NATIONAL ENERGY TECHNOLOGY LABORATORY

University Turbine Systems Research

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 : FY2015-FY2018
Cost: DOE: $798,594 / Non DOE: $216,896

Project Kick-Off Meeting Oct 5, 2015

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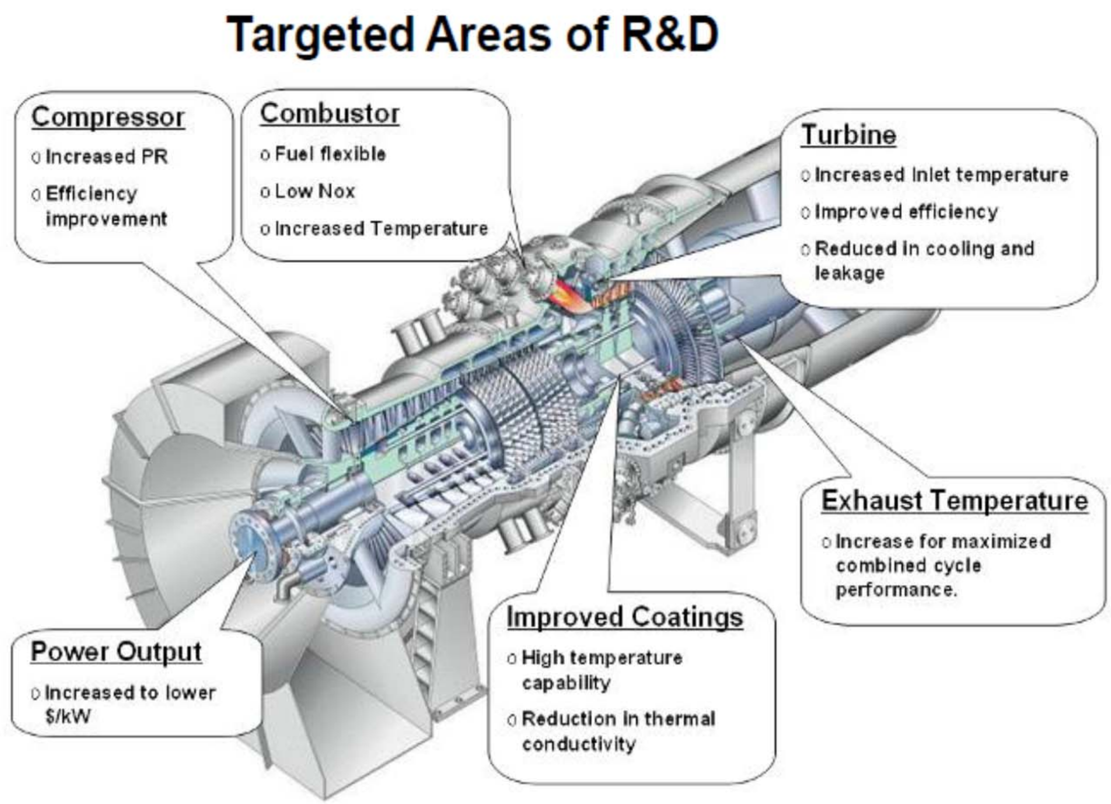
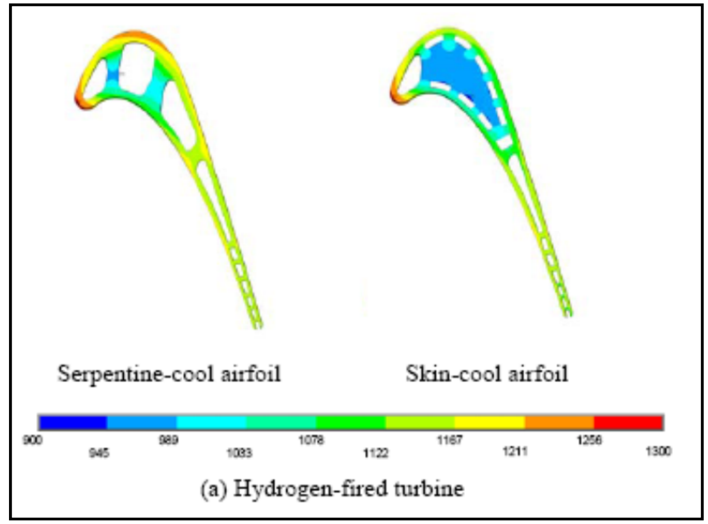
Outlines

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

Technical Background/Approach

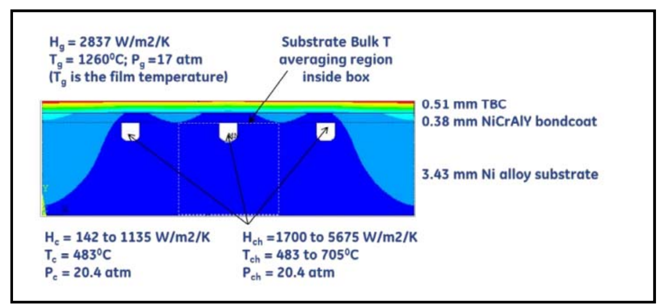




Siw, S.C., Chyu, M.K., Karaivanov, V.G., Slaughter, W.S., and Alvin, M.A., 2009, "Influence of Internal Coolinjg Configuration on Metal Temperature Distributions of Future Coal-Fuel Based Turbine Airfoils," ASME Turbo Expo 2009, Paper No. GT2009-59829.

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

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



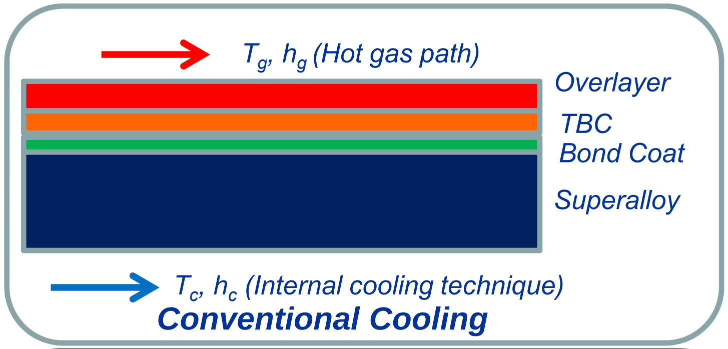
Skin Cooled Bulk Substrate Metal Temperature as a Function of Channel Heat transfer Coefficient and Coolant Temperature

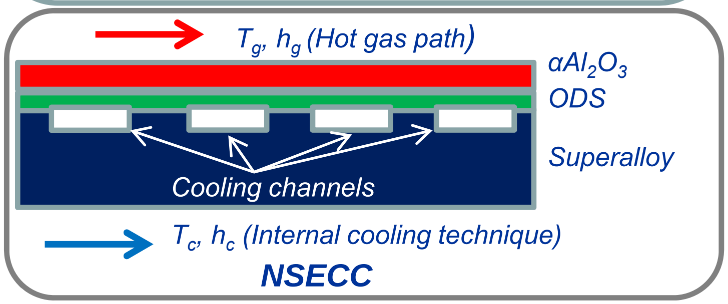
Near surface 'skin cooling' or 'double-wall' internal cooling arrangement leads to a significant reduction of metal surface temperature, ~50 – 100℃, compared to conventional serpentine cooling designs

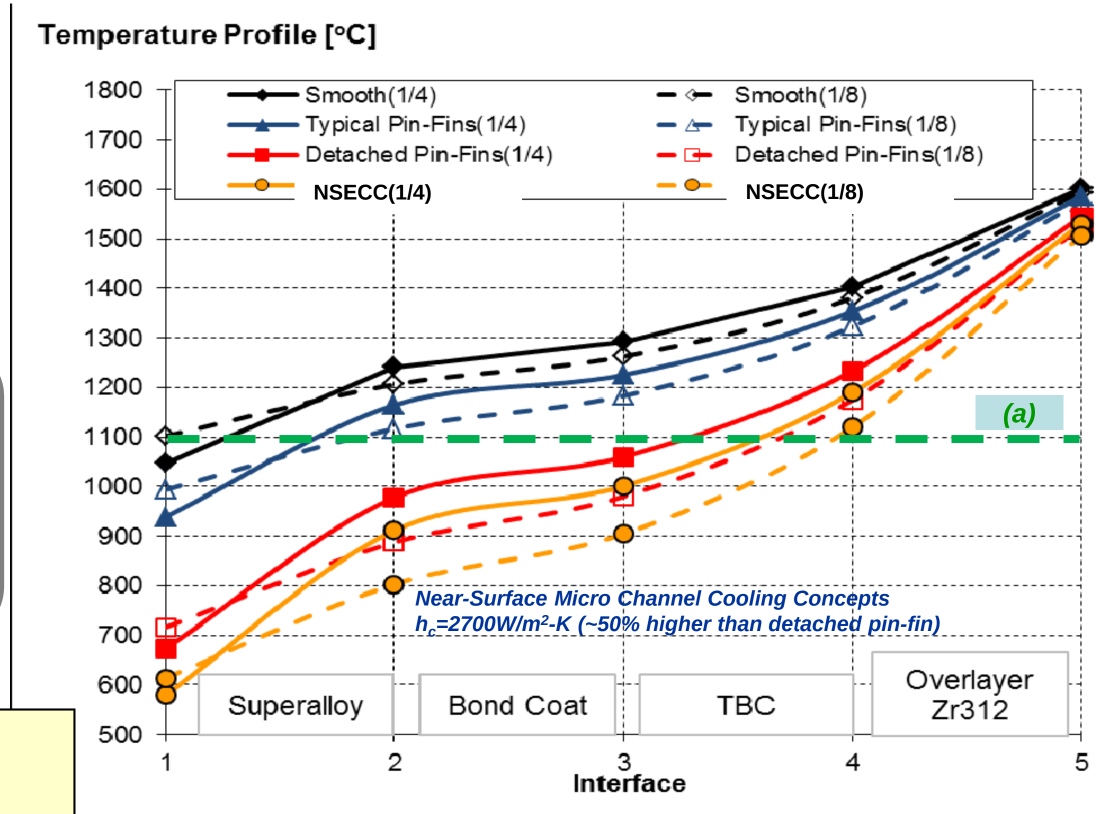
Bunker, R.S., 2013, "Gas Turbine Cooling: Moving from Macro to Micro Cooling," ASME Turbo Expo 2013, Paper No. GT2013-94277

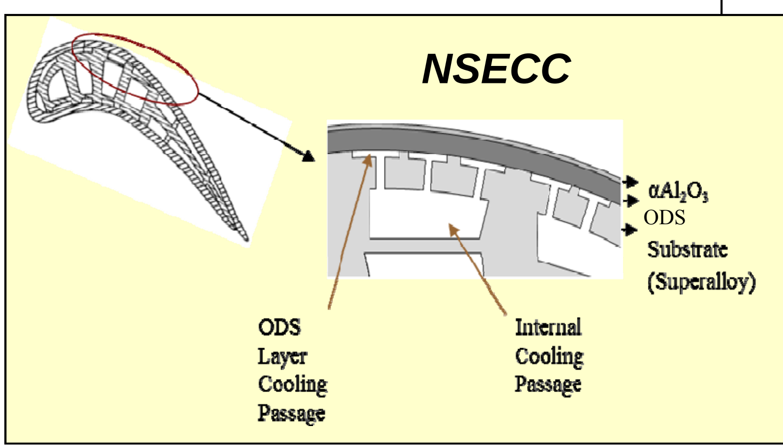
Turbine Thermal Management

– Advanced Cooling via NSECC Development –









Projected Temperature Profiles Incorporating Advanced Cooling Concepts

– S.Siw, M.Chyu, December 2011 –

Coolant properties @ Re=50,000, 600K

Hot Gas Temperature: 1700ºC; Gas Side h: 4000 W/m²K

(a) Maximum temperature considered for functional operation of bond coat systems

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Near Surface Embedded Channel Cooling

Technical Challenges

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

Project Objectives

- **To design highly-heat-transfer augmented and manufacturable internal cooling channels for the development of NSECC. The two heat transfer augmentation techniques to be explored first are:**
  (a) advanced impingement cooling
  (b) zig-zag channel configurations
- **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**

Benefits of Technology to the DOE Turbine Program

- **High heat transfer removal rate compared to conventional internal cooling techniques, mandated by the efficiency goals**
- **Currently proposed Near-Surface-Embedded Cooling Channel (NSECC) design can render 50-70% higher cooling effectiveness than existing internal cooling technologies. Even greater improvement is possible**
- **NSECC can be positioned at desired near wall locations**
- **NSECC can be optimally designed based on local cooling load demand, eliminating hot spot, resulting in more cooling uniformity**

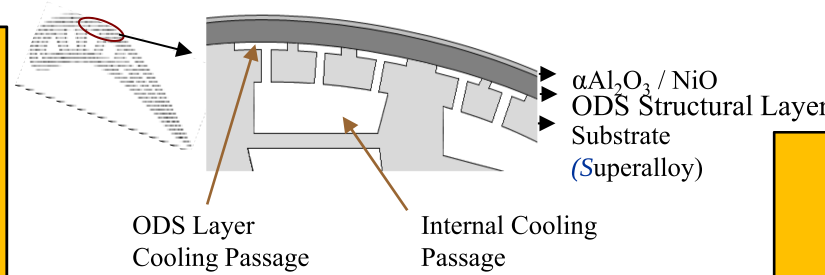
Current State of the Art, Patented Concepts, and Advanced Turbine Airfoil Configurations for Improved Near Surface Cooling

Cooling Configuration	Serpentine US Patent 005924843 1999	Double Wall (Skin Cooling) European Patent Specification, EP 1 617 043 B1, 2008	Surface or Near Surface ODS-Micro-Channel
Thickness	150 μm MCrAlY (SOTA)	150 μm MCrAlY (SOTA)	200-500 μm ODS (Max: >200 μm – 5 mm)
Maximum Surface Temperature	<1000°C (Bond Coat-Substrate Alloy)	<1000°C (Bond Coat-Substrate Alloy)	~1200°C (ODS)
Rupture Strength @ T>1000°C	Low (Metal Substrate)	Low (Metal Substrate)	High (ODS Layer)
Manufacturability	Casting – SOTA Issues Resolved; Commercial Process	Casting – Challenges wrt Core Pull-Out & Consistent Thin Wall Fabrication	Casting & ODS Cold/Hot Spray– Projected Ease of Fabrication
Cooling Channel	Internal (Deep)	100 μm from Surface	Outside or Near Metal Substrate Surface
Heat Removal Capacity	Reference Point	44% more	**50-70% more**
Comparative Predicted Airfoil Metallic Substrate Temperature	1100°C	950°C	900 - 850°C

Project Work Breakdown Structure

Enhanced Heat Removal Capability

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



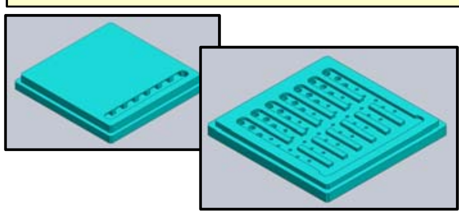
Near Surface Embedded Cooling Channel (NSECC)

Novel Metallic ODS Surface Coating

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

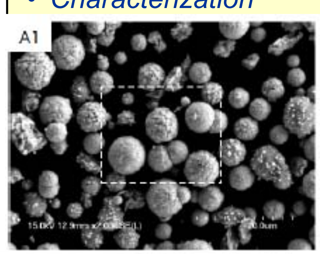
Task 1 – Advanced Impingement

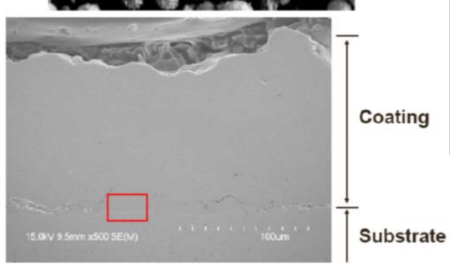
- *Design, CFD modeling & scaled testing*
- *Advanced impingement*



Task 2 – ODS Powder Fabrication and Characterization

- *ODS powders fabrication*
- *Characterization*





Task 3 – ODS Coating (AM Assisted)

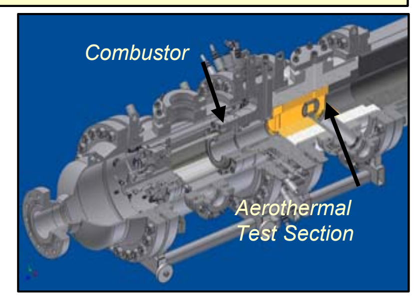
- *Process development and optimization*

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

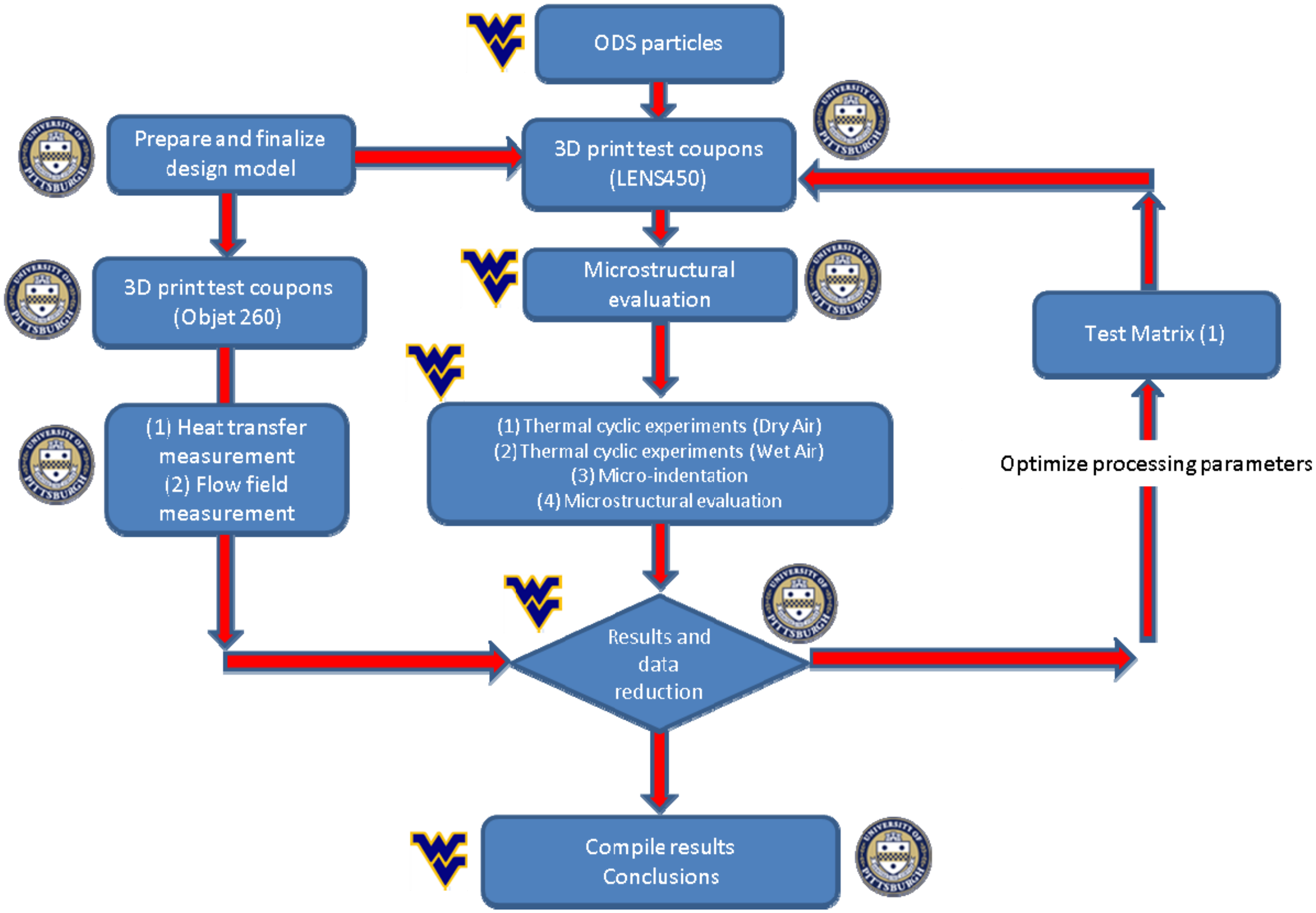
Solar Turbines
A Caterpillar Company

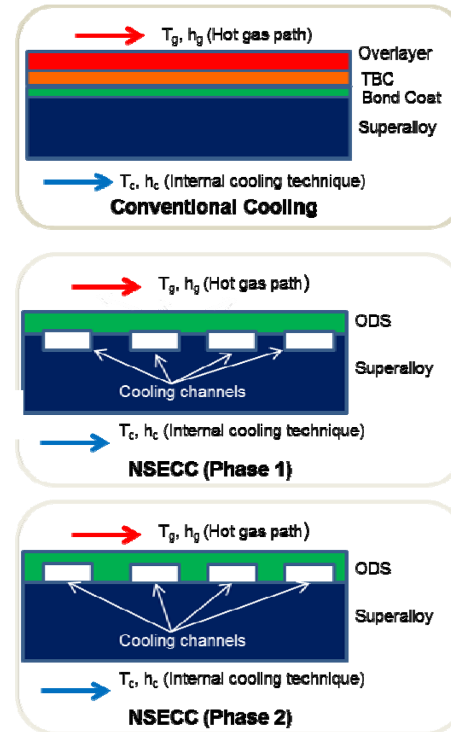
HOSOKAWA MICRON

University of Pittsburgh

West Virginia University

Research Task Plan (3 years)





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Task 1 Advanced Impingement

Objective: Develop internal air foil cooling technologies capable of yielding a heat transfer enhancement factor nearly 5 times the smooth channel and which are reasonably manufacturable

- Leading Edge Cooling - screw (helical) cooling

Challenge: Some of the promising intricate vortex generating geometries which were studied in the up-scaled research models cannot always be reproduced in actual size blade castings or are very sensitive to the manufacturing tolerances, particularly when small internal holes and sharp edge features are required

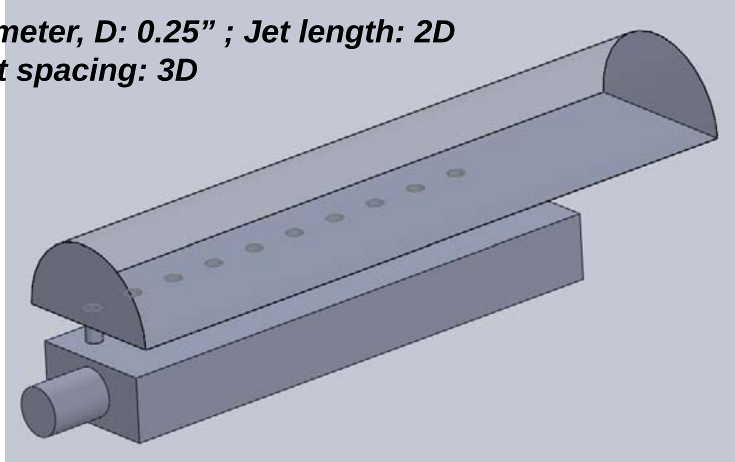
Why? Advantages?

- Swirling flow structure, move radially, generating 3D screw-shaped flow
- Optimized screw cooling configurations resulted in more uniform cooling ~ more efficient than direct impingement
- Less sensitive to fabrication tolerances than highly effective internal cooling technique, ~ more attractive for industrial applications

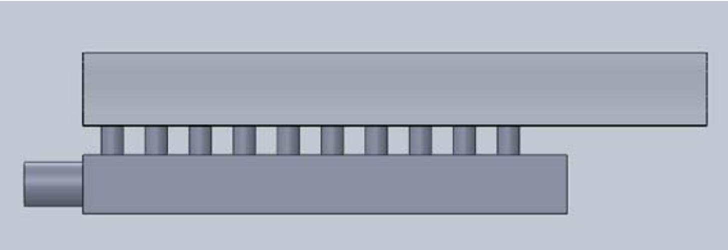
Task 1 Advanced Impingement

Test #1 Inline 90º jets

Jet diameter, D: 0.25" ; Jet length: 2D
Inter-jet spacing: 3D



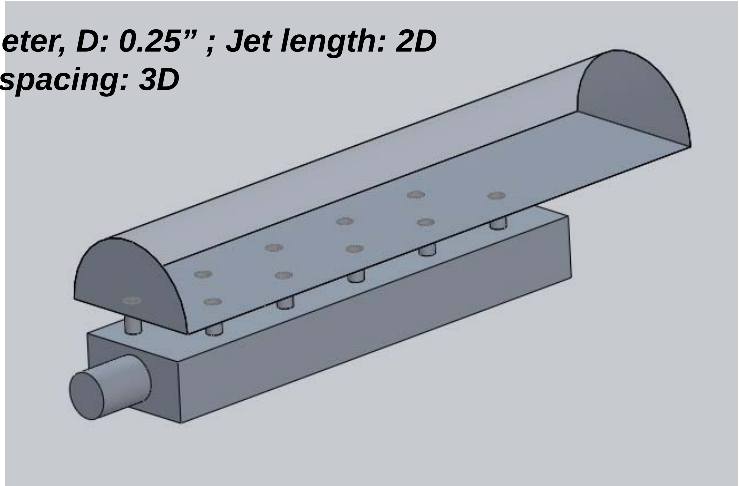
Test #3 Inline 90º jets



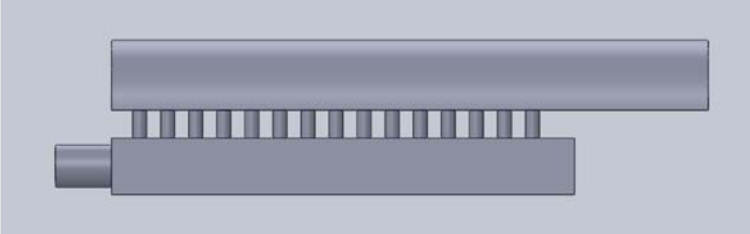
Jet diameter, D: 0.375" ; Jet length: 1.33D
Inter-jet spacing: 2D

Test #2 Staggered 90º jets

Jet diameter, D: 0.25" ; Jet length: 2D
Inter-jet spacing: 3D



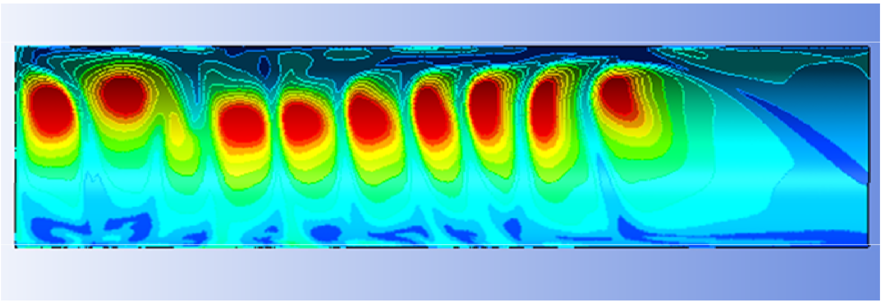
Test #4 Inline 90º jets



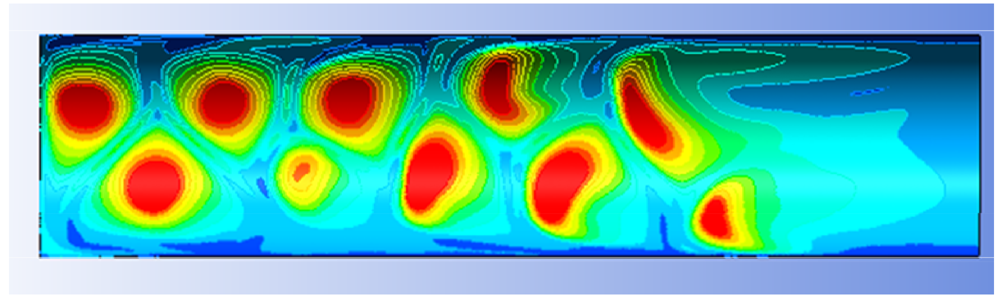
Jet diameter, D: 0.25" ; Jet length: 2D
Inter-jet spacing: 2D

Task 1 Advanced Impingement

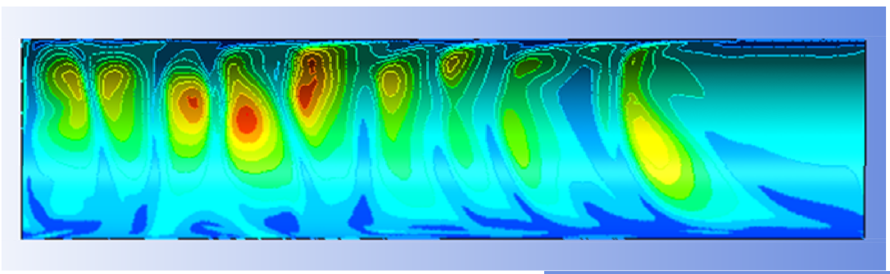
Test #1



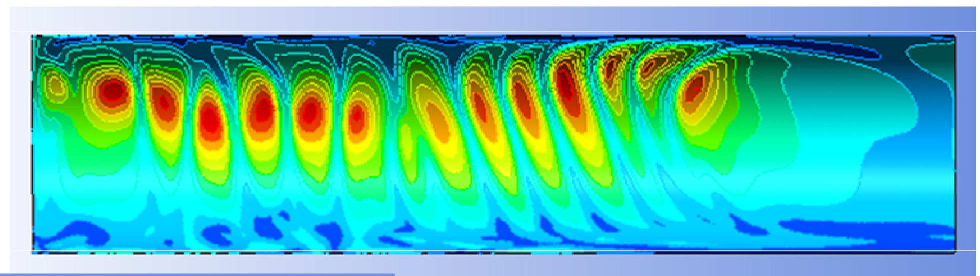
Test #2

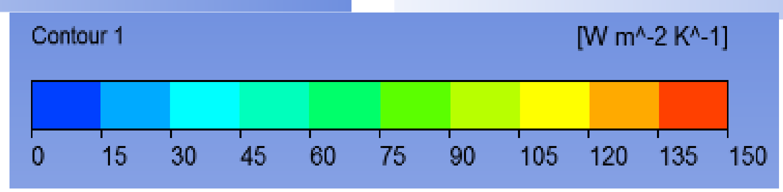


Test #3



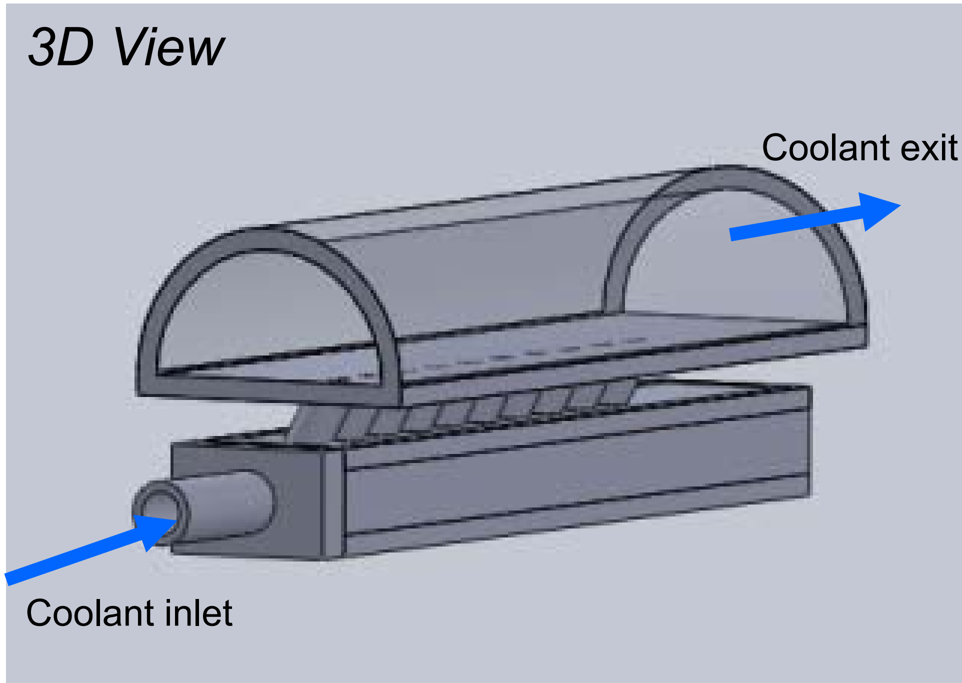
Test #4



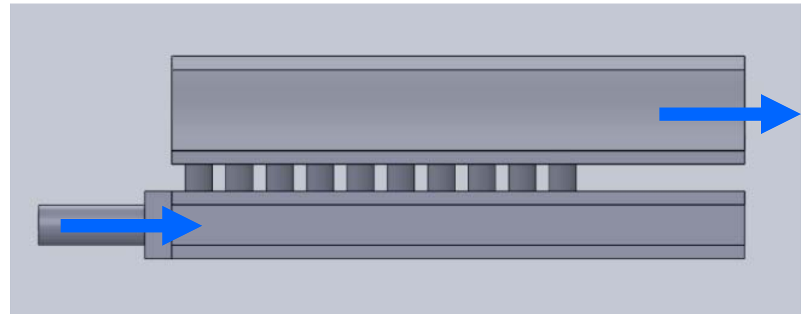


- *Test#1 and #2 – Significant impingement from the jets*
- *Test#3 - larger jet, reduce the bulk velocity, very minimal impingement effects, most uniform heat transfer distribution among all tested cases*
- *Test#4 - total number of jets is 50% more than other test cases*
  - impingement effects are preserved
- ***Design and fabricate scaled-up test section for detailed experimental study, for validation with CFD results***

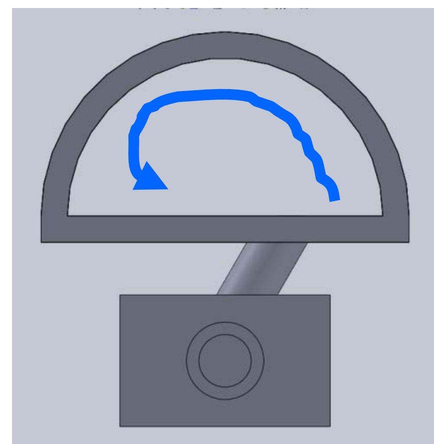
Task 1 Advanced Impingement



Side View



Front View



- Jet diameter, d: 6.4mm (0.25”)
  Inter-jet spacing: 1.5d
  Jet angle, θ: 30°
- Semi-circular channel diameter, D: 10d
- Test section thickness: 12.7mm (0.5”)

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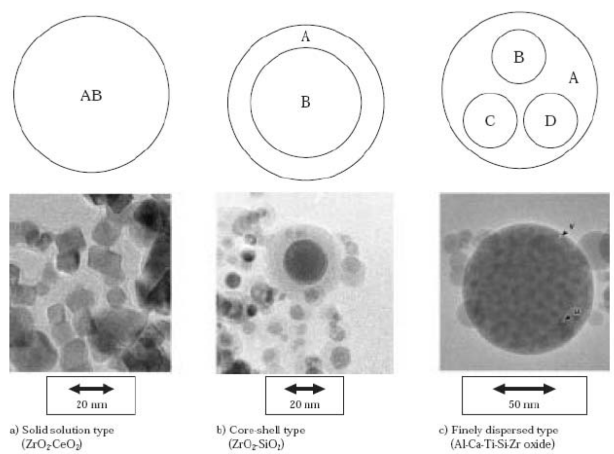
Task 2: ODS Powders Fabrication and Characterization

Objective: Develop and optimize ODS fabrication process for additive manufacturing

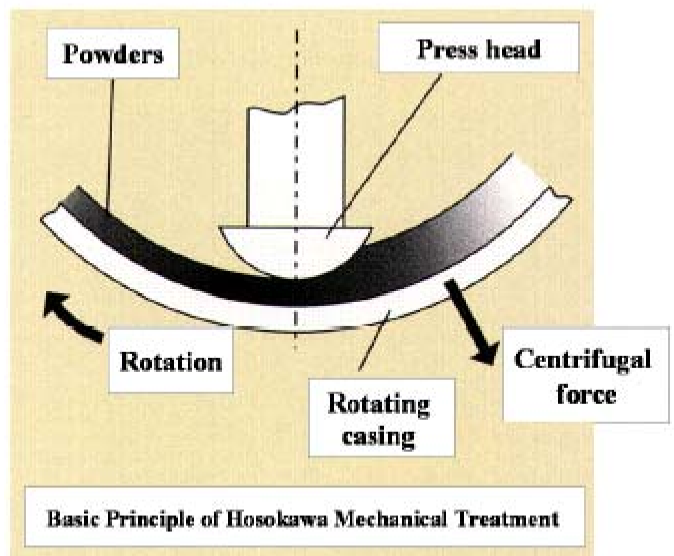
Approach

- 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 nano-oxide particles,
  - minimized grain growth during sintering.

Why MCB + BM?



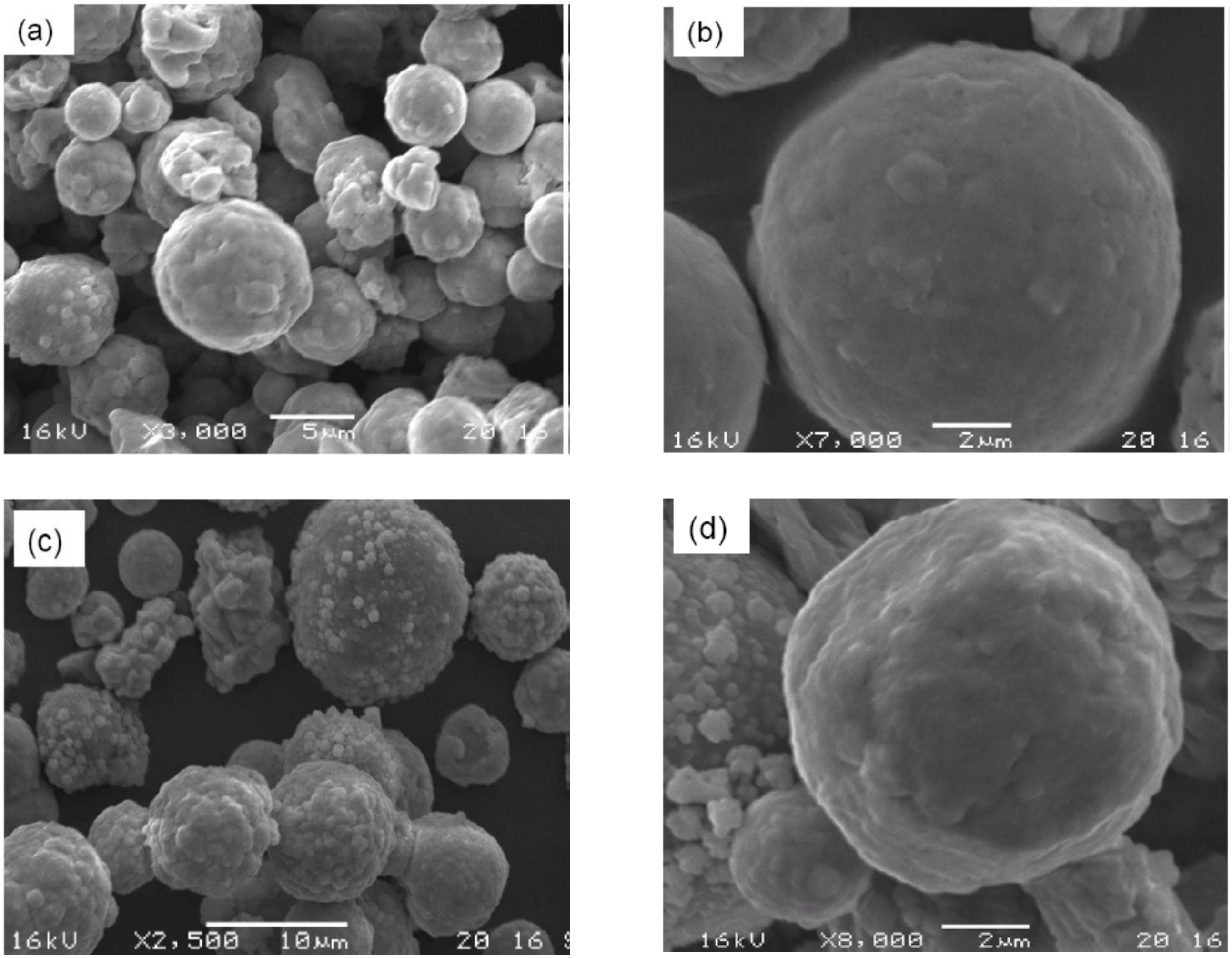
Structural patterns of nanocomposite particles
[T. Yokoyama and C. C. Huang, KONA No.23 (2005)]



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 %)

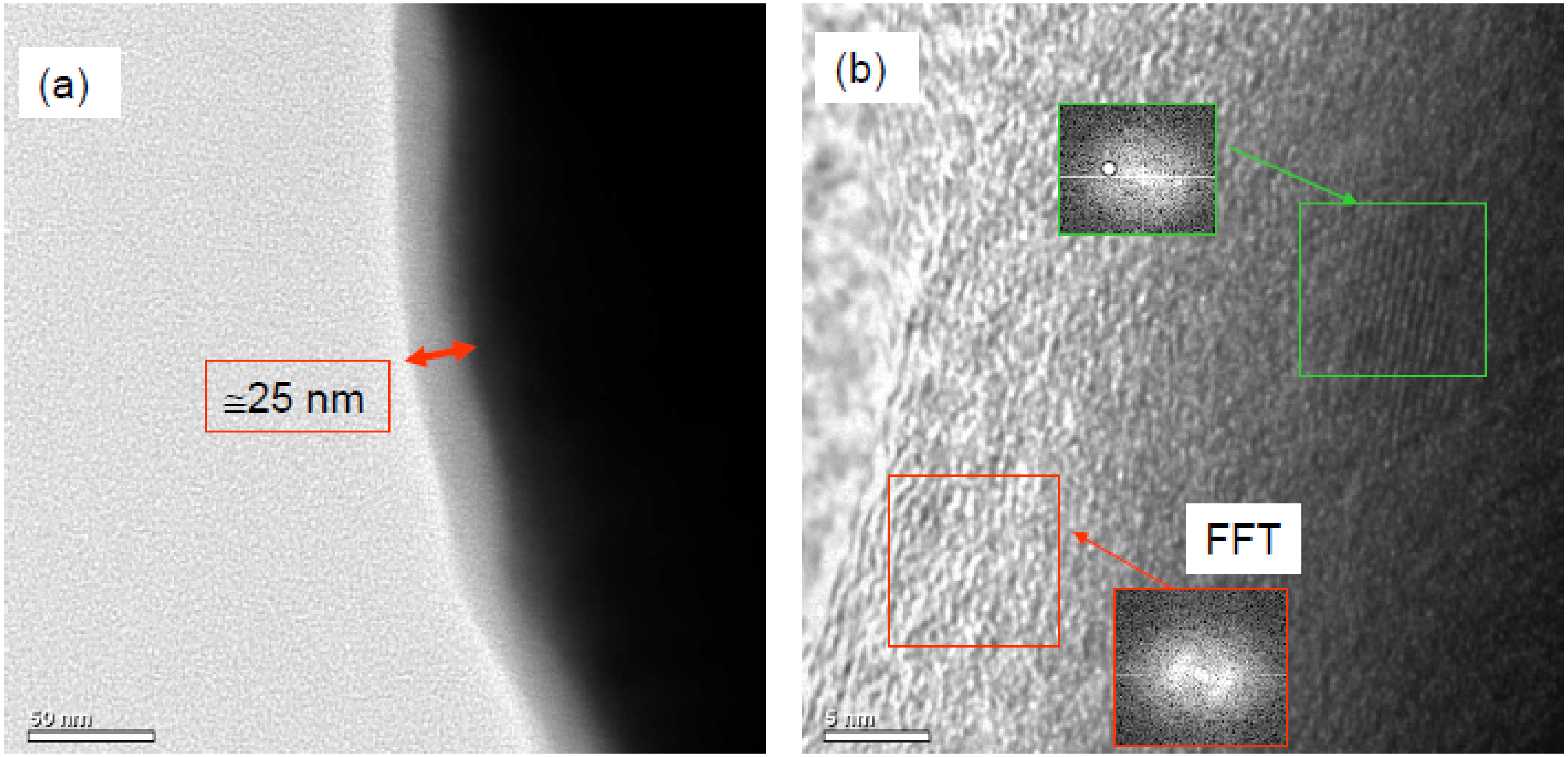
	Cr (7.5~10 µm)	Al (4.5 ~ 7 µm)	Y_2O_3 < 50nm	W (~1 µm)	Ni (4 ~ 8 µm)
A1	**20**	**5**	**1.5**	**0**	**73.5**
A2	**20**	**5**	**1.5**	**3**	**70.5**



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

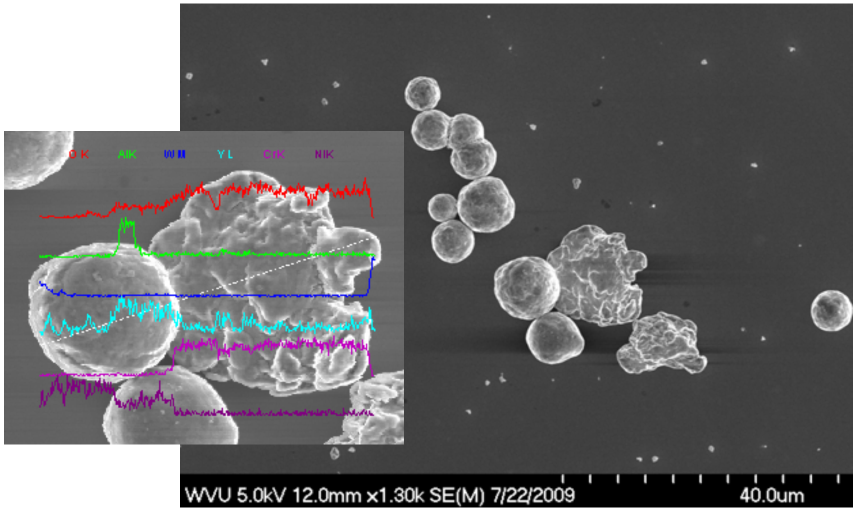
TEM BF and HREM imaging – A1 Sample



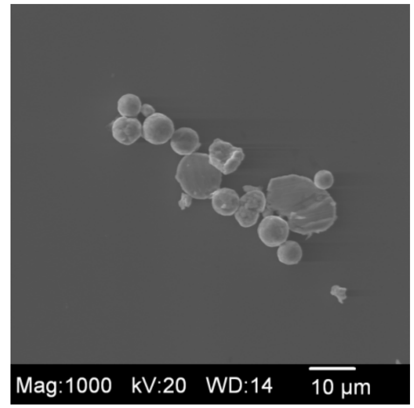
- TEM BF image (a) shows a layer of Y_2O_3 thin film with thickness about 25nm around the edge of particle. The film thickness is relatively homogeneous.
- HREM image (b) shows the fine structure of the thin film. Most area of the film is amorphous and the corresponding FFT (Fast Fourier Transform) image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

ODS Powder Fabrication

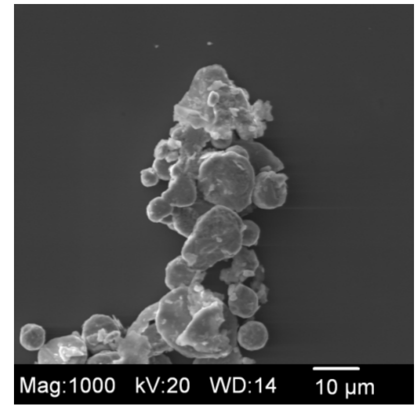
MCB + Ball Mill *(sample R1)*



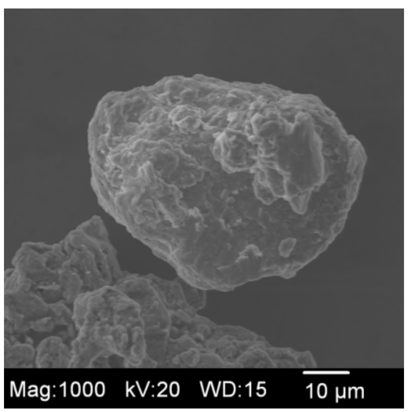
Before ball milling



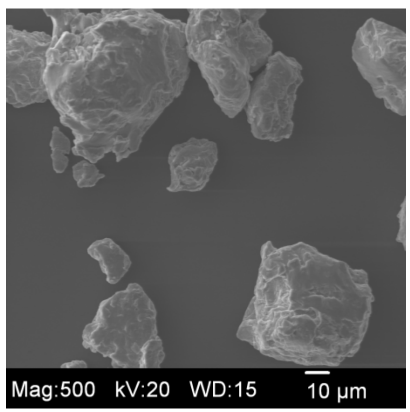
Ball milling for 2 hrs



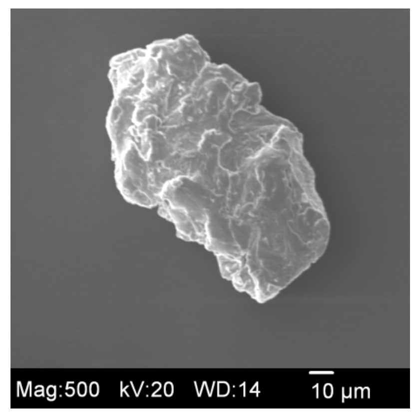
Ball milling for 6 hrs



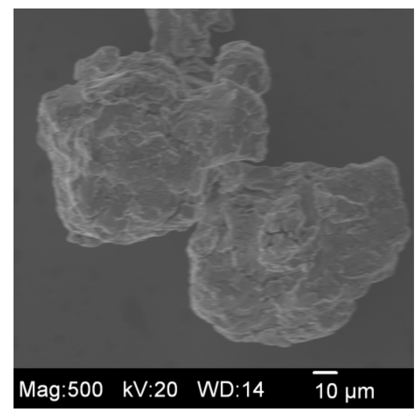
Ball milling for 15 hrs



Ball milling for 30 hrs



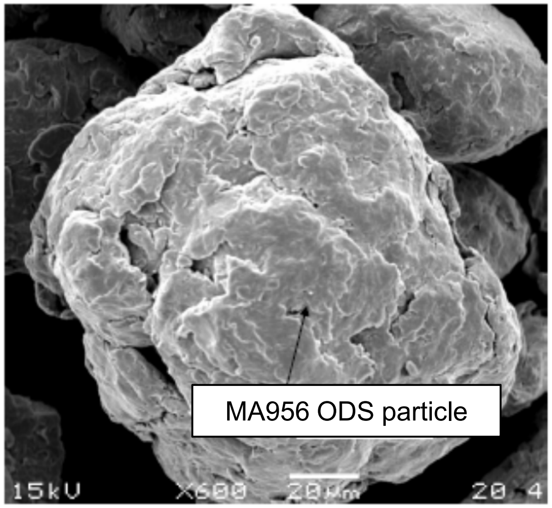
Ball milling for 60 hrs

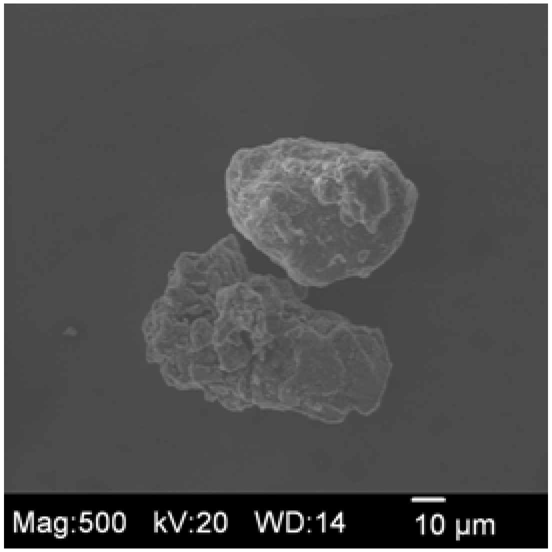


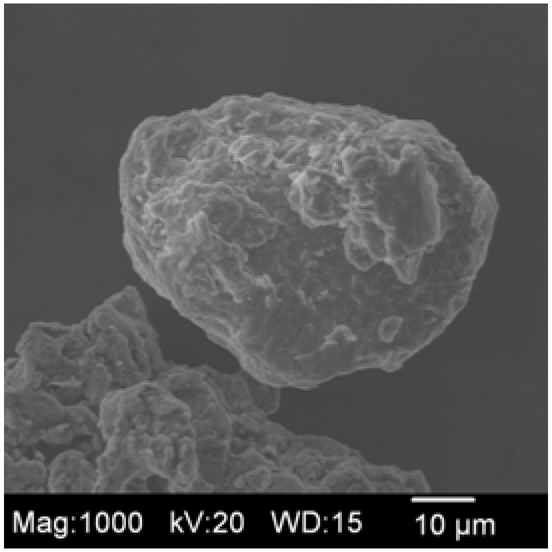
Ball milling for 84 hrs

ODS Powder Fabrication

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

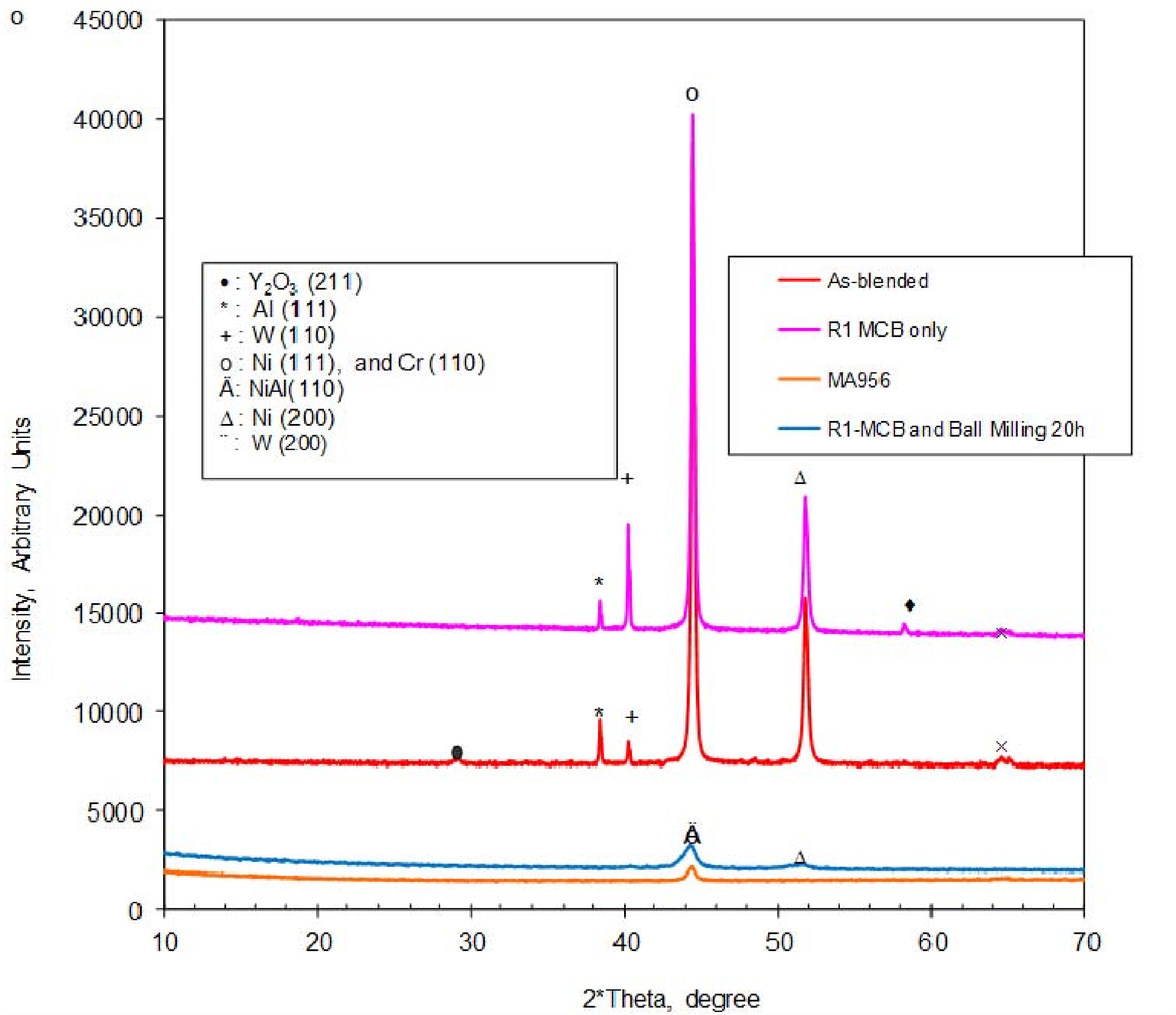




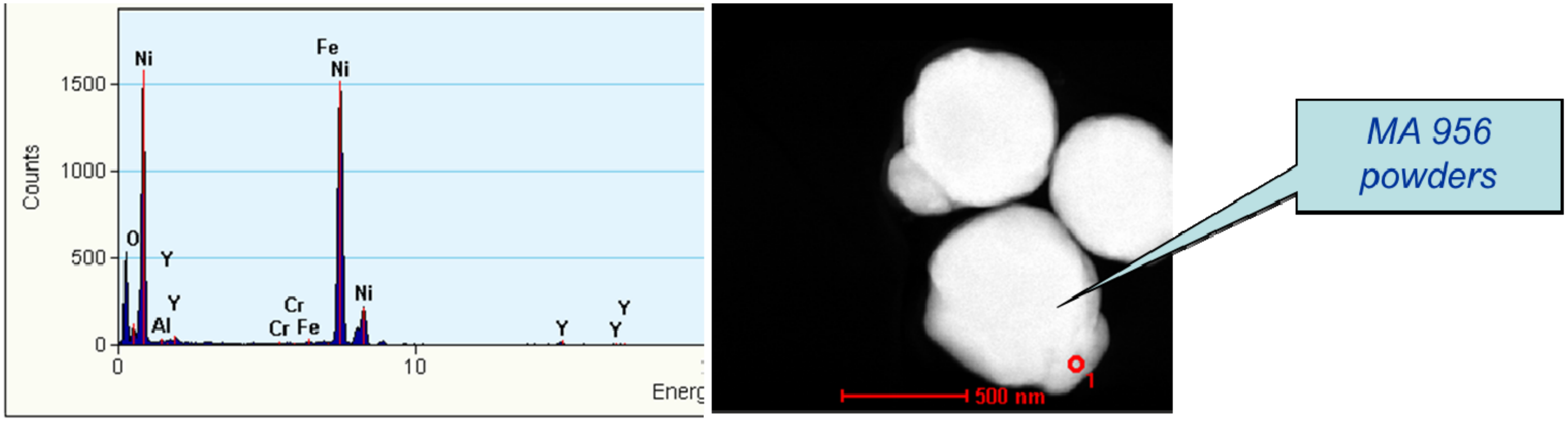


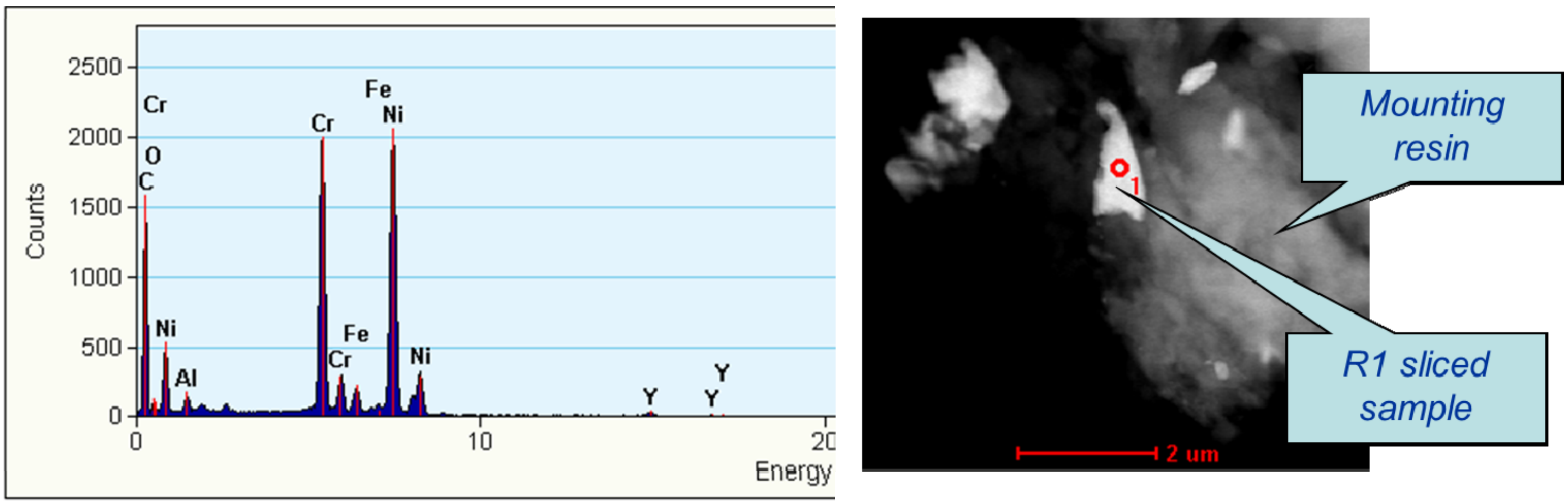
R1 sample with 15 hrs ball milling

ODS Powder Characterization



ODS Powder Characterization

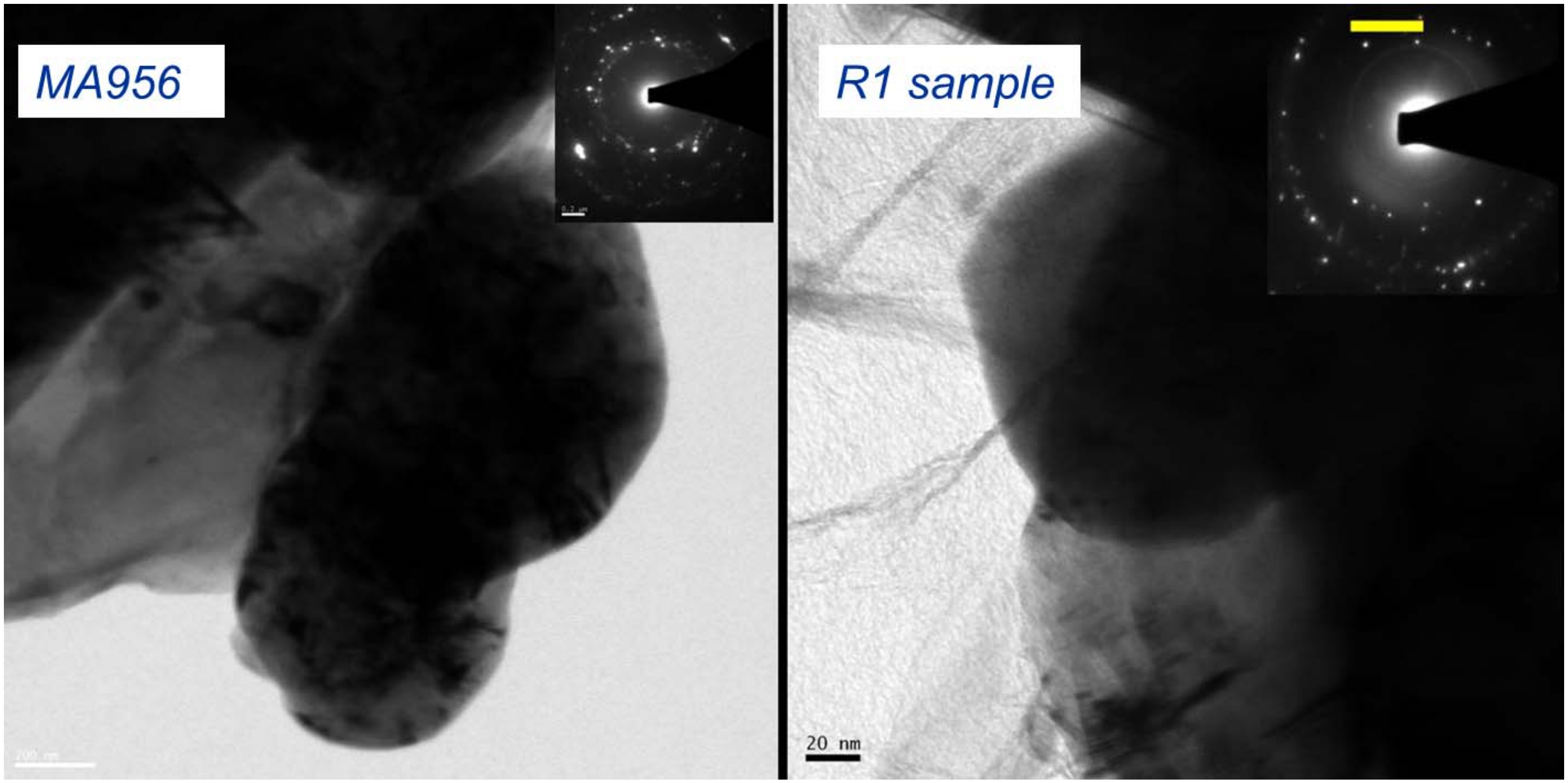




STEM and EDX

- For MA 956, hosting particles consist of Ni and Fe, and a few of Cr, Al, indicating Fe and Ni were well mixed.
- For R1 sample, cross section of powder shows Fe, Cr, Al, Ni and Y were well mixed. There are relatively higher Al, Cr and Y counts in R1 sample than in MA 956.

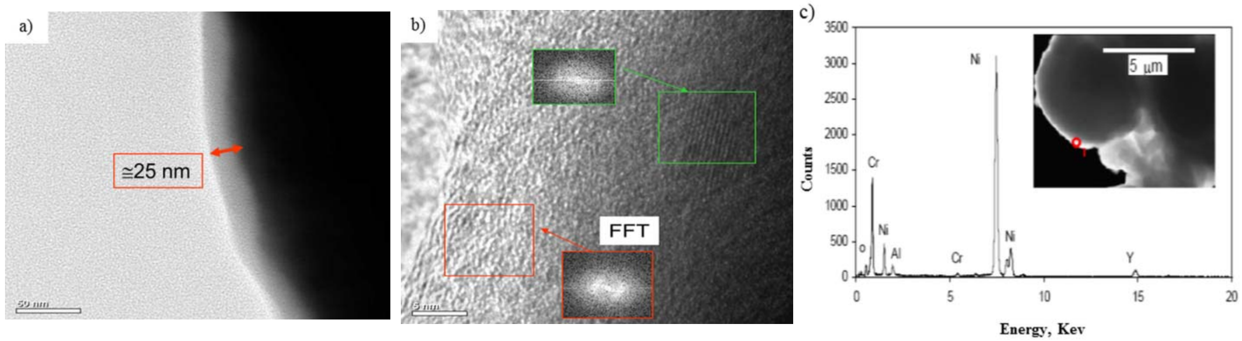
ODS Powder Characterization



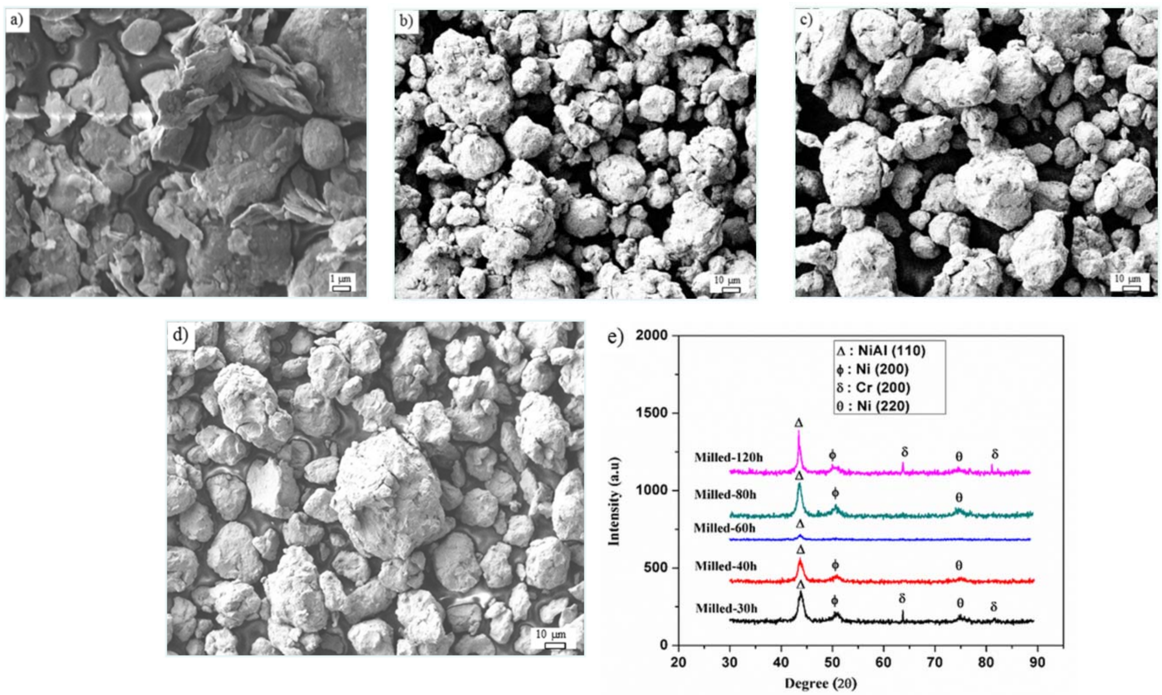
TEM results

- For MA 956, many dislocations were found inside particles, indicating heavy deformation during ball milling as well as many tiny particles were embedded into particles. SAD shows particle is polycrystalline.
- For R1 sample, TEM image and SAD show the similar structure to MA 956, indicating heavy deformation, well mixed and polycrystalline structure.

Summary - ODS Powder Characterization



MCB processed ODS powders images, (a) TEM BF, (b) HR TEM, (c) STEM EDX



SEM micrographs of milled ODS powders for (a) 5 hrs, (b) 40 hrs, (c) 60 hrs, (d) 120 hrs, and (e) XRD spectrum.

Outlines

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

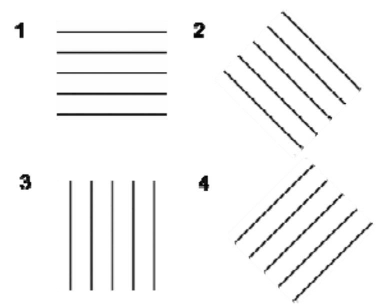
Task 3: ODS Coating (AM Assisted)

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

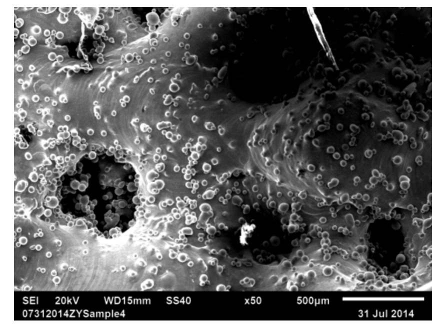
Approach

- *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

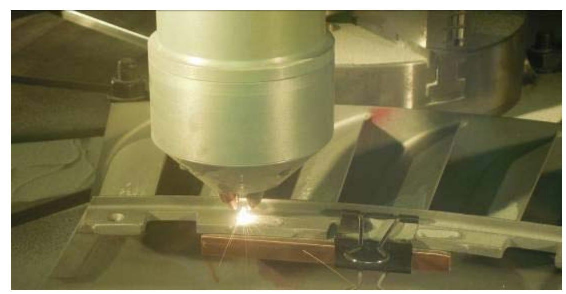
LENS450 (Direct Laser Deposition Process)



Hatch pattern

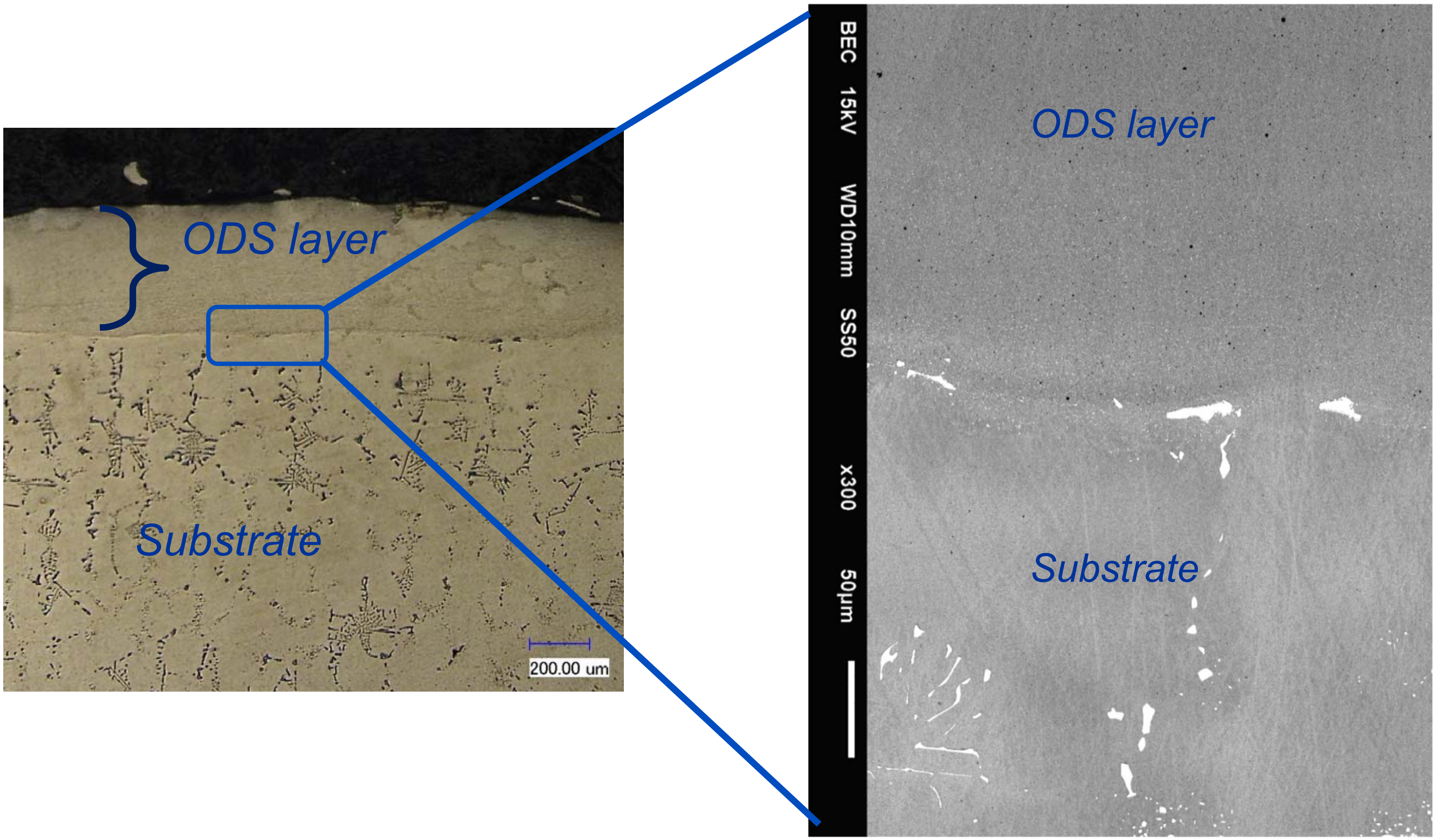


Hatch spacing



Laser power

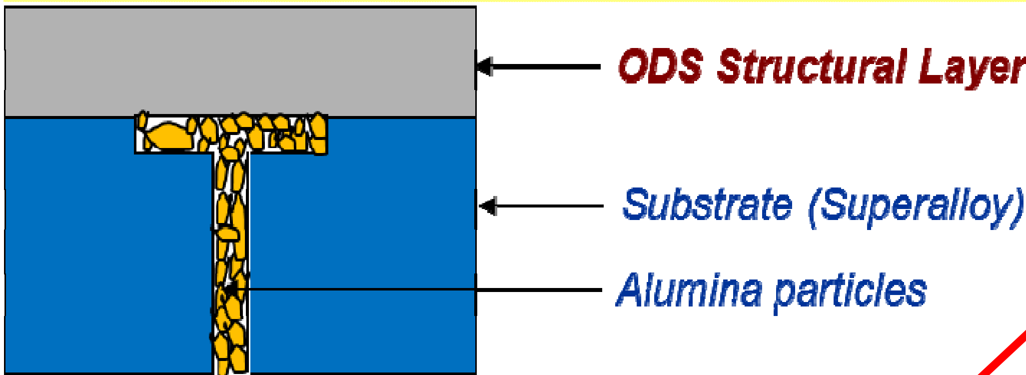
Task 3: ODS Coating (AM Assisted)



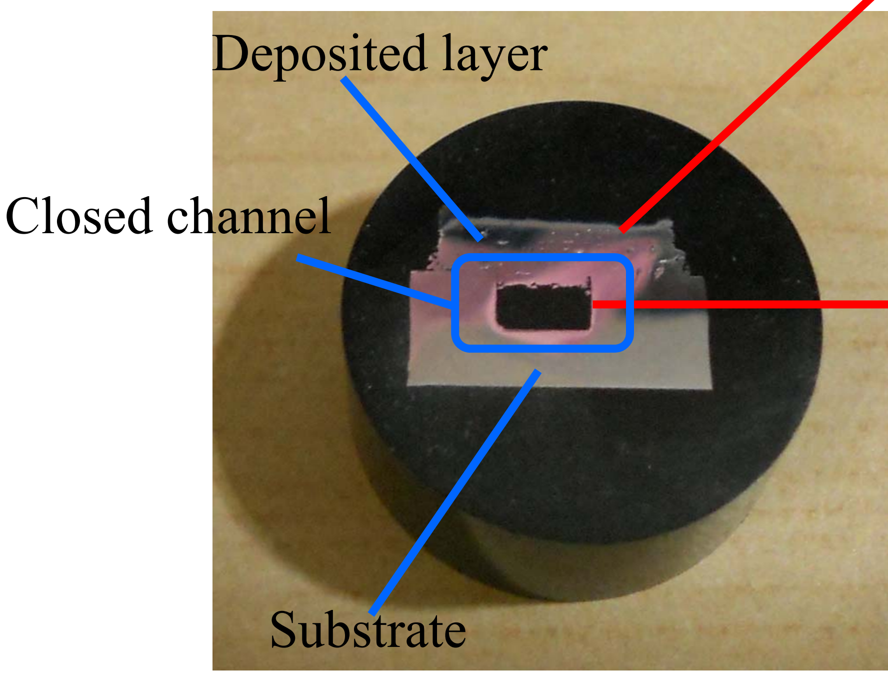
- Preliminary result
  Test coupon – single crystal nickel based superalloy with densified ODS layer

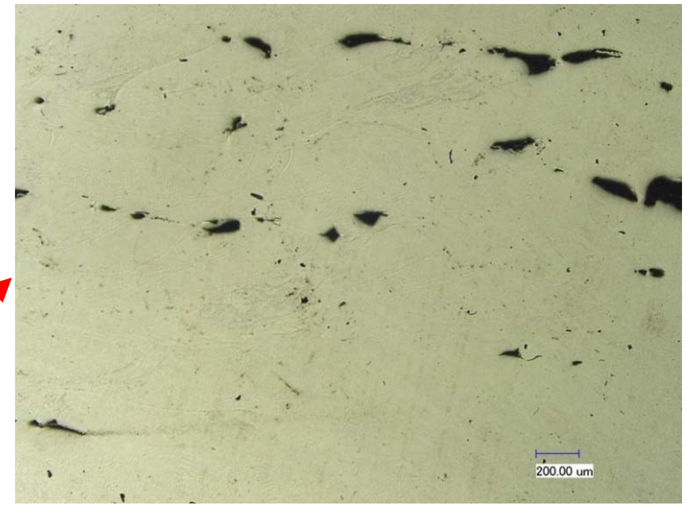
Task 3: ODS Coating (AM Assisted)

- SS316L substrate with deposited layer (as proof-of concept)

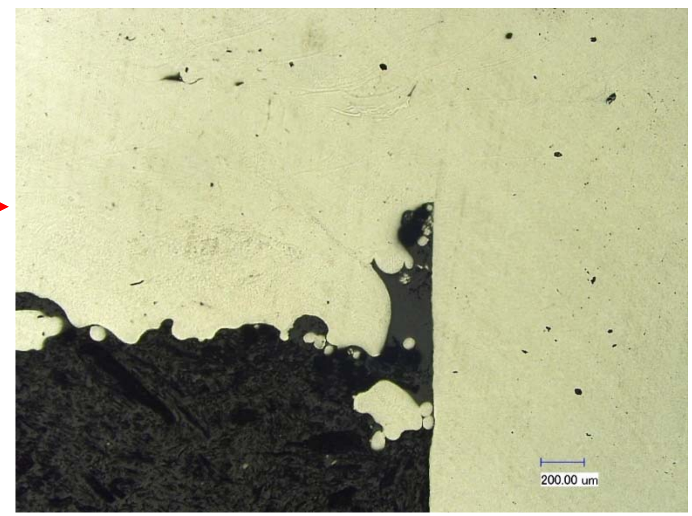


NSECC Development (Phase 1)





Deposited layer



Side wall

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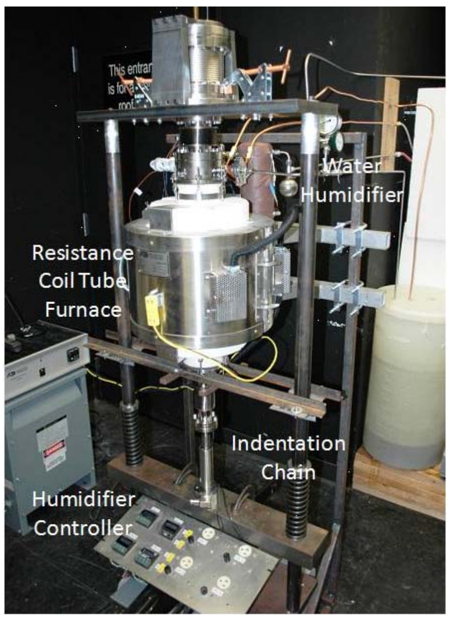
Task 4: Microstructural and Mechanical Properties Evaluations

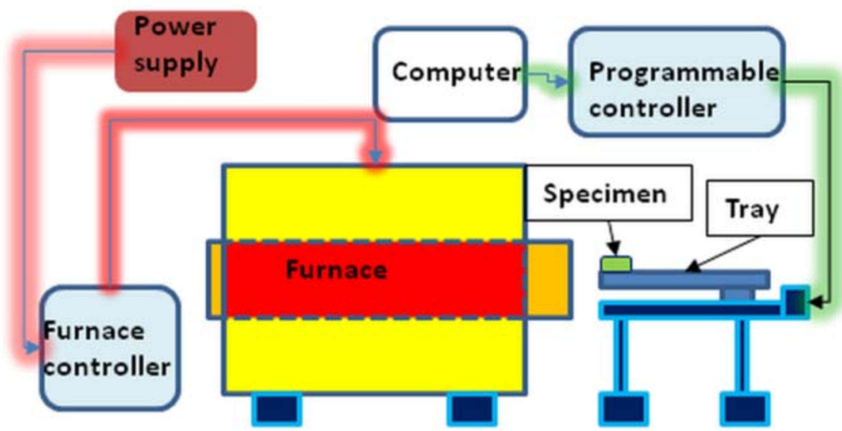
Objective: Characterize the microstructural and mechanical properties of ODS coating under (1) dry air, and (2) highly moisture content

Approach

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



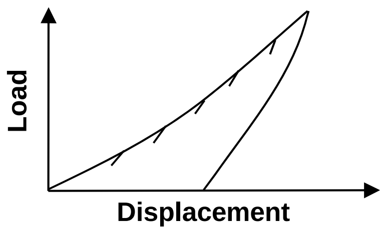
Controlled environment high temperature micro-indentation system

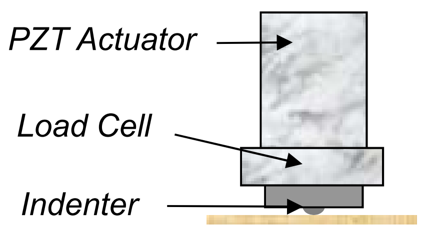


Schematic of the cyclic thermal exposure apparatus setup

Durability/Damage Assessment of Advanced Turbine Components

Multiple Loading/Partial Unloading Micro-Indentation





Applications:

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

Potential:

- **In Situ Material Characterization**
- **Portability**
- **Variable Influence Zone**

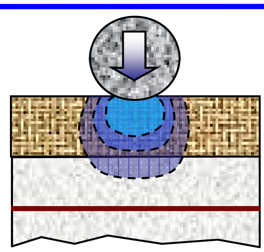
Load Based vs. Contact Area Based

$$P = \frac{4}{3} \cdot \frac{\sqrt{R}}{k_0} h^{3/2}$$ *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)***



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

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

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

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

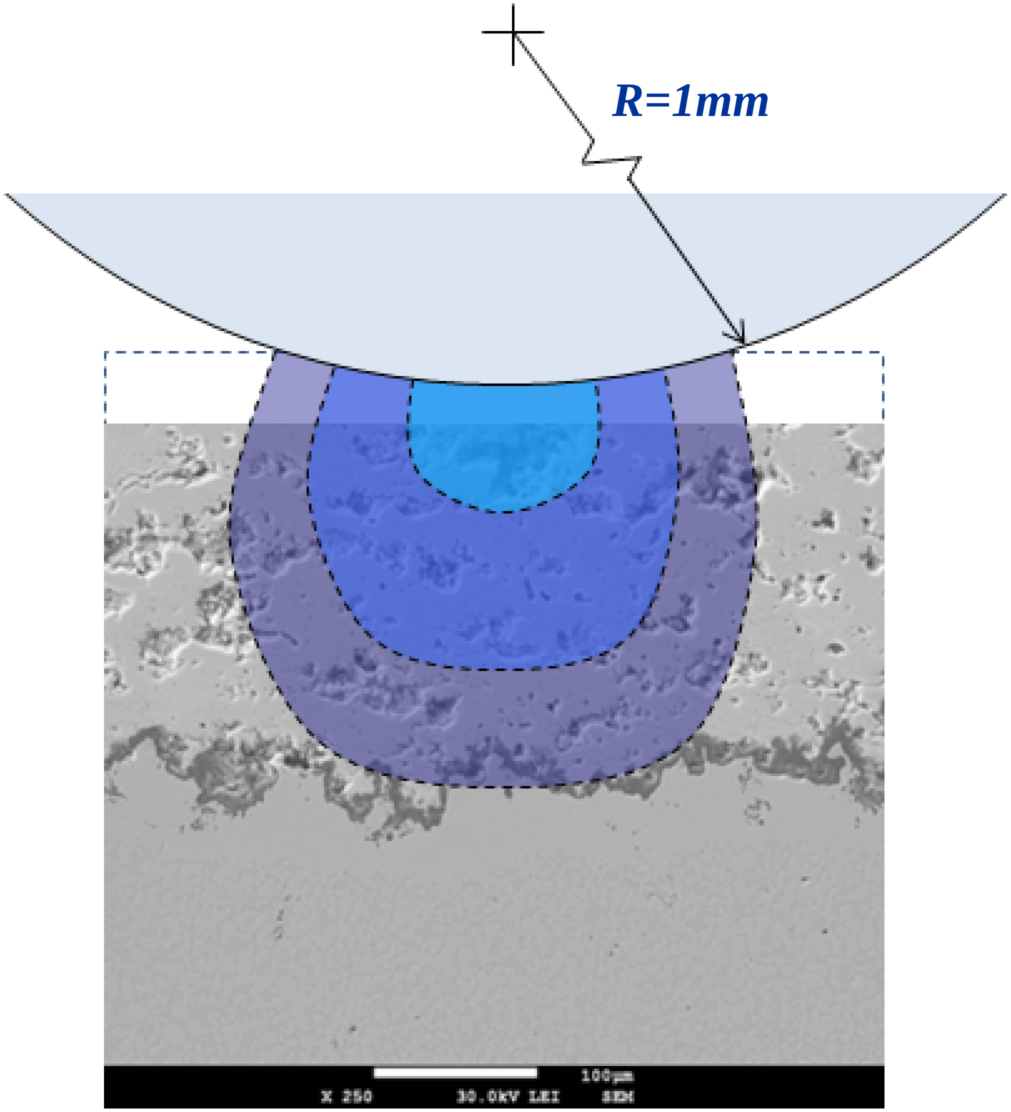
$$x = \frac{1}{p^{1/3}}, \quad y = \frac{dh}{dp}$$

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

Technique Benefits

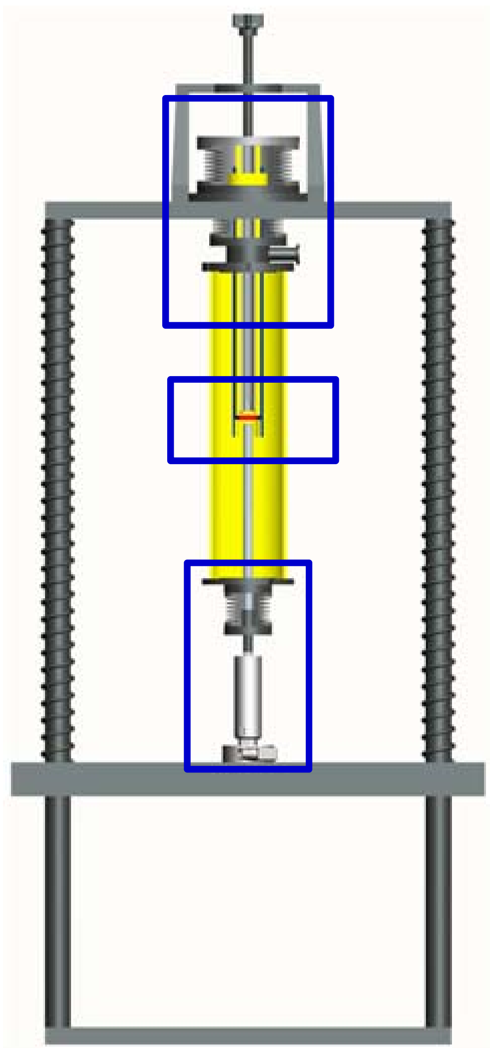
- **Designed for TBC/Bond and ODS Coating specimen**
  – Measurement of surface stiffness responses as a means to correlate the evolution of the microstructural changes of the coating layer/substrate subjected to high temperature thermal cycles.
  – Can also be correlated to the damping effect
  – No 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.

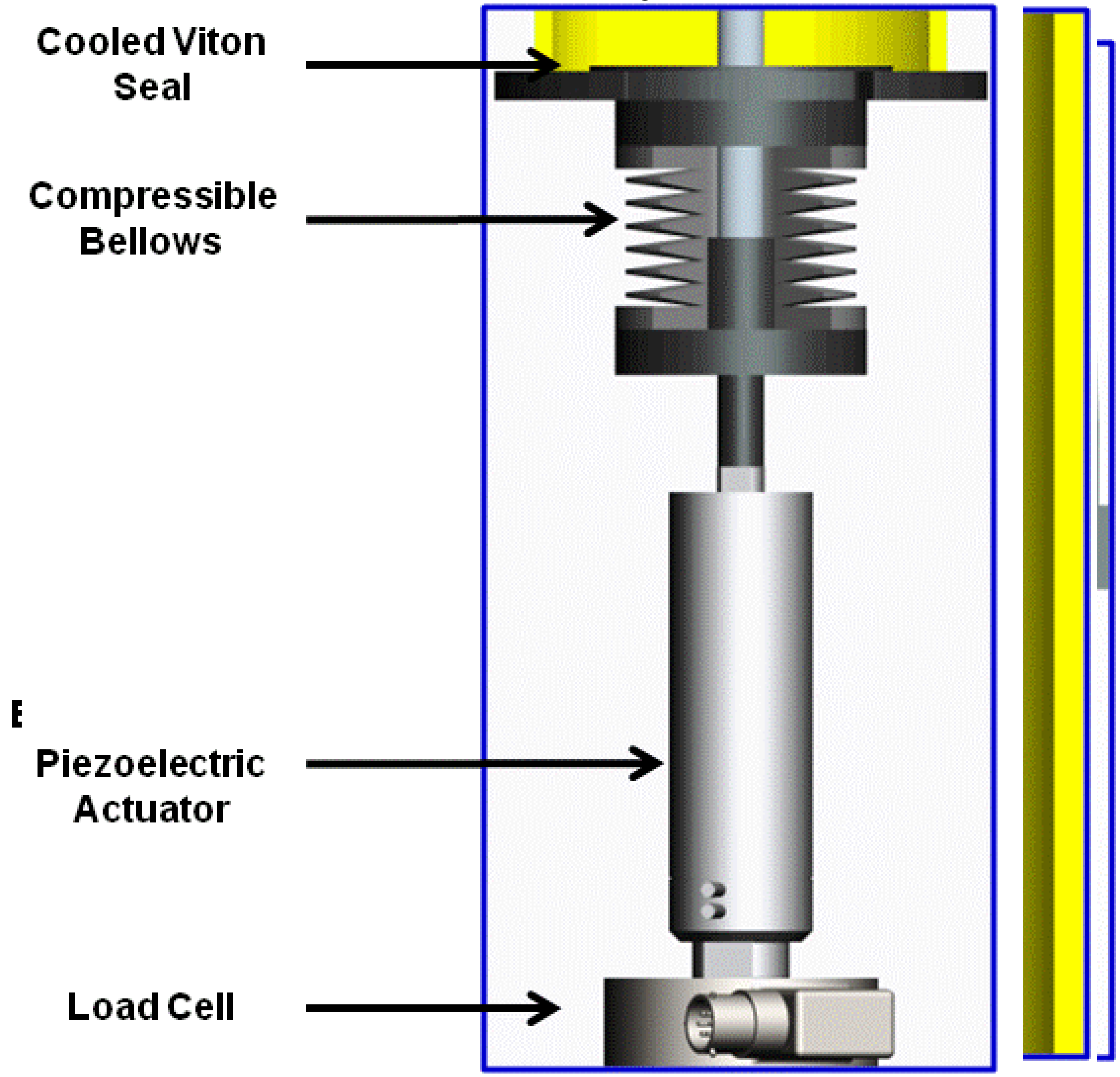
Durability/Damage Assessment of Advanced Turbine Components



Durability/Damage Assessment of Advanced Turbine Components

Controlled Environment Indentation System

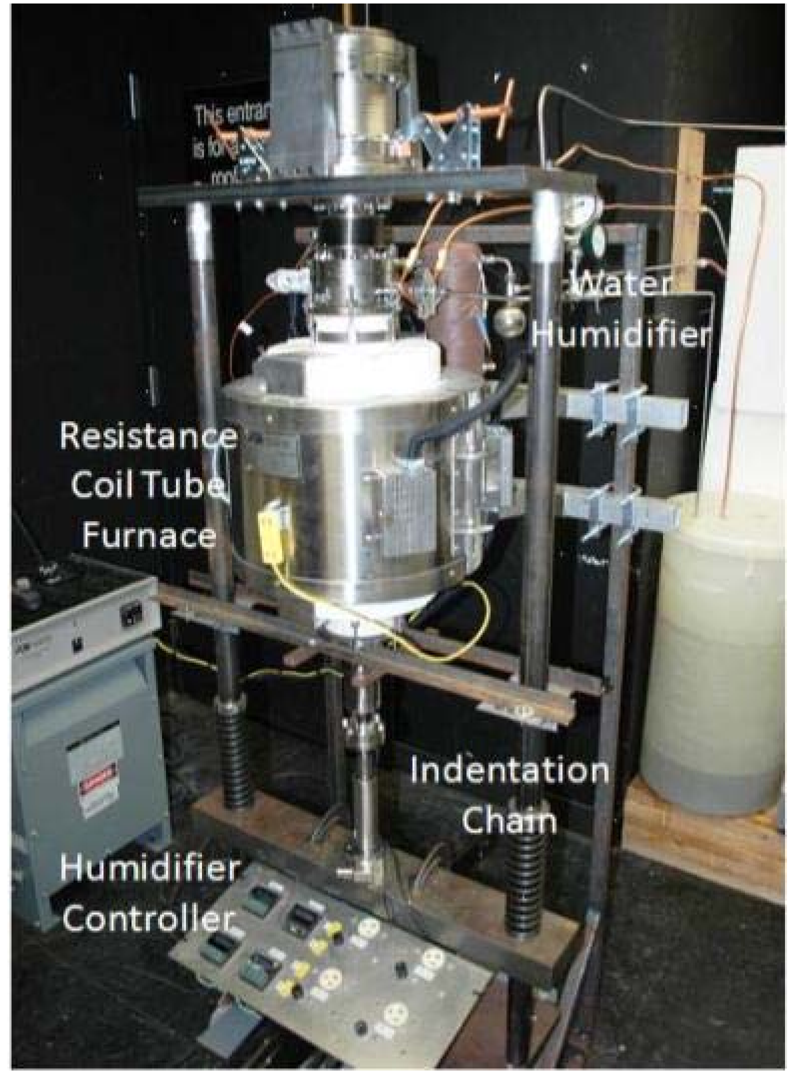




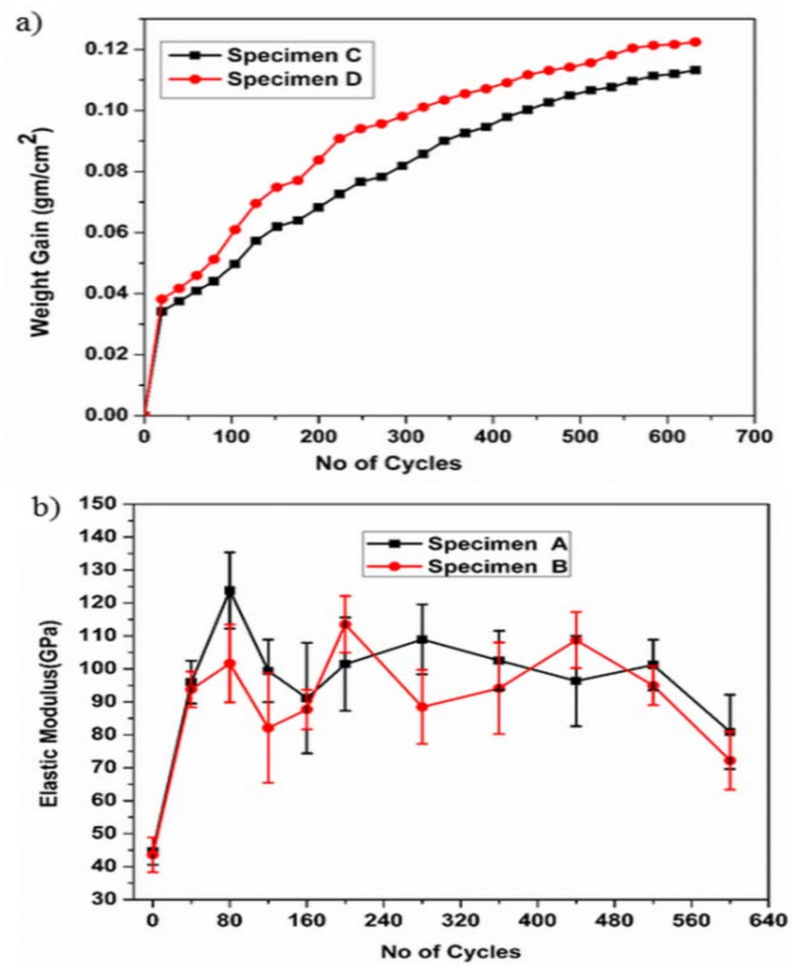
Durability/Damage Assessment of Advanced Turbine Components

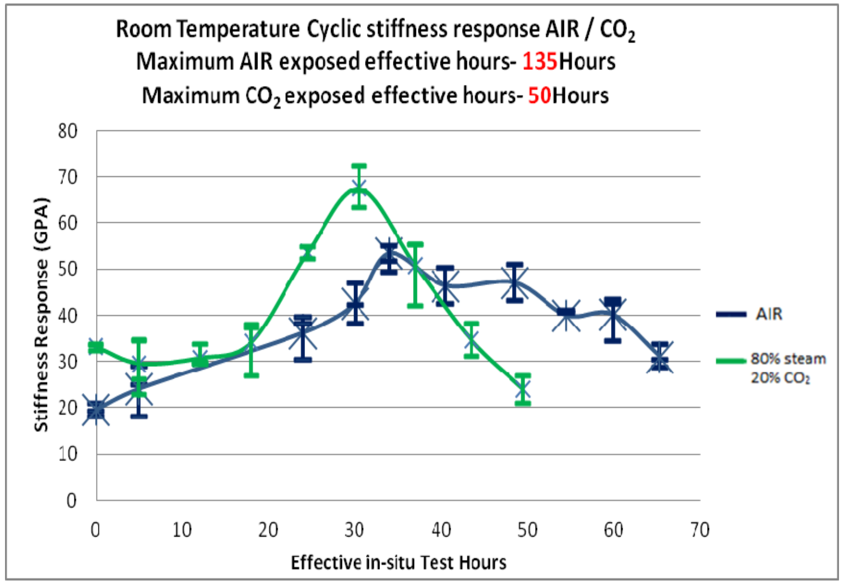
Controlled Environment Indentation System

- Continuous Water or Air Cooling
- Applied Test Systems Resistance Coil Tube Furnace
- Humidifier Numerically Controlled by 3 Separate PIDs
- Copper Gaskets Insure Proper and Efficient Sealing at Elevated Temperatures
- Controllable Thermal Ramp Rate
- Potential to Vary Internal Pressure



Mechanical Properties Evaluations

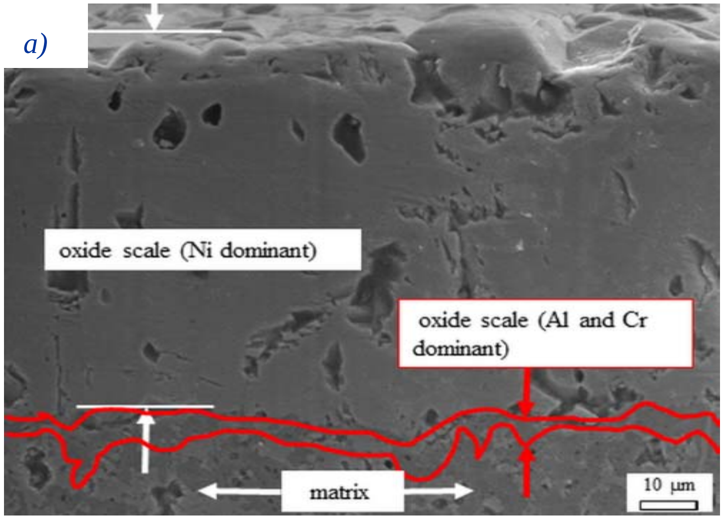




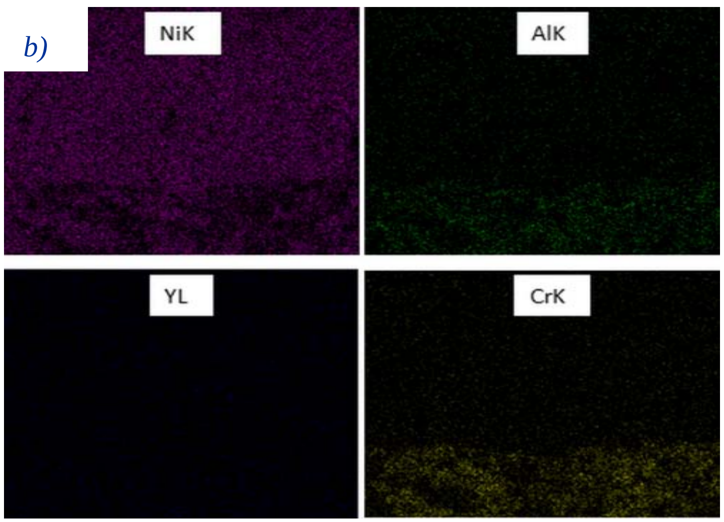
In-situ micro-indentation stiffness response of APS/MCrAlY/RenéN5 coupon under cyclic oxidation room to 1100°C under air and wet (80% steam/20% CO_2) conditions

ODS specimen under cyclic oxidation room to 1100°C in air:
(a) weight gain, (b) micro-indentation stiffness response

Oxidation Kinetics – Stable NiO Formation

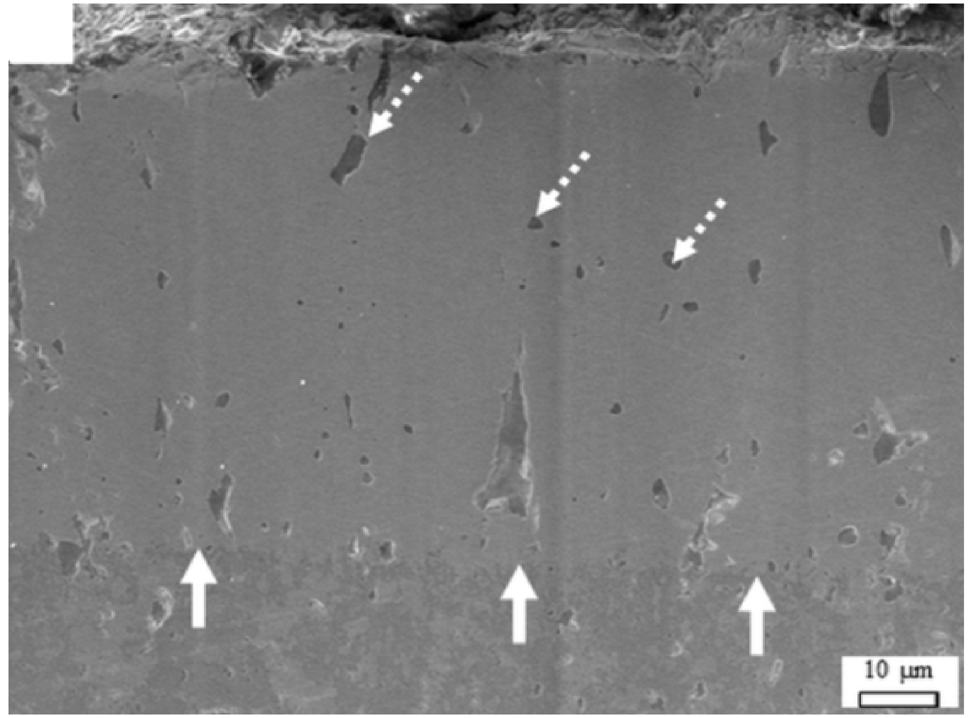


(a) oxide scale at 120 cycles



(b) EDX maps at 120 cycles

SEM metallographic cross-section micrographs



SEM metallographic cross-section micrographs of NiO oxide scale at 600 cycles

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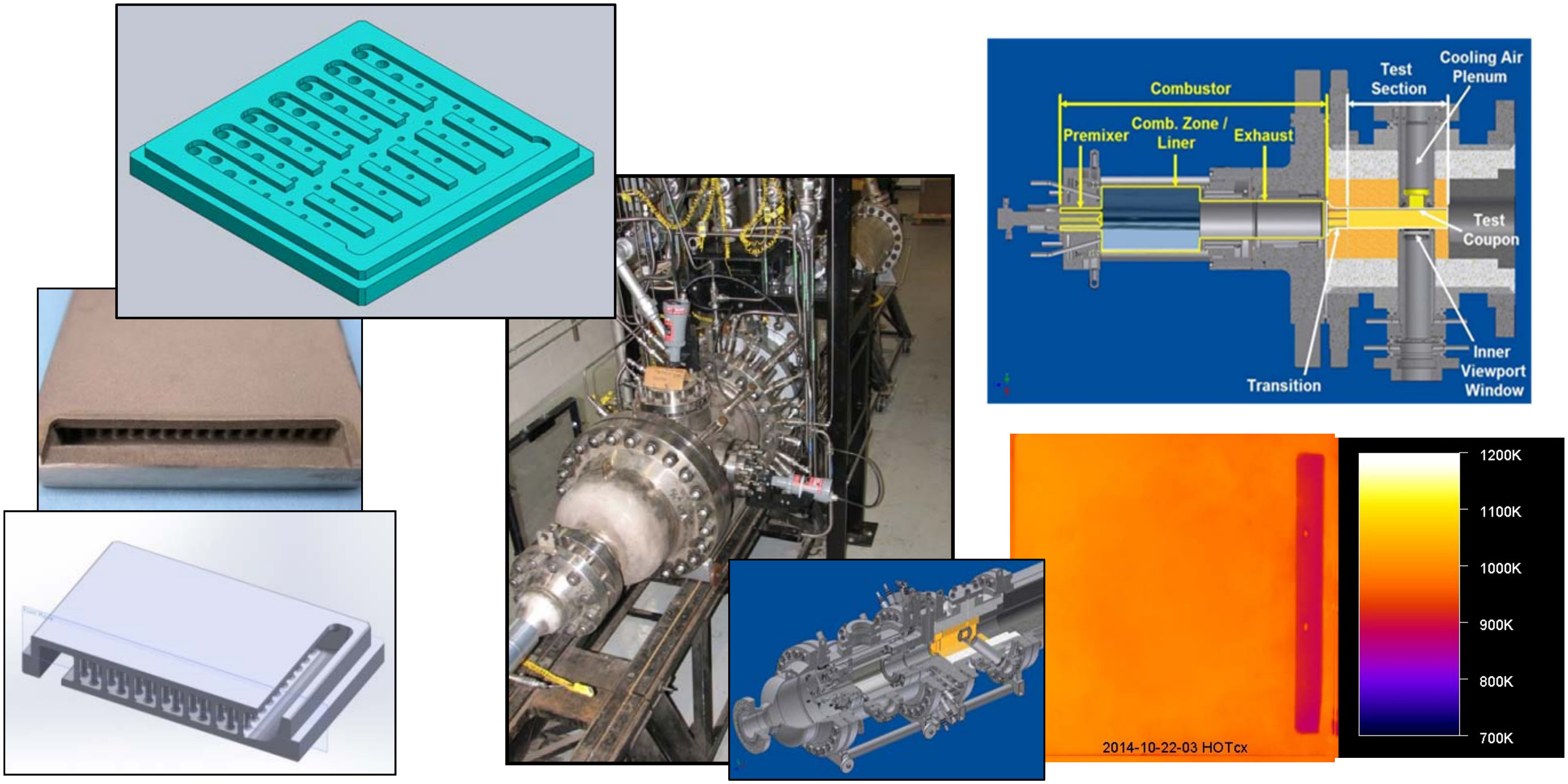
Task 5: Detailed Experimental Measurements and Validation



- ➢ 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

Project Timeline

Task Description	1st Year				2nd Year				3rd Year			
	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter
Bi-weekly, quarterly and final reports	←	—	—	—	—	—	—	—	—	—	—	→
Dr. M.K. Chyu, Dr. S.C. Siw - University of Pittsburgh (Pitt)												
Project management and planning	←	—	—	—	—	—	—	—	—	—	→	
Task 1.1 Heat Transfer Characterization of Optically Clear Scaled Test Section and Test Coupon	←	—	—	—	—	—	→					
Task 1.2 Development and Process Optimization to Coat an ODS Layer on Single Crystal Superalloy Substrate	←	—	—	—	—	—	—	—	→			
Task 1.3. Heat Transfer Characterization of ODS/NSECC Protected Single Crystal Superalloy Coupon under High Temperature Environment									←	—	—	→
Dr. Bruce S. Kang - West Virginia University (WVU)												
Task 2.1 Fabrication approach to produce ODS powder	←	—	—	—	—	—	→					
Task 2.2. Thermal cyclic experiment on ODS Alloy Specimens		←	—	—	—	—	—	—	—	—	→	