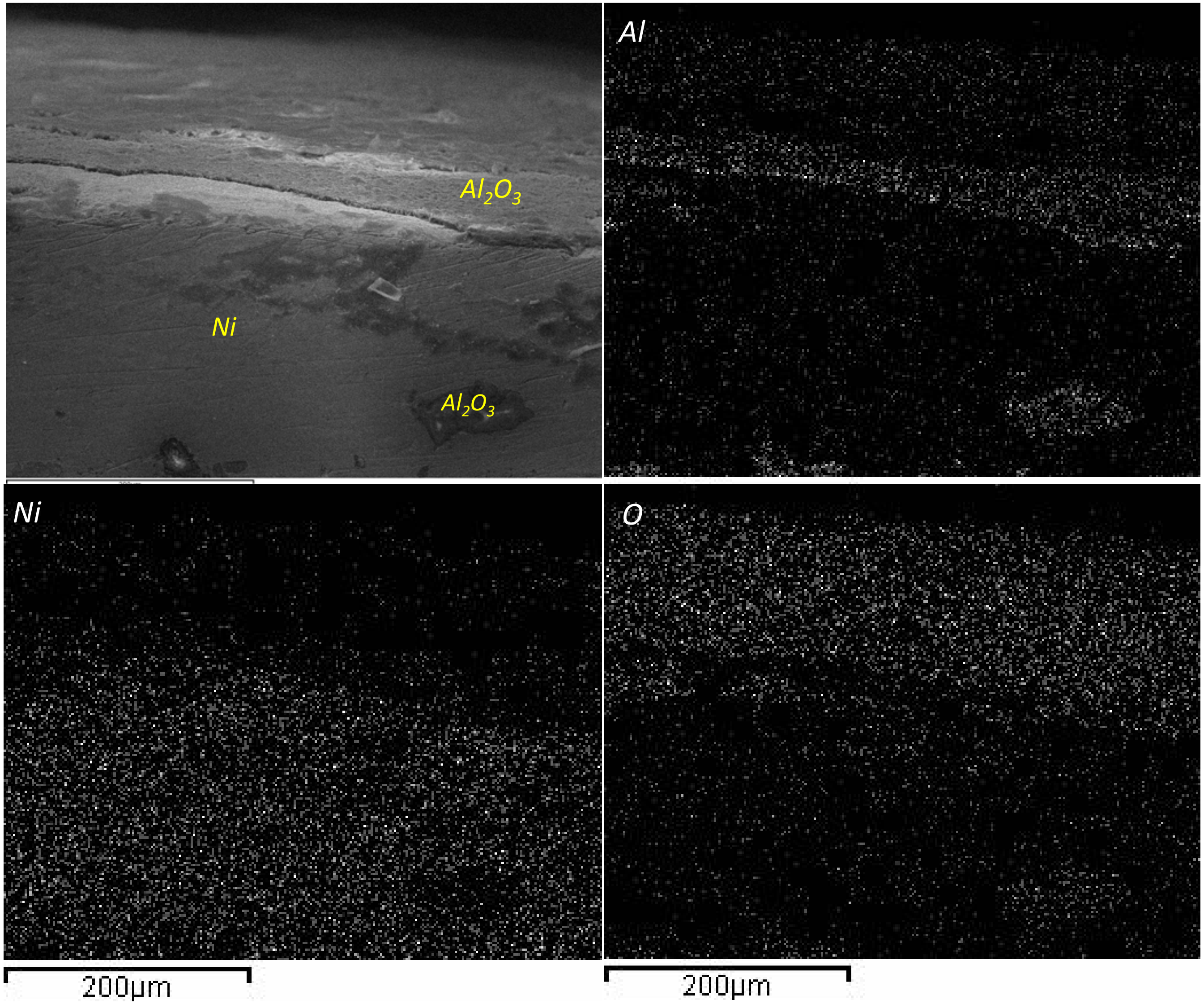
*** Each cycle consists of moving test sample to the furnace within 15 minute and kept at 1100 °C for 45 minutes and moved out within 15 minutes, kept for 45 minute at room temperature.***

ODS Mechanical Property (cont.)

	200 W	150 W	100 W	Substrate
1280 cycles	165.4	171.8	144.7	
	132.9	134.0	124.4	
1480 cycles	202.6	116.3		
	162.8	142.3		
1880 cycles	164.5	104.3	93.2	
	110.3	102.7	104.7	
2080 cycles	148.8	116.8		
	113.4	95.7		

***** 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.***

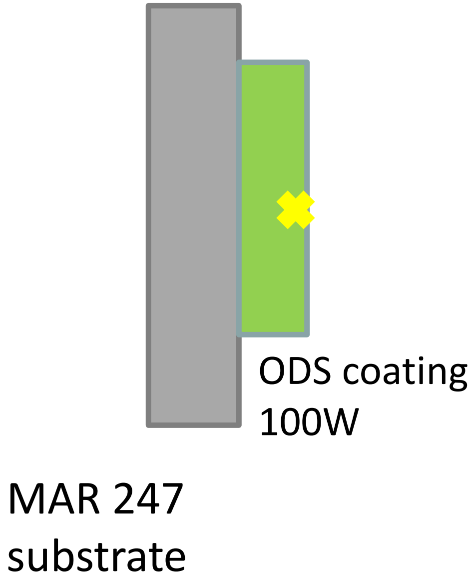
Stable alpha Al_2O_3 oxide layer at 240 cycles (200 W sample)

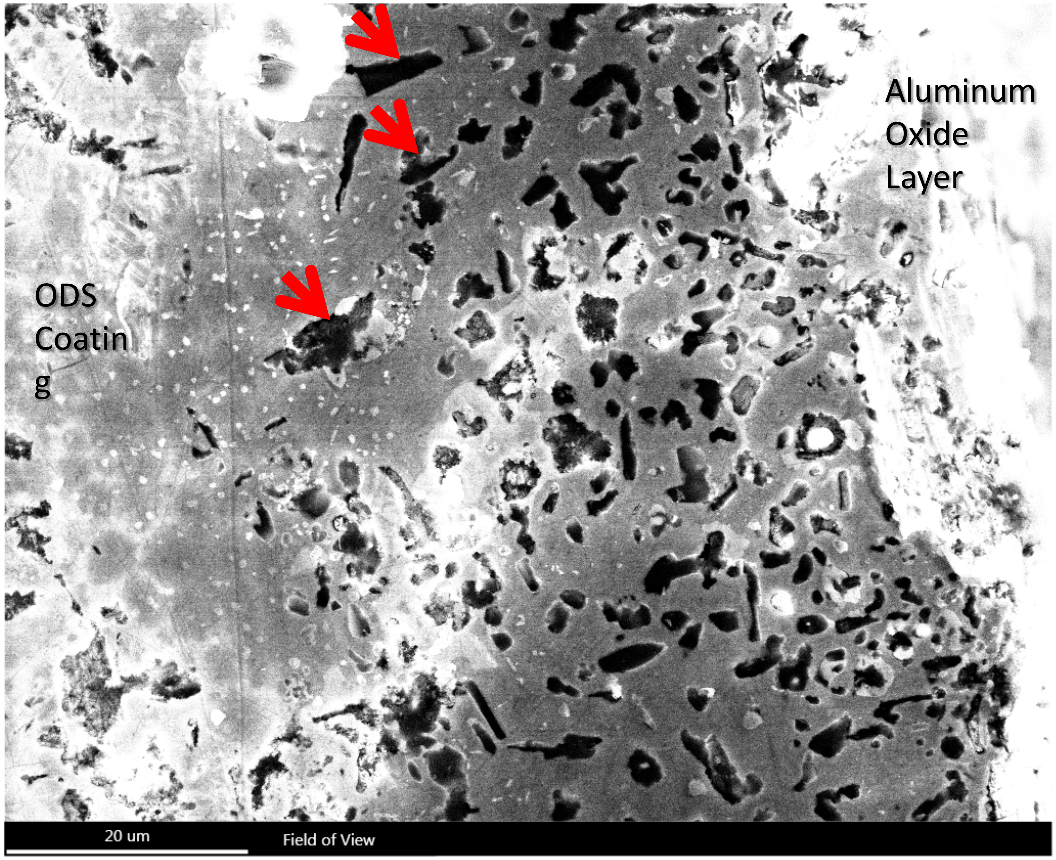


100W ODS Coating, 1280 cycles

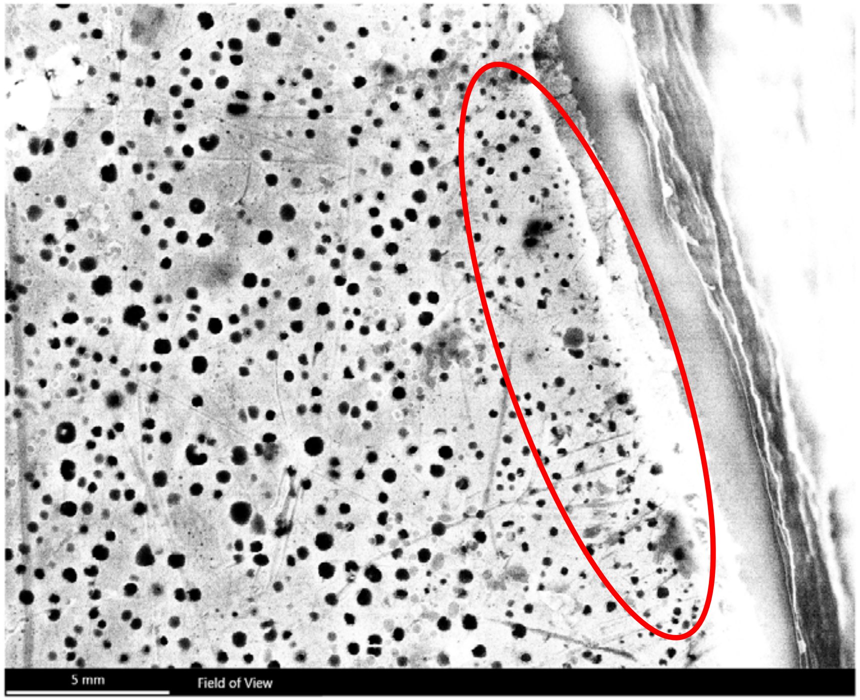
- **Oxide Layer Failure**
- **Oxygen diffused into the ODS layer**
- **Abnormal aggregation of Aluminum Oxide inside ODS layer**

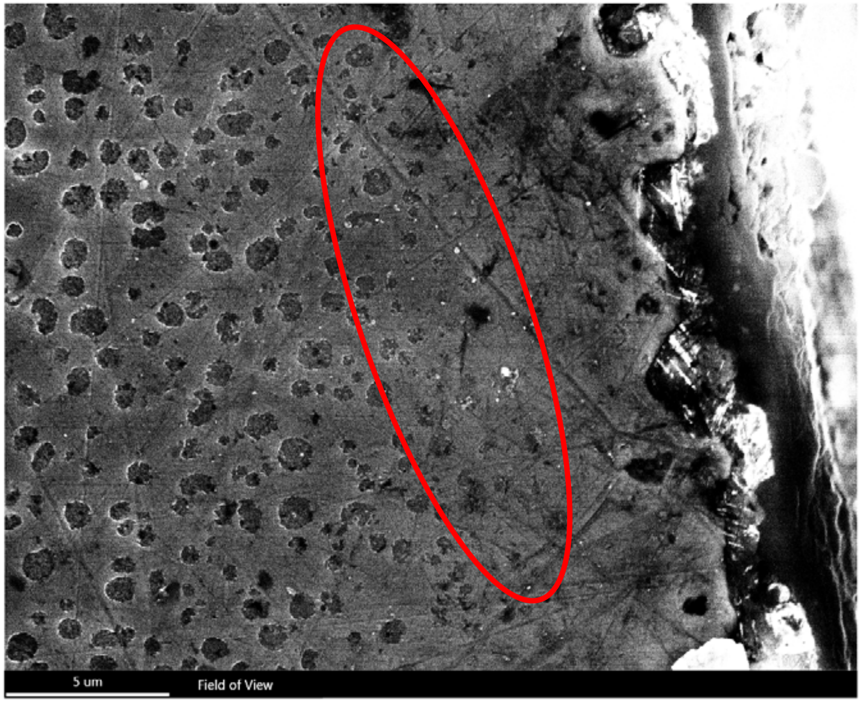
100W ODS Coating, 1280 cycles





γ' Phase Transition (150 W ODS Coating)





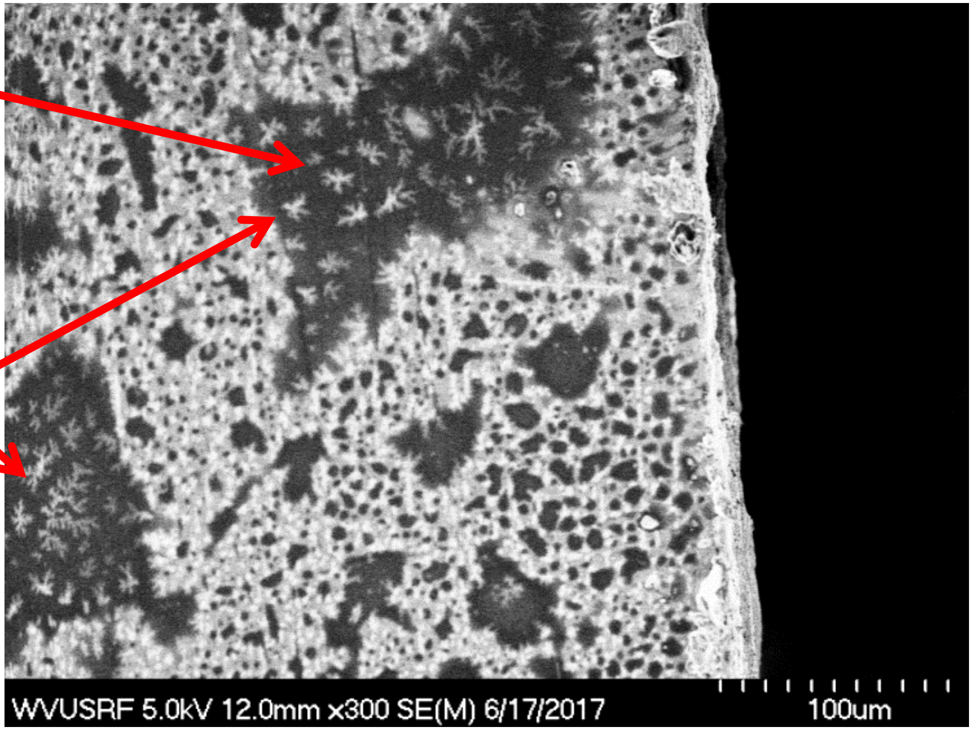
1280 thermocycles
Young's Modulus, E = 126.8 GPa

1480 thermocycles
Young's Modulus, E = 97 GPa

2080 cycles 150W ODS layer

Coarsened
γ' phase

Dendrite
s



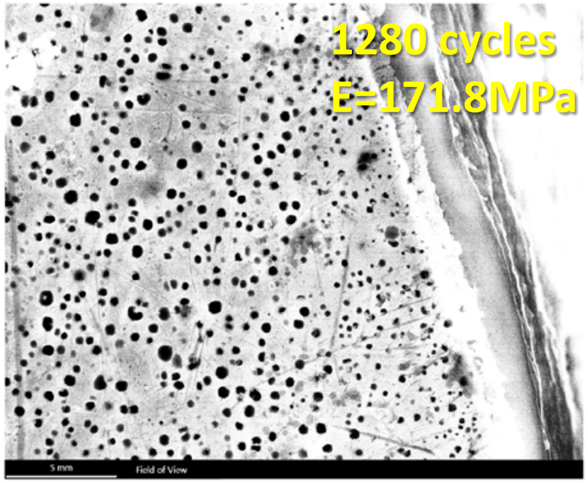
γ' Phase Transition (150 W ODS Coating)

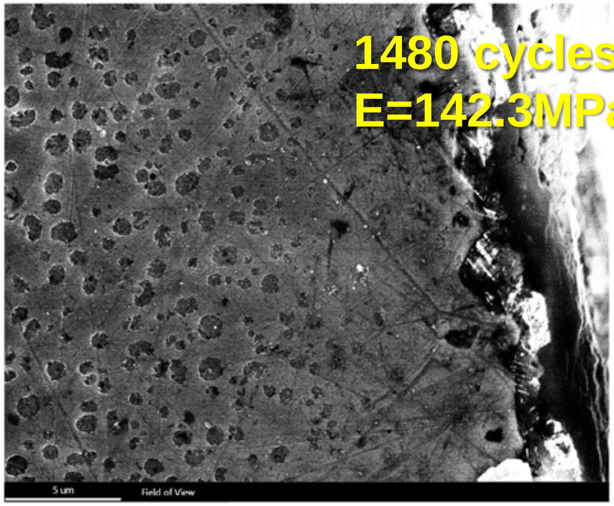
- After 1480 cycles, the γ' phase near oxide layer disappeared, and coarsening phenomena began to occur.

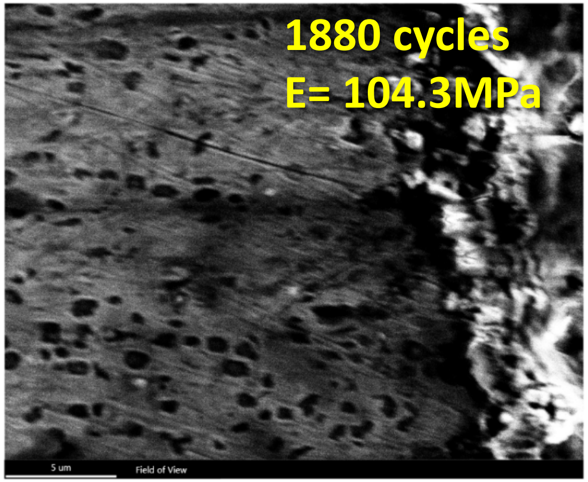
- After 1880 cycles, the γ' phase coarsened and migrated toward oxide layer

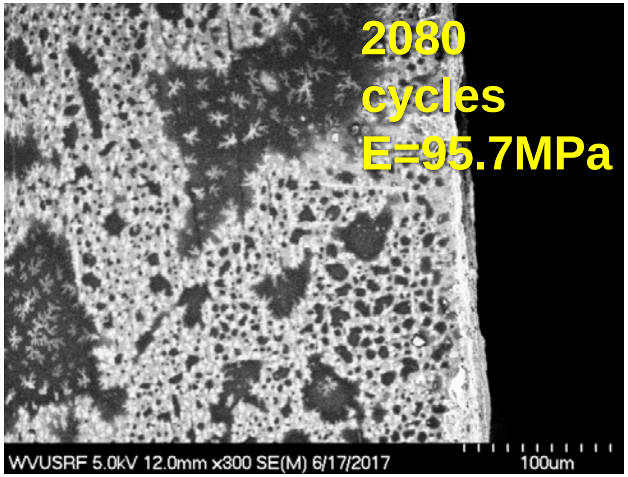
- After 2080 cycles, continued and accelerated coarsening and coalesce of γ' phase with phase changed to **dendrite** crystal structure at the coalesce site

150W ODS Coating - Summary

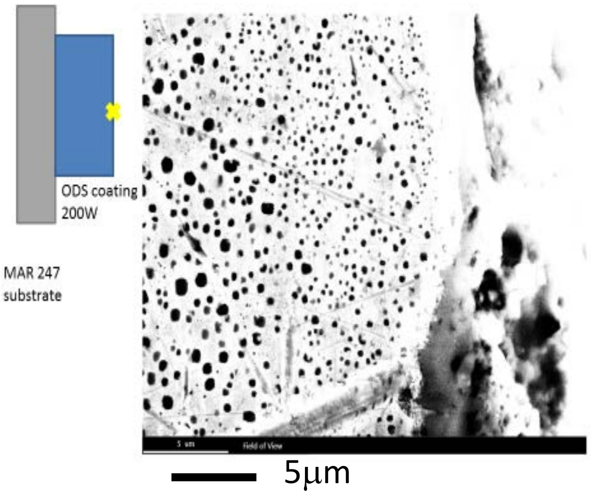


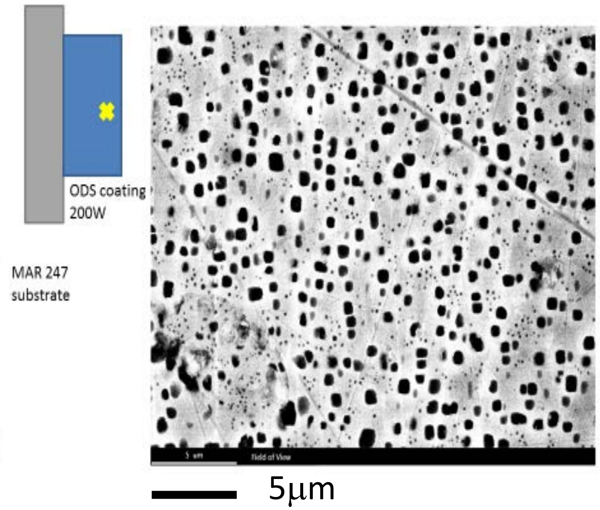


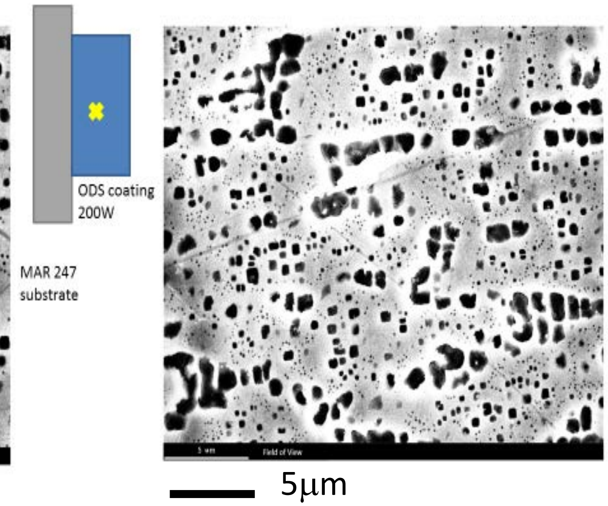


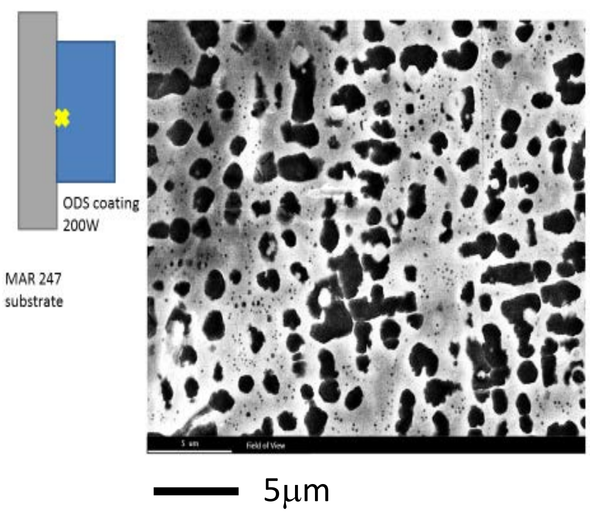


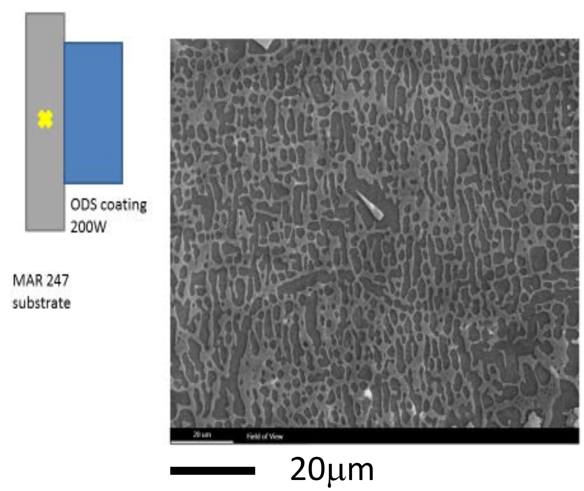
AM-assisted ODS Coating Characterization



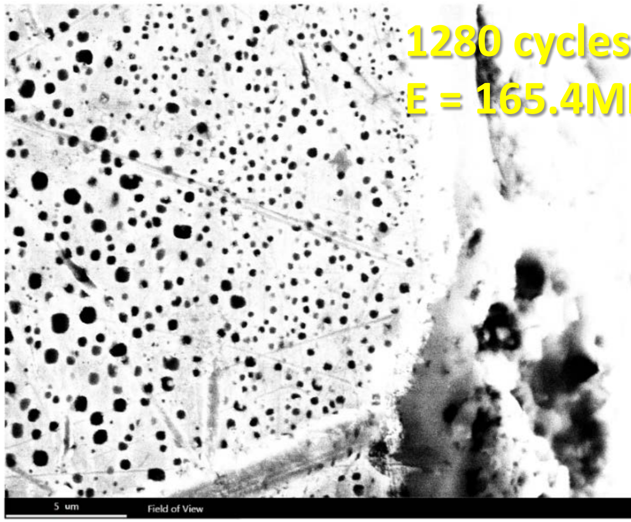


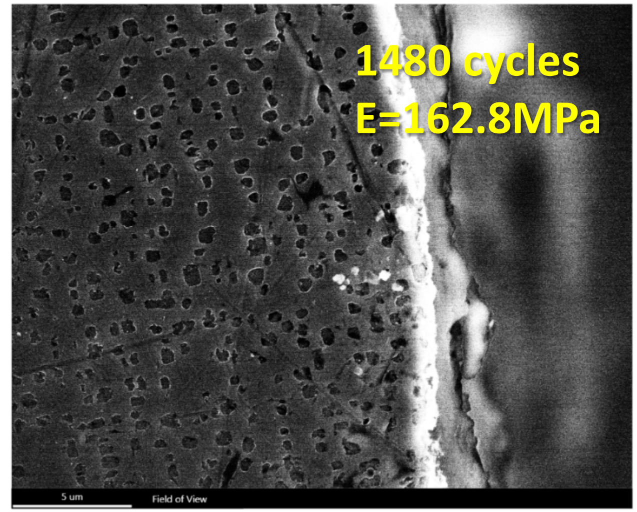


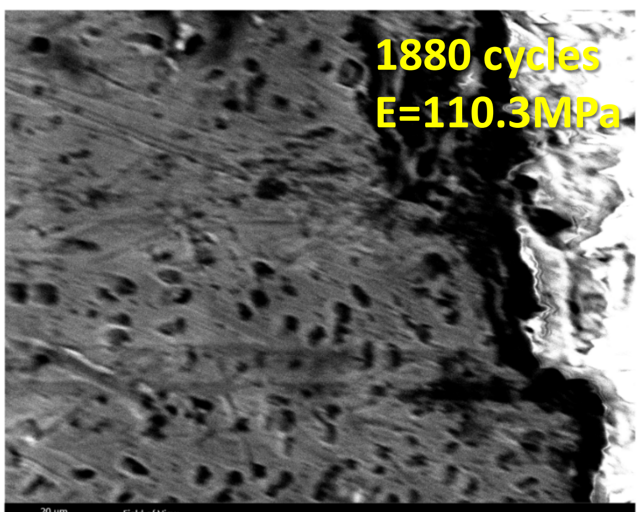


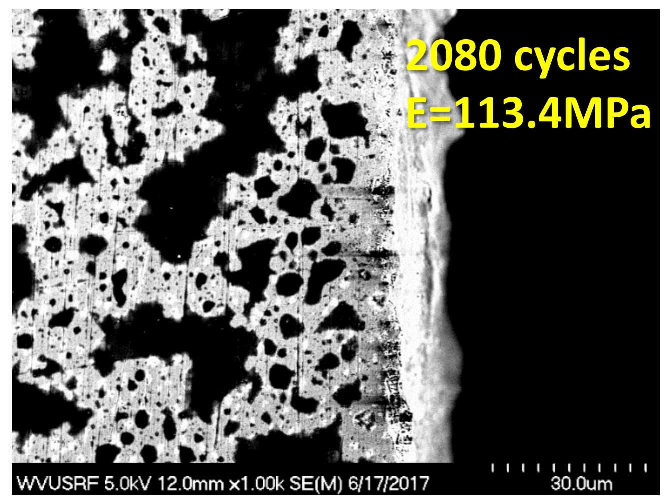


γ' phase in 200W ODS Coating



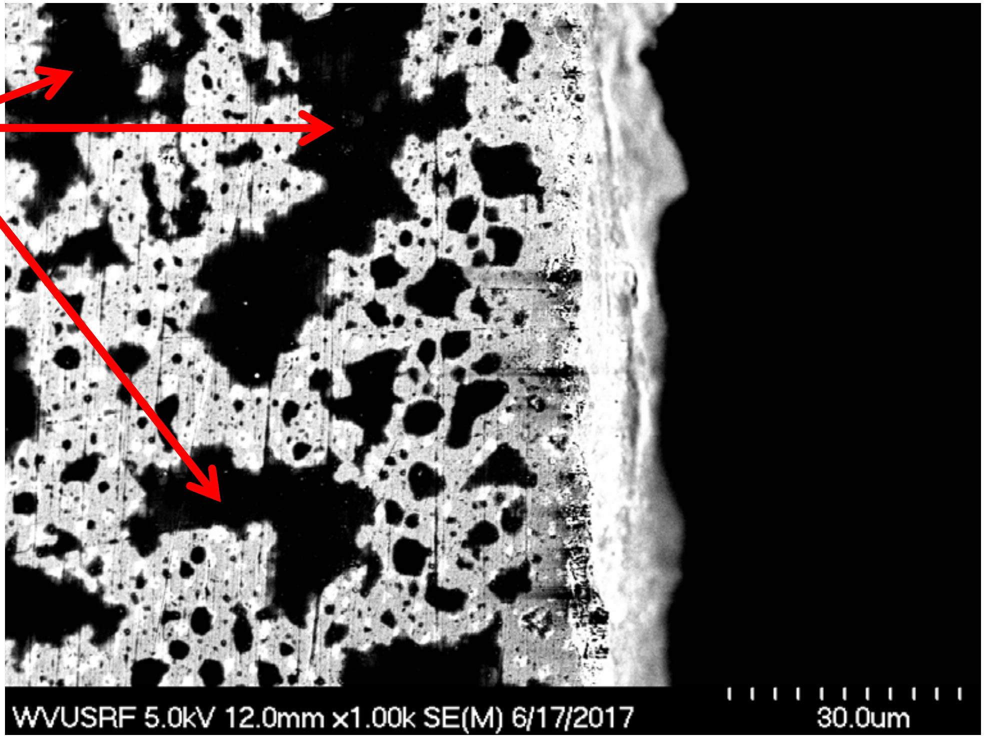






2080 cycles 200W ODS Coating

Coarsened
γ' phase



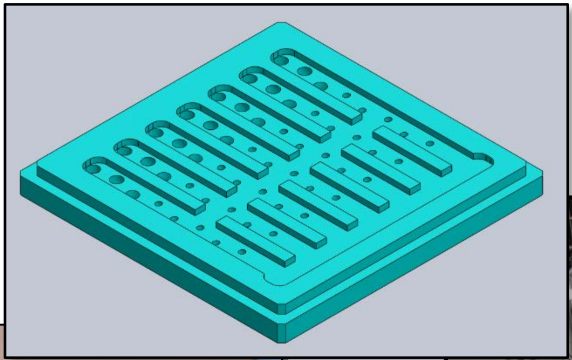
200W ODS Coating - Summary

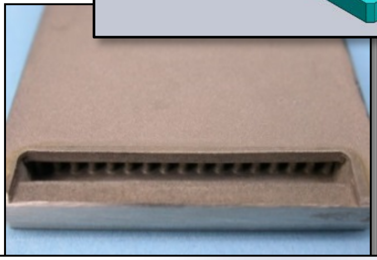
- Stable secondary γ' phase near oxide layer up to 1880 cycles
- After 1880 cycles, the γ' phase coarsened with higher coarsening rate near the oxide layer. However, no dendrite phase is observed at 2080 cycles.
- Ostwald ripening mechanism – γ' phase will form larger particles and tend towards spherical in shape. (T. J. Carter, 2004)
- The γ' will slowly diffuse into γ-matrix (in dendrites form), and will cause the creep strength diminishes.
- Due to coarsening of γ' phase (eventually the dendrite phase formation), mechanical property/strength will be substantially weakened. The measured reduction of Young's modulus correlated well with this change of surface microstructure, which can be used as NDE failure/damage assessment tool.
- The 200W ODS coating has coarsening phenomena as well but occurred at much longer thermal cycles. ODS coating strength may still be preserved until formation of dendrite phase.

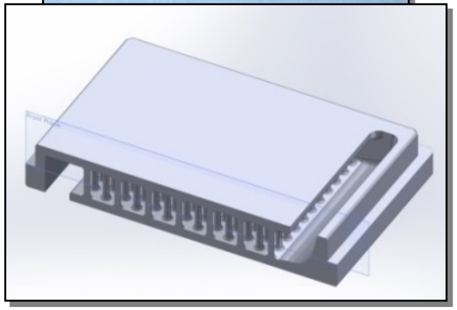
Outlines

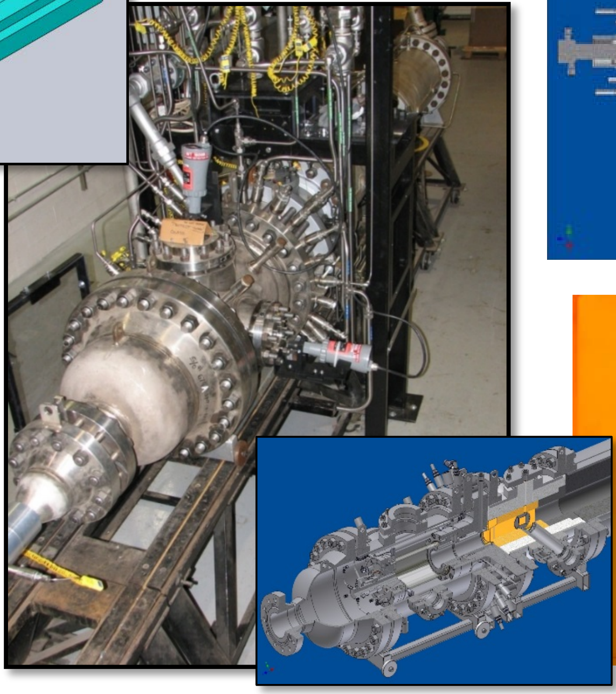
- *Introduction and Background*
- *Challenges, Objectives, Benefits of Technology, Research Task Plan*
- *Tasks*
  1. *Heat Transfer Characterization*
  2. *ODS Coating (AM Assisted)*
  3. *ODS Powders Fabrication and Characterization*
  4. *Microstructural and Mechanical Properties Characterization*
  5. ***Detailed Experimental Measurement and Validation***

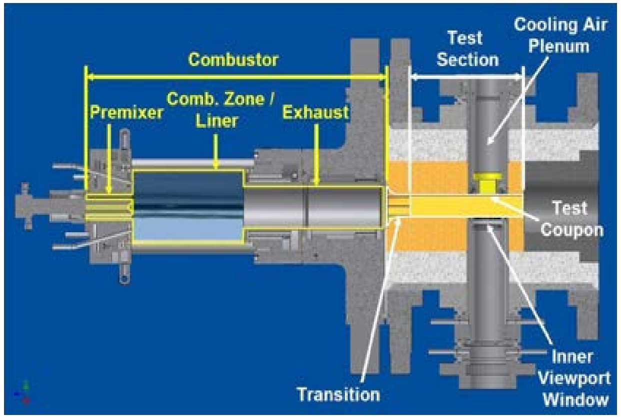
Task 5: Detailed Experimental Measurements and Validation

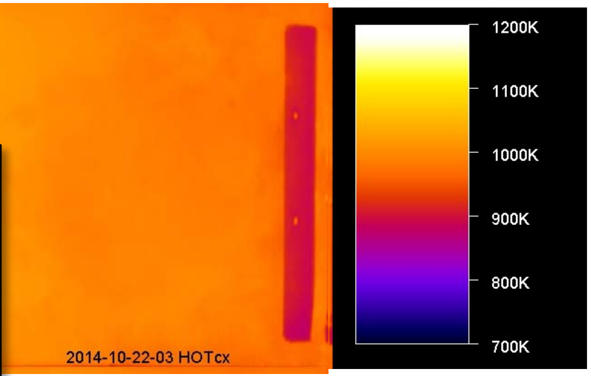












- ➢ Conduct HT/P testing at 1100°C demonstrating ~50-70% enhancement of NSECC over smooth channel and pin-fin arrays
- ➢ Further optimization of the NSECC configuration for enhanced cooling performance
- ➢ Address additive manufacturing capabilities for production of parts

Summary

- ***Reporting period (10/01/2016-10/31/2017)***

- ***Concept of surface wall jets developed in this research was a good candidate to improve the cooing efficiency for turbine blades.***

- ***Application of AM-assisted ODS coating for high temperature materials research is presented. Fabrication of ODS coatings and cooling channels were completed and successful. The three phases of work proved the concept that ODS was additively manufacturable.***

- ***Long-term isothermal and cyclic thermo-loading tests of AM-assisted ODS coatings and cooling channels were conducted. Existence of gamma prime phase in AM-assisted ODS coating is confirmed.***

- ***Further research effort to cover research issues such as:***
  Stable oxide formation mechanism – oxidation kinetics of non-equilibrium material system
  ODS power optimized for AM applications
  Model-based AM Processes – 3D manufacturing optimization, scale-up route, cost, efficiency, etc.

Thank You!