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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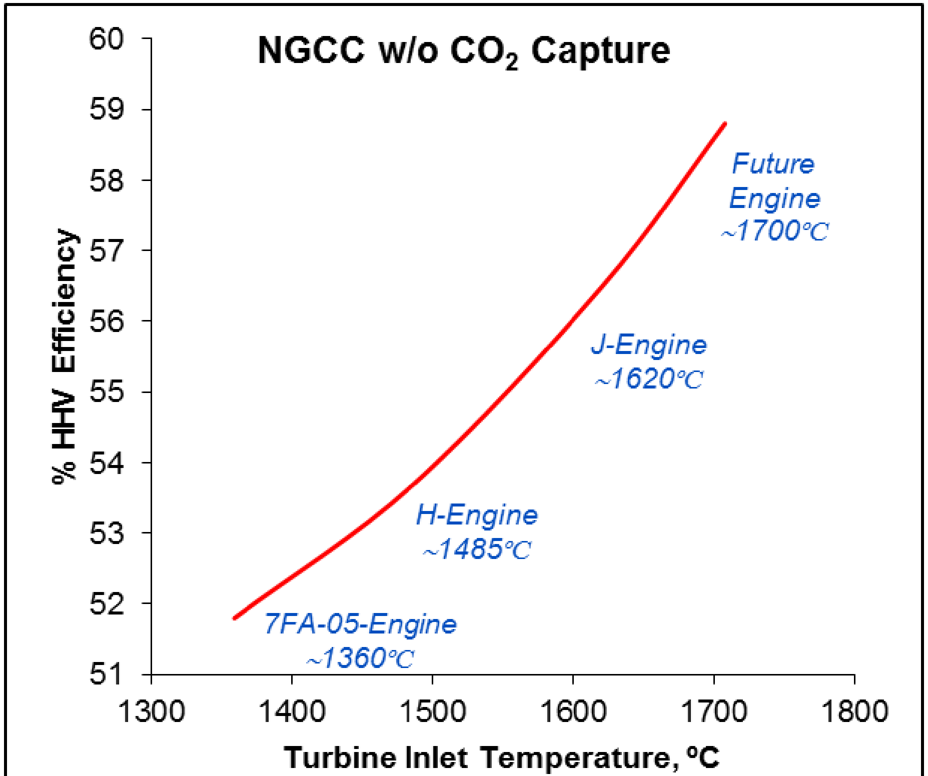
West Virginia University

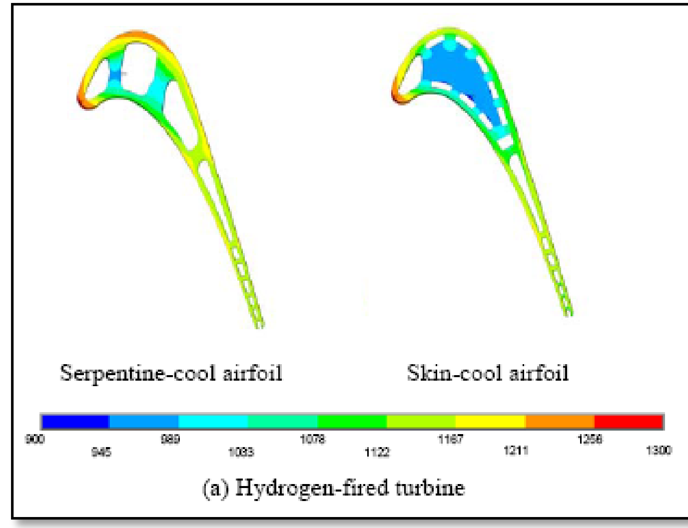
Outlines

- ***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 –

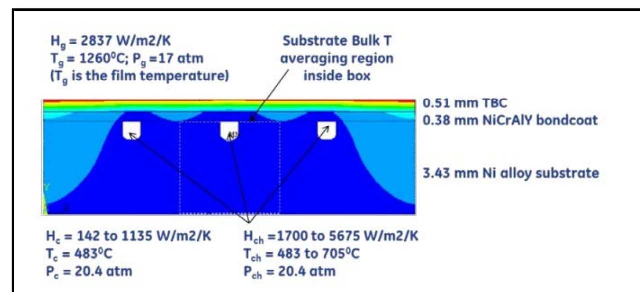


Siw, S.C., Chyu, M.K., Karaivanov, V.G., Slaughter, W.S., and Alvin, M.A., 2009, "Influence of Internal Coolinjg Configuration on Metal Temperature Distributions of Future Coal-Fuel Based Turbine Airfoils," ASME Turbo Expo 2009, Paper No. GT2009-59829.

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

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

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**

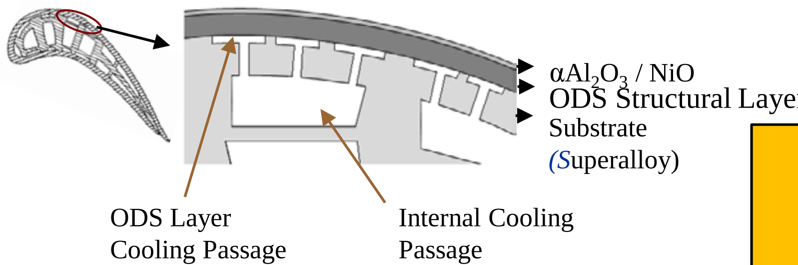
- **To develop fabrication process through additive manufacturing for coating either a densified ODS layer over a grooved single crystal superalloy substrate to form an enclosed NSECC, or an ODS layer with cooling channels embedded within the ODS layer atop a single crystal superalloy metal substrate**

- **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.



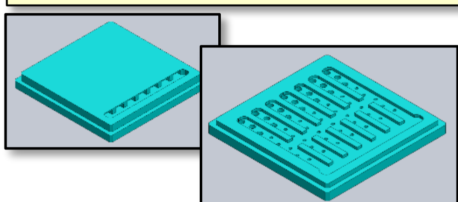
Near Surface Embedded Cooling Channel (NSECC)

Novel Metallic ODS Surface Coating

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

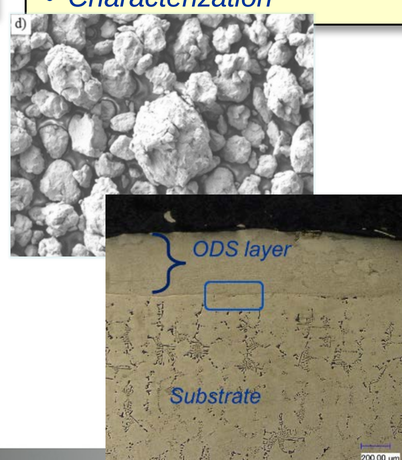
Task 1 – Advanced Impingement

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



Task 2 – ODS Powder Fabrication and Characterization

- *ODS powders fabrication*
- *Characterization*



Task 3 – ODS Coating (AM Assisted)

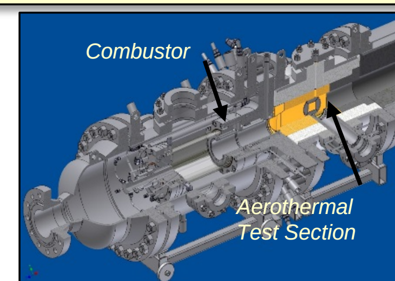
- *Process development and optimization*

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

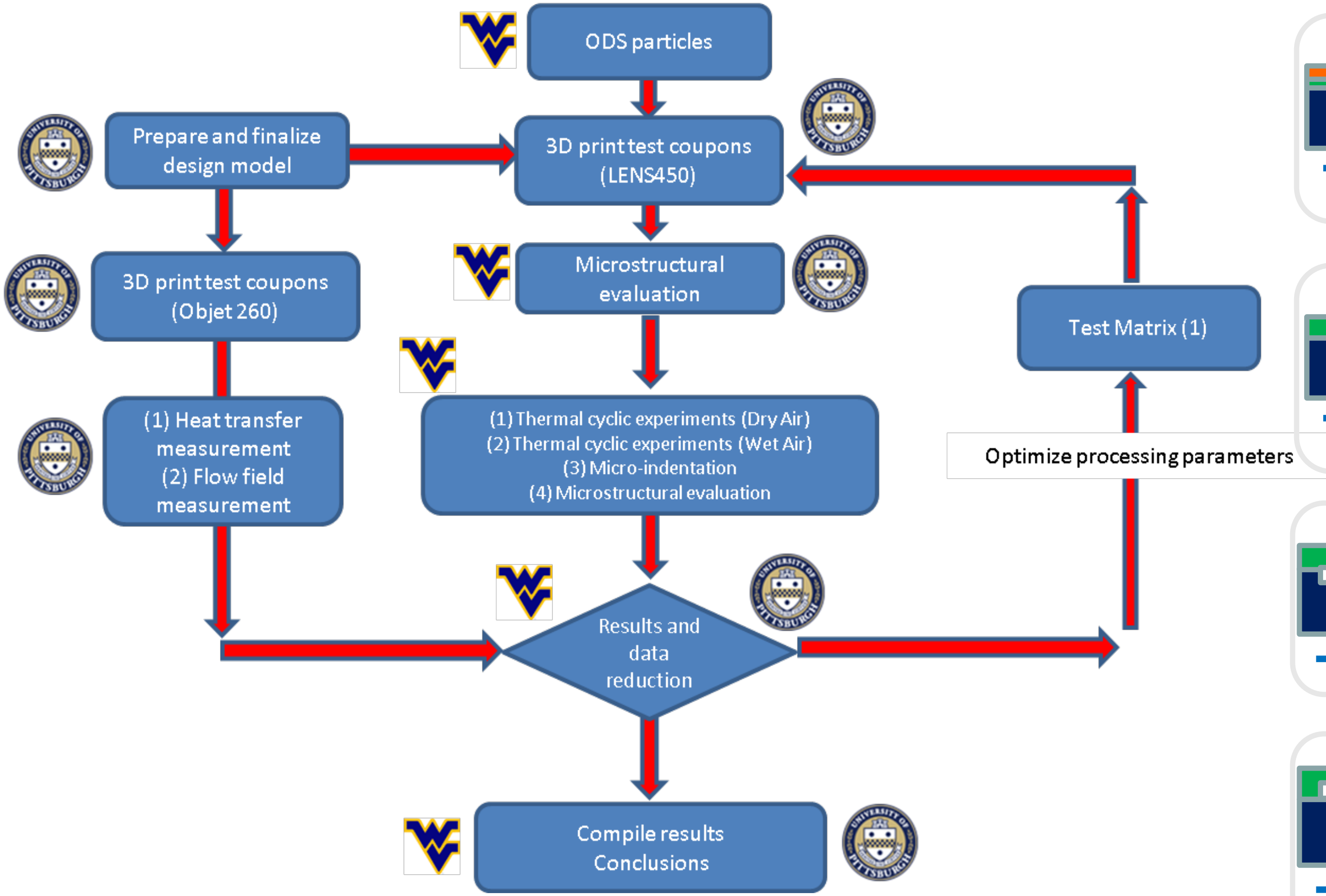
Solar Turbines
A Caterpillar Company

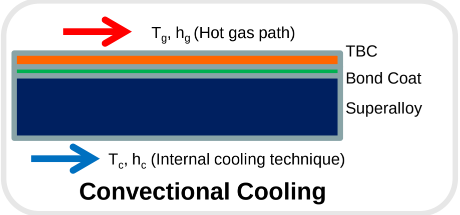
HOSOKAWA MICRON

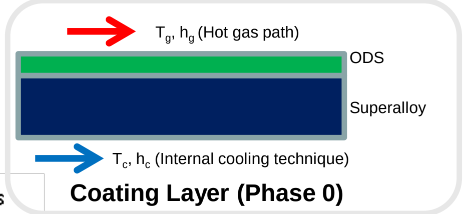
Design, Fabrication and Performance Characterization of Near-Surface Embedded Cooling Channels with an Oxide Dispersion Strengthened (ODS) Coating Layer

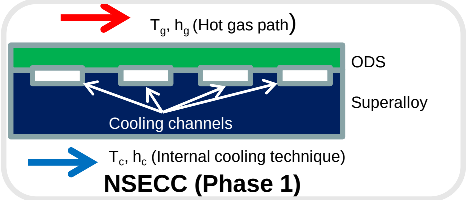
University of Pittsburgh
West Virginia University

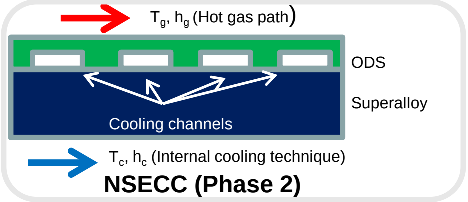
Research Task Plan (3 years)











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

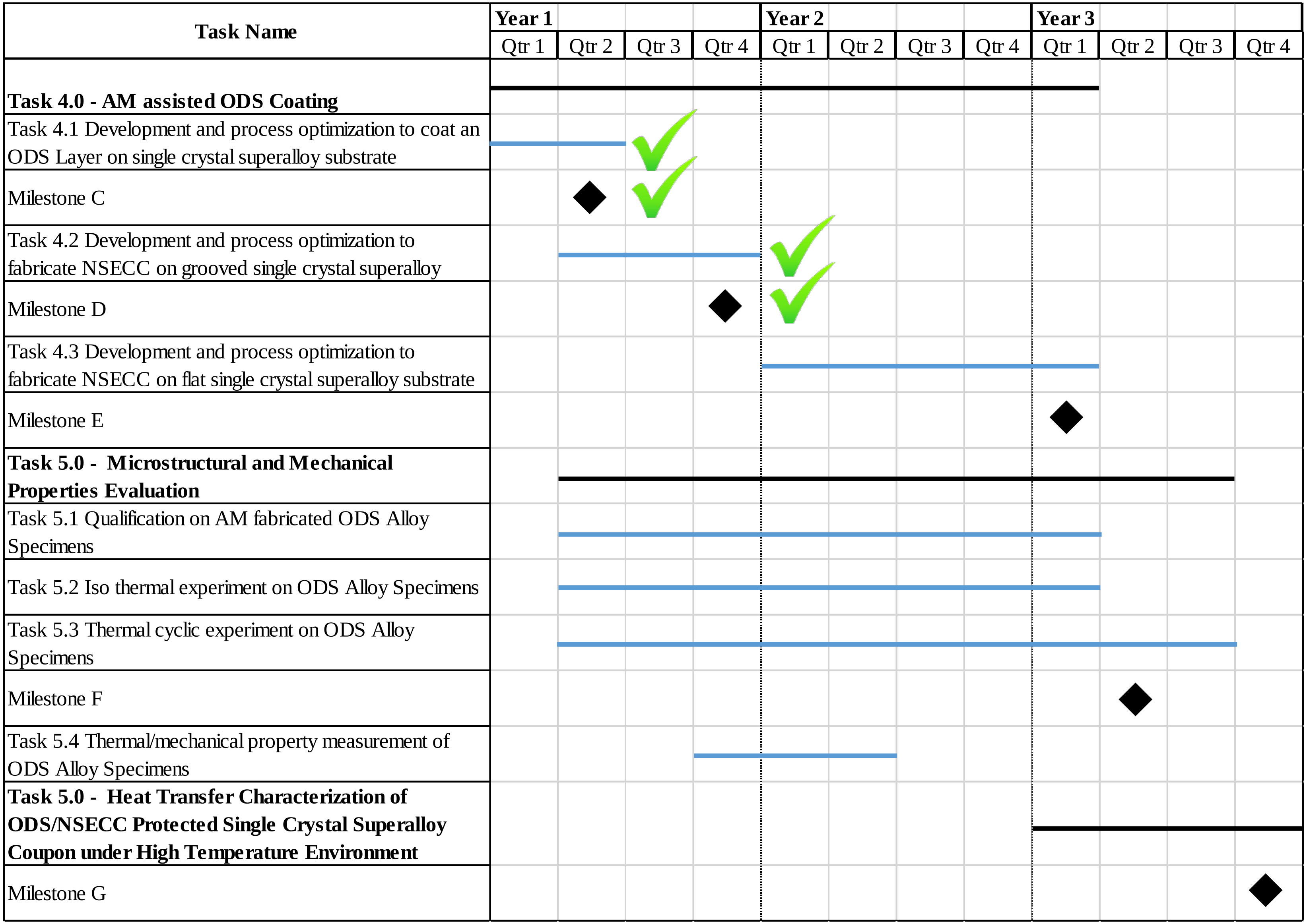
Title	Planned Date	Verification Method
A - Heat transfer and fluid flow experiments of test sections and test modules	3/31/2017	Data analysis and comparison to bench data
B - Produce and characterize ODS powders	3/31/2017	XRD and SEM
✓ **C - ODS coating on substrate**	3/31/2016	Optical micrographs, SEM
✓ **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)

Solar Turbines
A Caterpillar Company

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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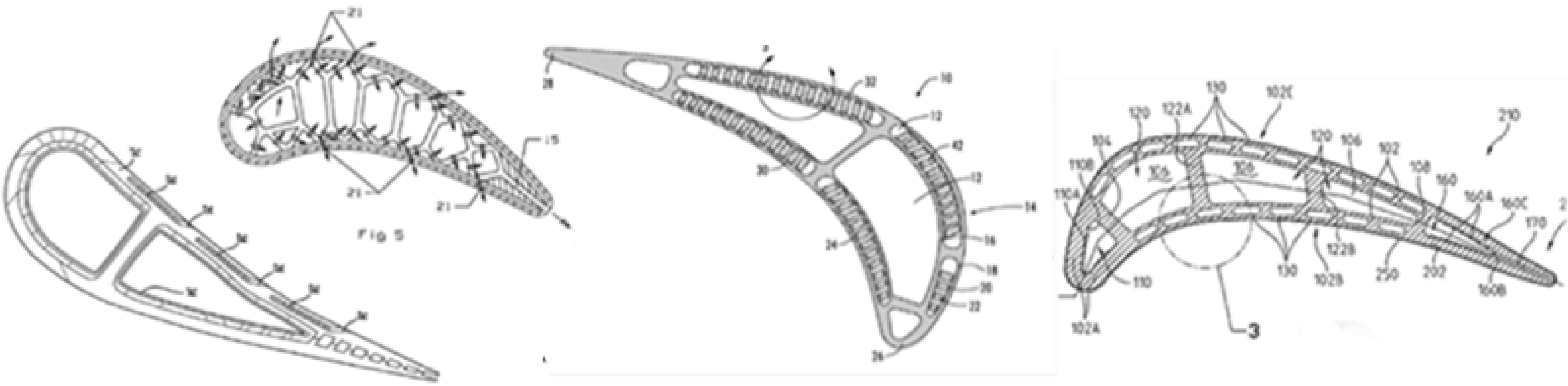
Task 1 Advanced Impingement

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:

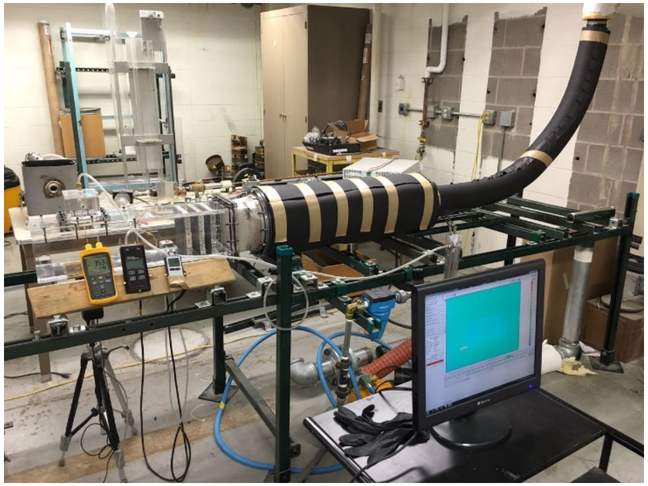
  Cooling channels embedded near the outer surface have small sizes and irregular shapes. Distributing the coolant to feed the channels will be more difficult than traditional cooling concepts. In the meantime, this novel cooling concept still requires further enhancement of local heat transfer to achieve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



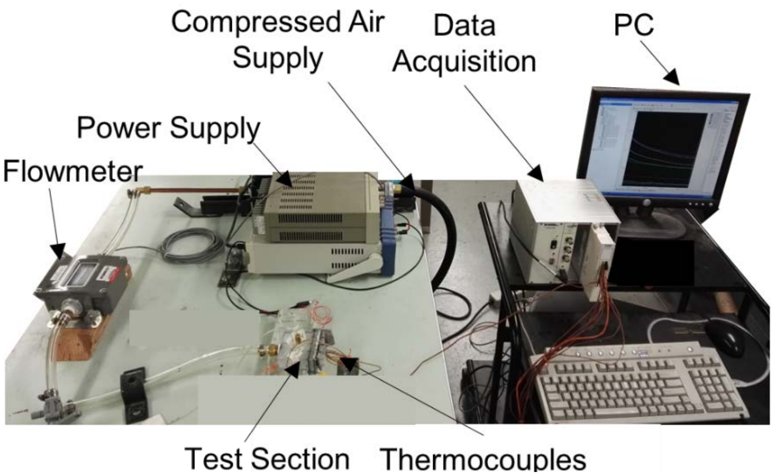
Different patents showing double wall cooling by UTC, Siemens and Florida Turbine Technologies

Heat Transfer Test Facilities

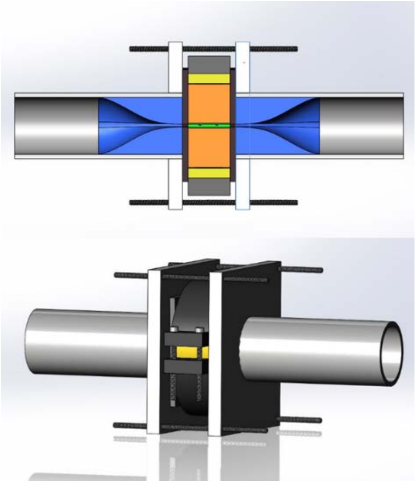
Test Rig for Scaled up Models
based on TLC



Test Rig for Conjugate Heat Transfer
based on IR

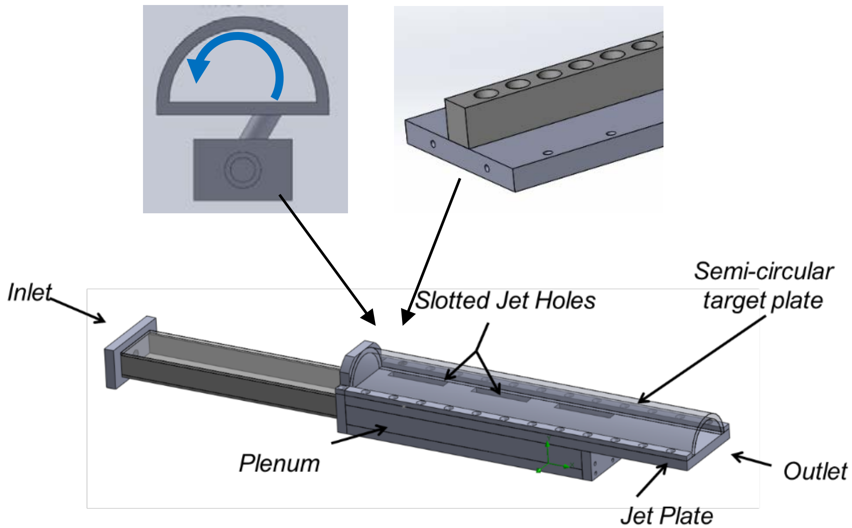


Test Rig for Steady State
based on thermocouples

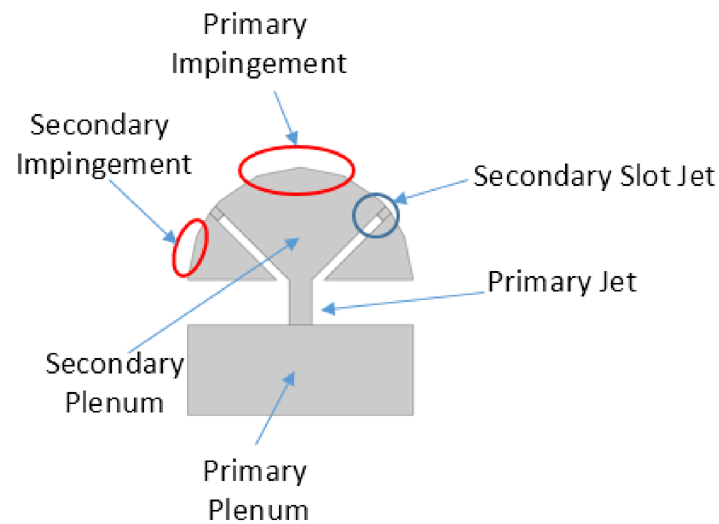


Test Rig for AM Parts
based on thermocouples

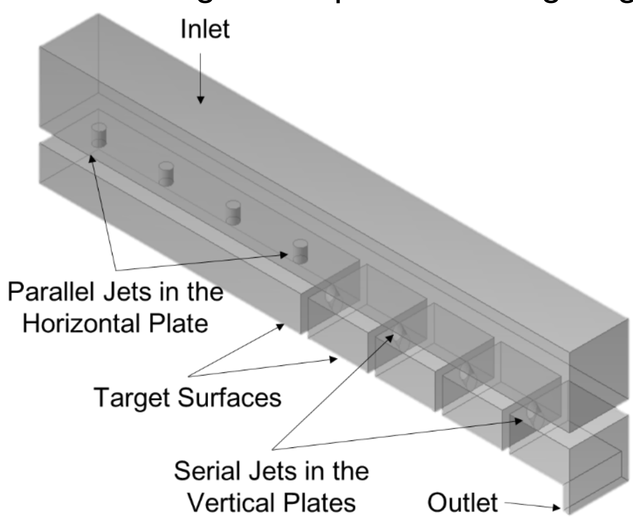
Innovational Designs of Impingement



"Screw" Cooling Concept for Leading Edges



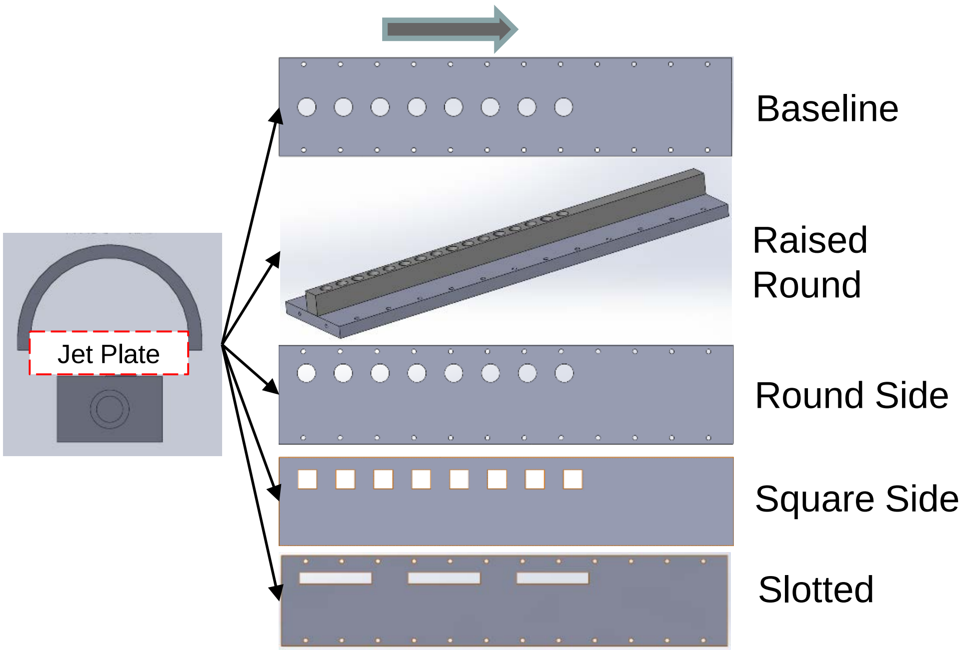
"Screw" Cooling with "Secondary Jets"

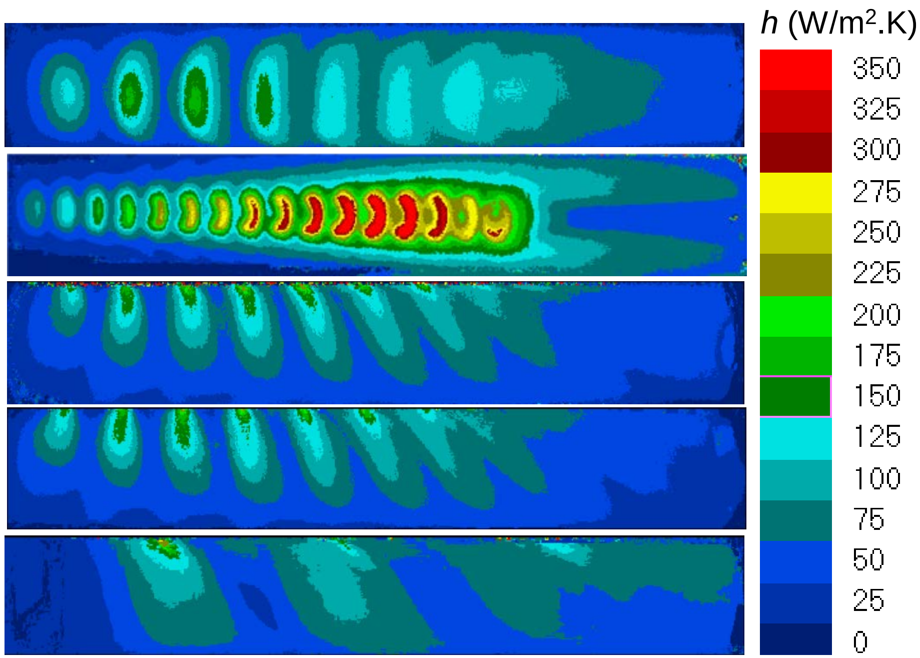


Hybrid Linked jet Impingement Concept

- Additive manufacturing provides more flexibility to turbine airfoils and promotes more advanced impingement cooling technologies.
- Novel impingement concepts developed in this project attempt to make full use of the state-of-the-art metallic additive manufacturing.

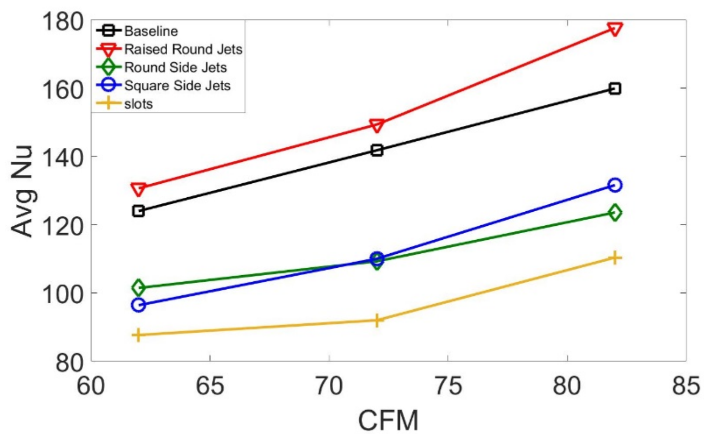
Prelim Designs of "Screw" Cooling





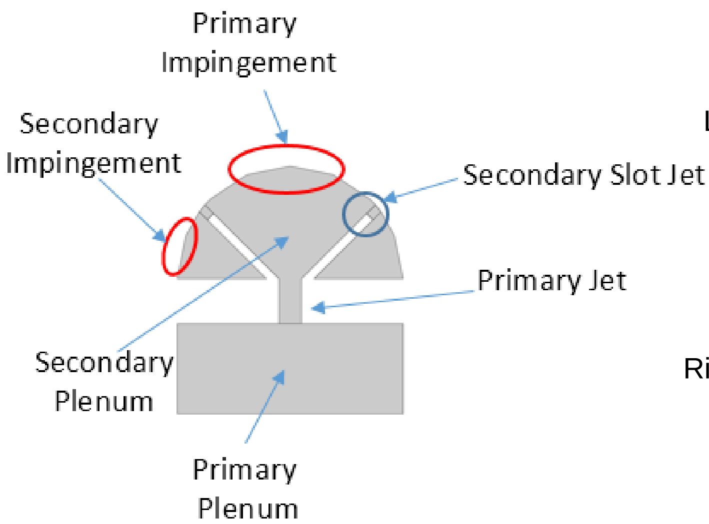
Heat Transfer Distribution

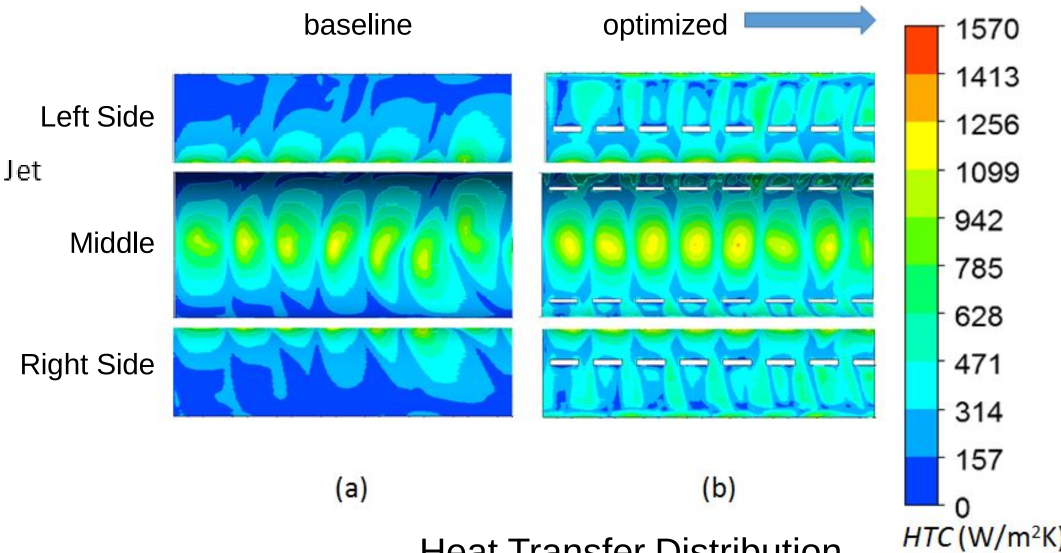
- **Side Jets (Round, square, slotted):** non-symmetric but more uniform heat transfer.
- **Highest Heat transfer:** raised jets.
- Entrainment and recirculation causes low heat transfer zones upstream of first jet.
- Raised round jets show up to 36% higher heat transfer @ ~90% higher pressure drop.
- Round, Square and Slot jets have lower heat transfer and lower pressure drop.



Averaged Heat Transfer

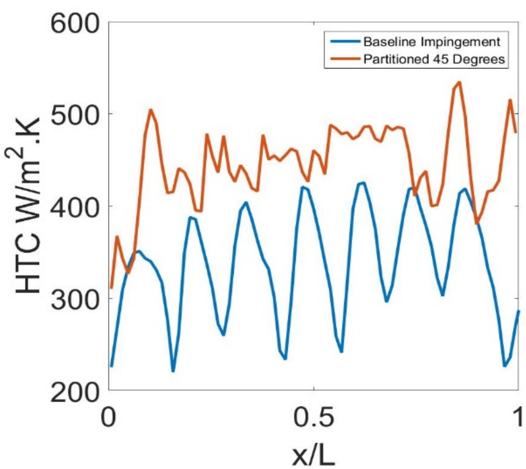
Optimized Leading Edge Cooling Scheme



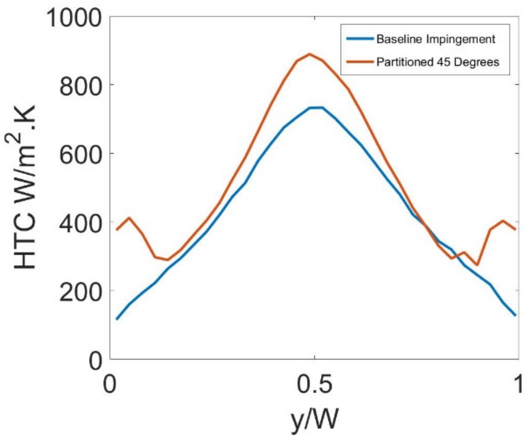


Heat Transfer Distribution

- **Geometry Feature:** *two 45° walls forming discrete secondary jets*.
- The secondary surface jets exhibited a 40% higher area averaged total heat transfer @ 1.5 times higher pressure drop.
- The secondary surface jet configuration has a significantly more uniform heat transfer distribution.

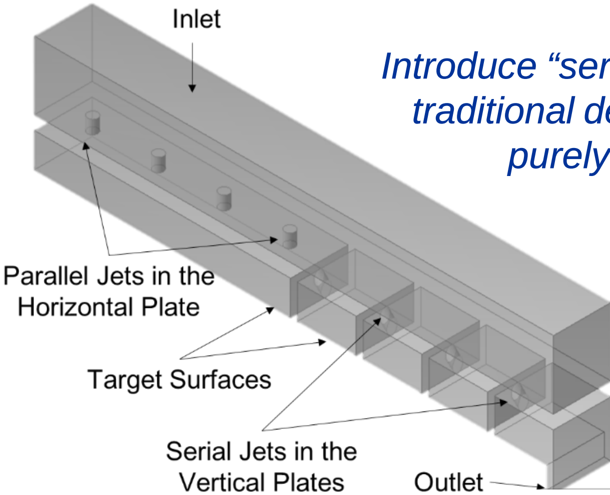


Spanwise Averaged HTC

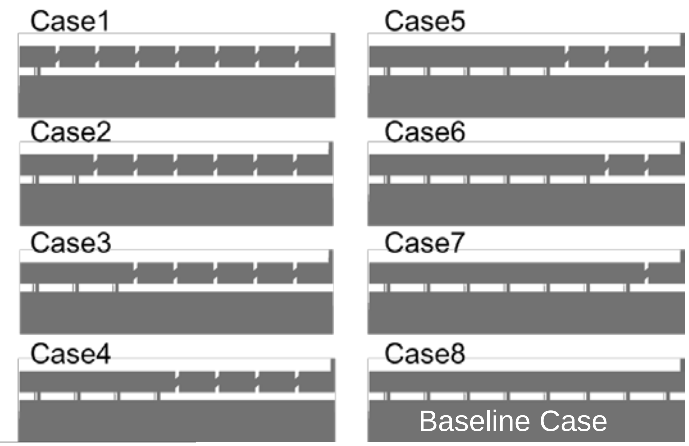


Streamwise Averaged HTC

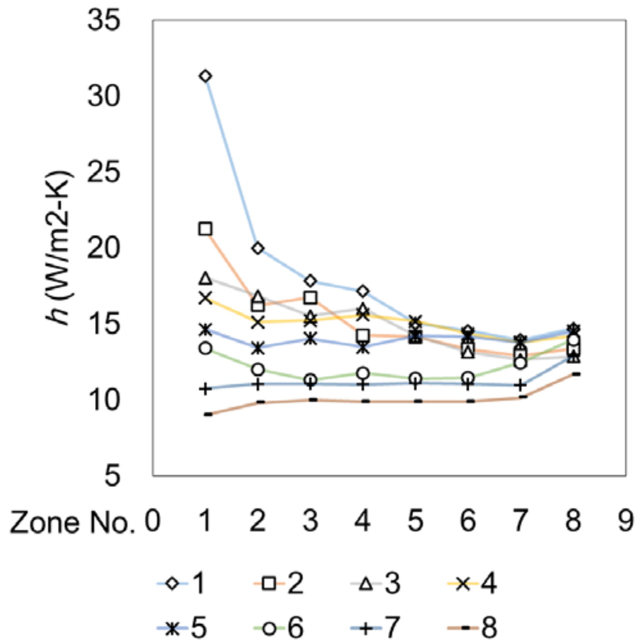
Enhancement of Hybrid Linked Jet Impingement



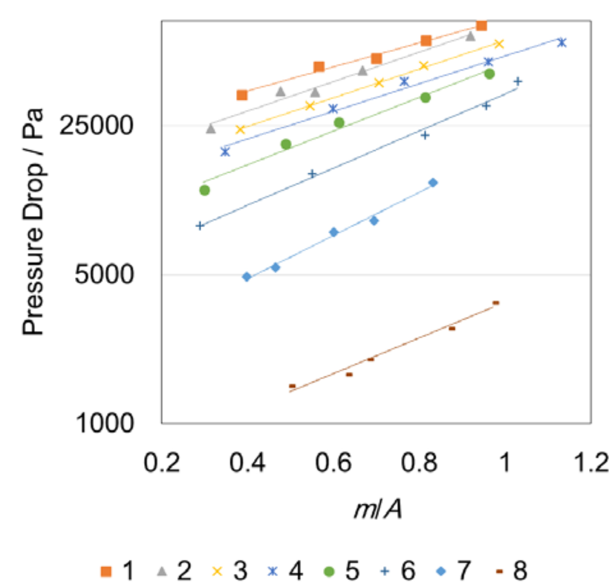
Introduce "serial linked jets" to traditional design, which is purely parallel.



- More serially linked jets leading to more heat transfer.
- Completely serially linked jets give more than 50% heat transfer enhancement compared to the traditional jet impingement designs, but with 5 to 20 times of pressure drop.



Heat Transfer Distribution



Pressure Drop

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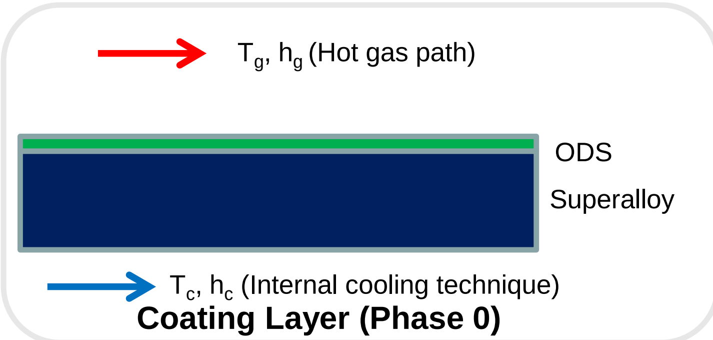
Task 3: ODS Coating with AM Assisted

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



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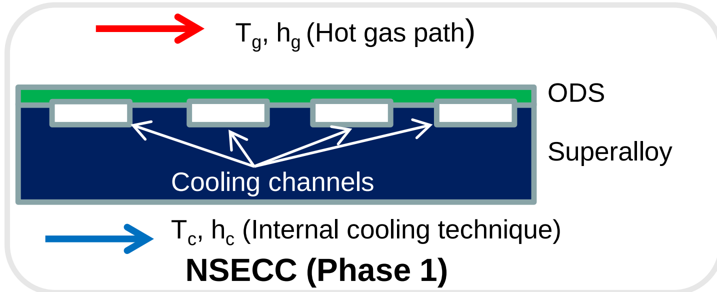

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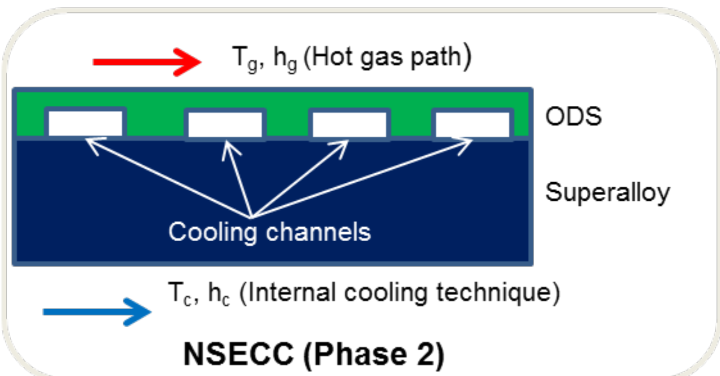
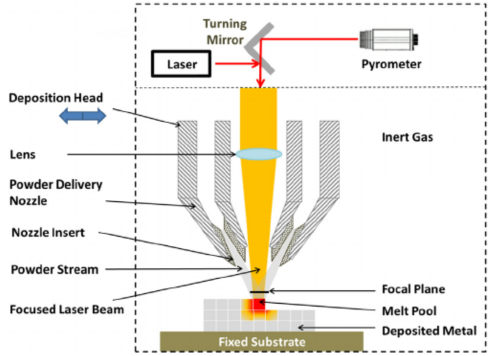


(to be done)

LENS 450 System in Pitt

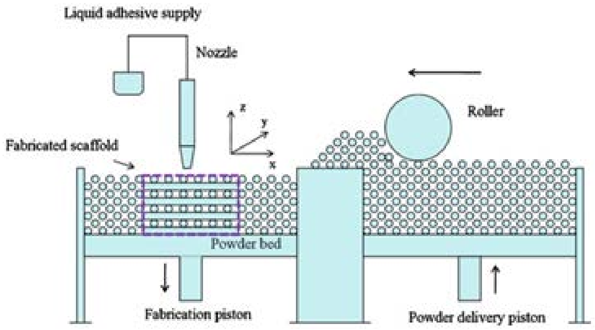


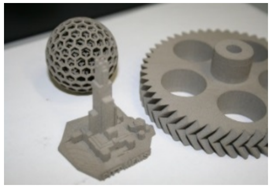
Scott M. Thompson et al.

Metallic Additive Manufacturing

Bind Jetting (EXOne)

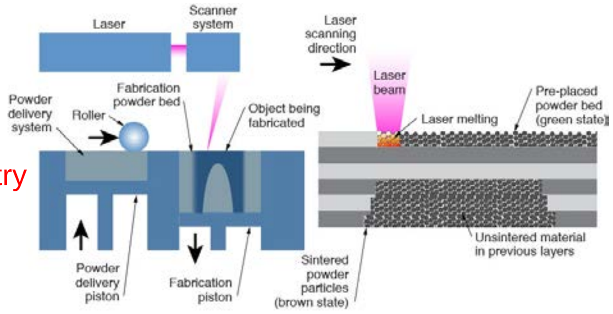
Pros: geometry free
cons: high porosity





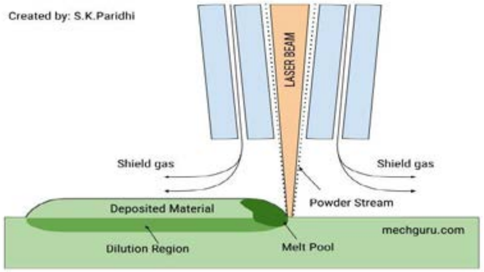
Powder Bed Fusion (EOS)

Pros: complex geometry
cons: single material



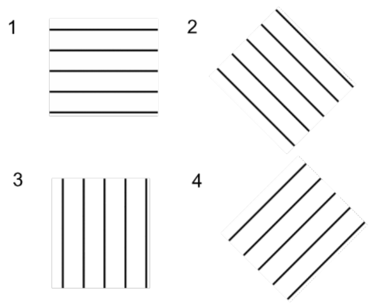
Direct Energy Deposition (LENS)

Pros: multiple materials
cons: no overhangs or unsupported structure

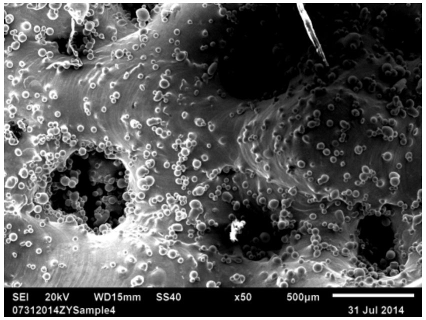


As metallic additive manufacturing technologies advance significantly over the recent past, complex metal products, such as turbine components, can be manufactured by this innovative technology.

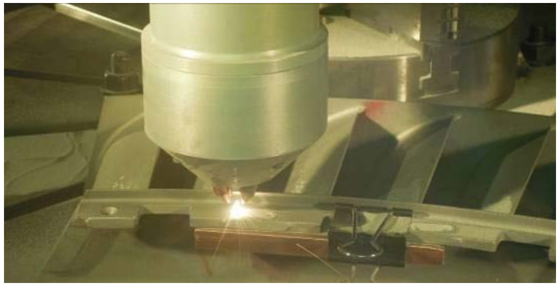
AM (LENS) Control Parameters



Hatch pattern

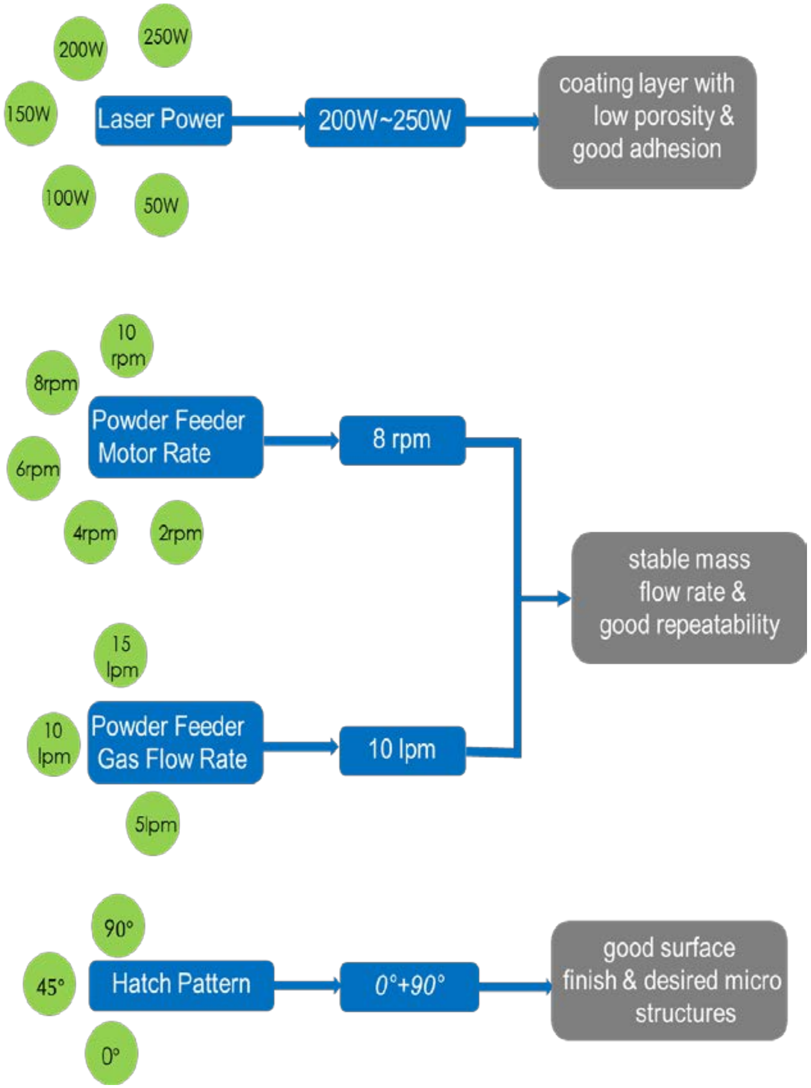


Hatch spacing



Laser power

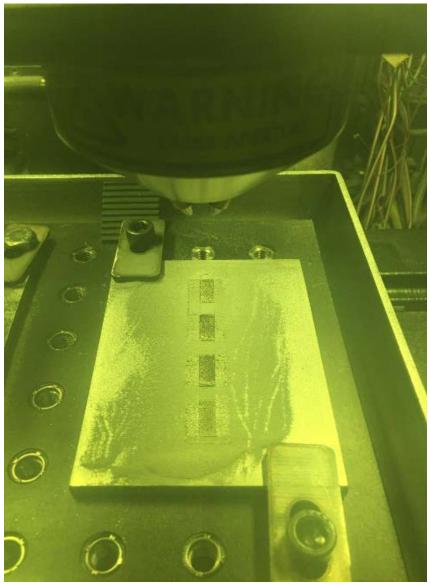
- **Objective**: Develop and optimize processing parameters for fabricating an ODS layer atop of substrate
- **Test Matrix**: 7 parameters, 45 tests
- **Key Parameters**: laser power, motor rate, gas flow rate, hatch pattern

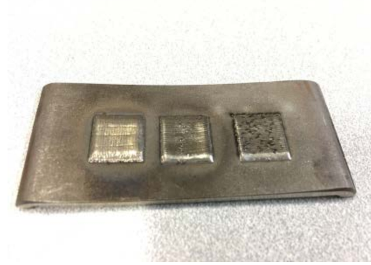


Optimization of AM Control Parameters

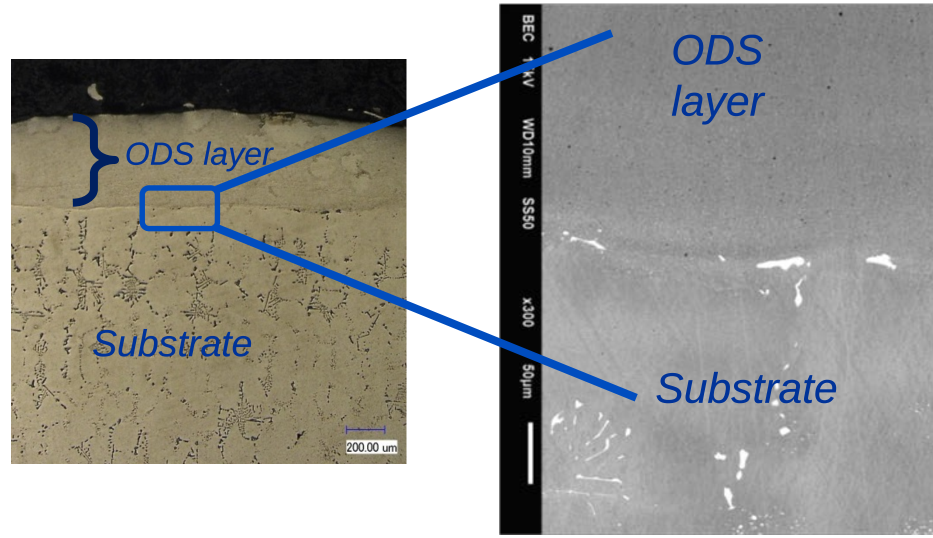
Additive Manufactured ODS Coating Layer

Objective: Produce a series of test coupon with densified ODS layer atop of single crystal nickel based superalloy substrate.

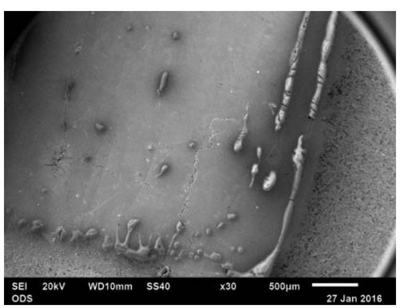




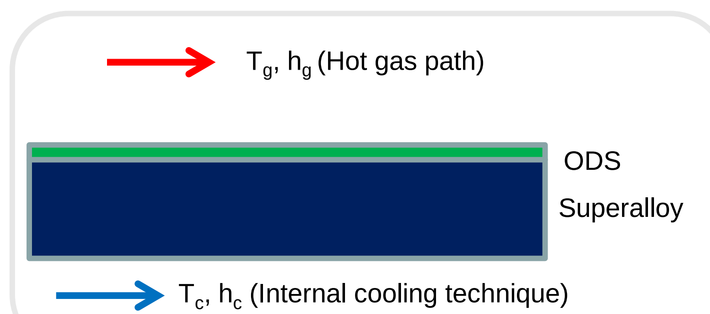
AM Samples of ODS Coating Layers



Cross Section View of ODS Coated Coupons

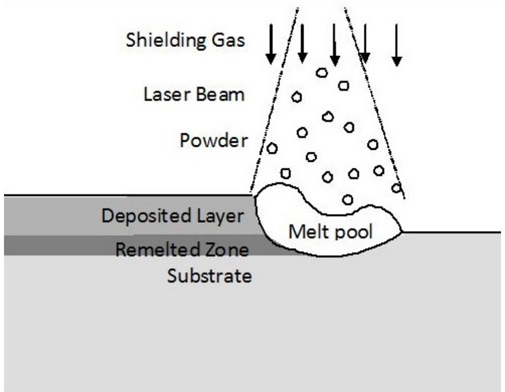


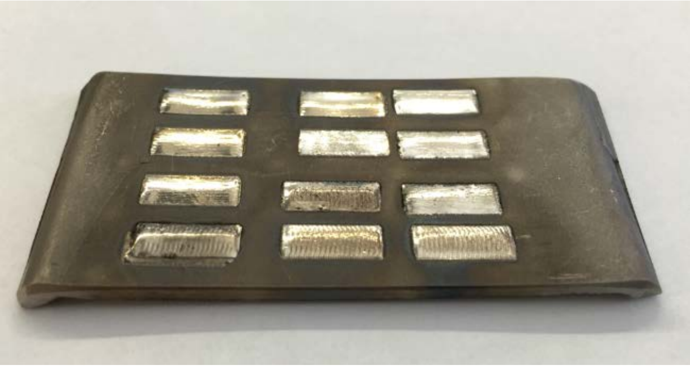
Surface Finish of ODS Coating Layer



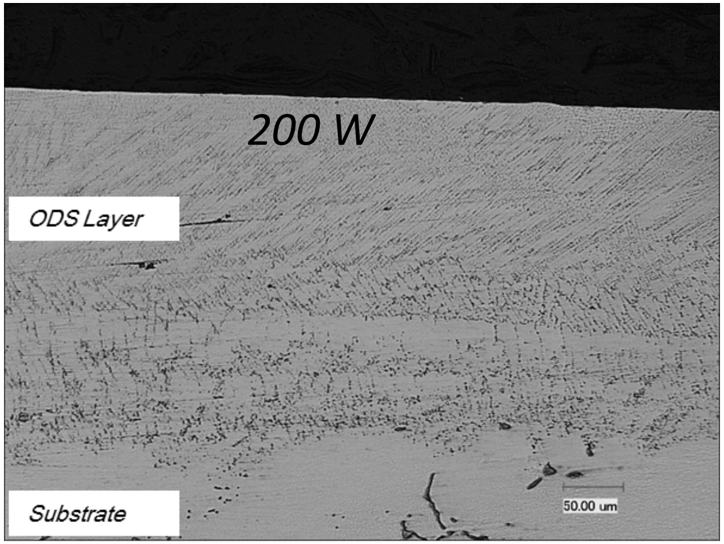
Coating Layer (Phase 0)

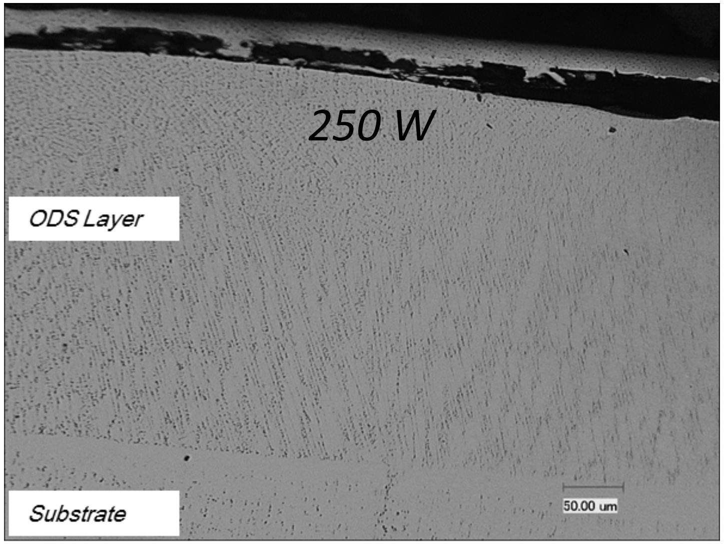
ODS Coating (AM Assisted)





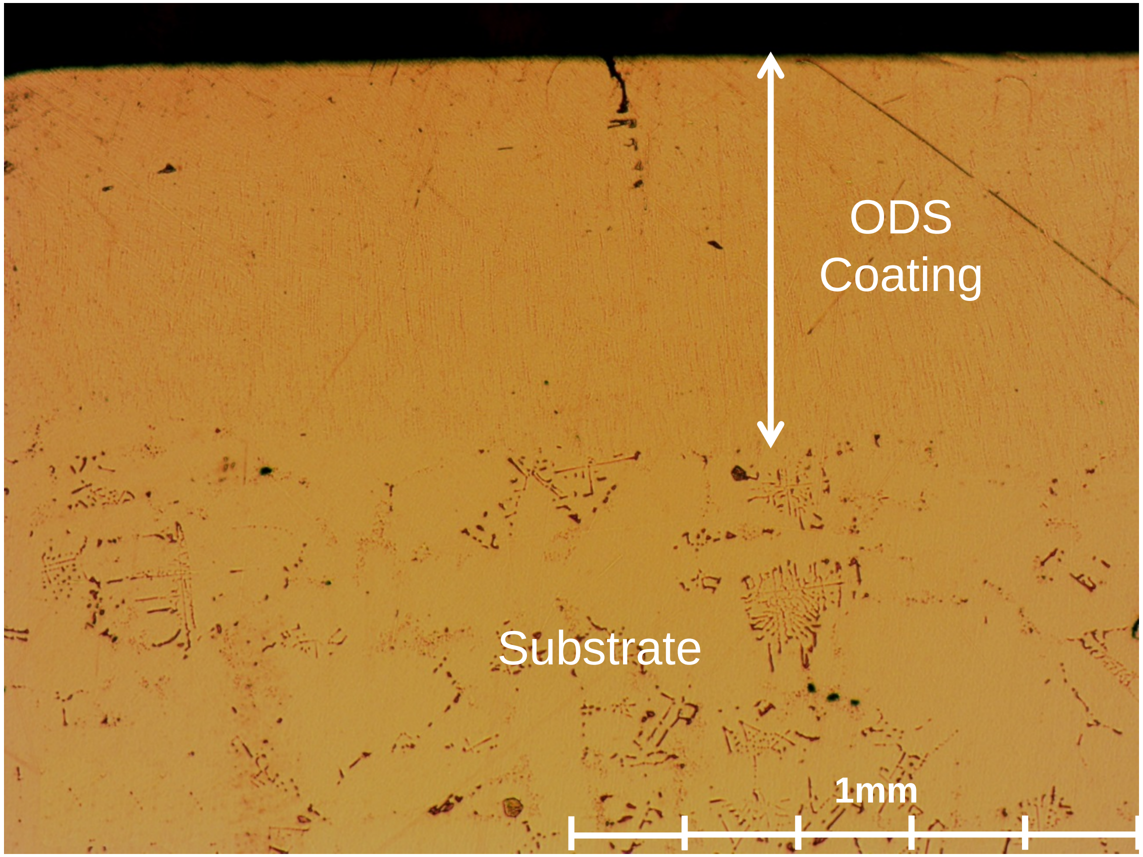
ODS Strip Deposition Samples





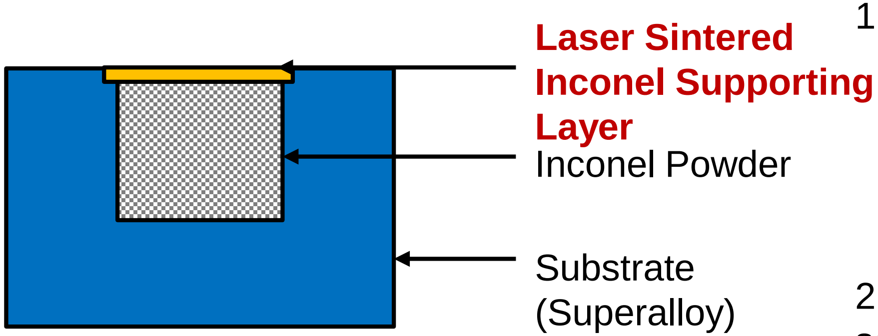
Cross Section of Laser Deposited Samples

275 W Laser Power (no etching)



Effort to Make Unsupported Structures

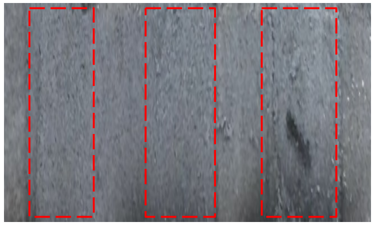
Challenges: Direct Energy Deposition systems (LENS 450) are not capable of making unsupported bridges or overhangs such as top layers for cooling channels.



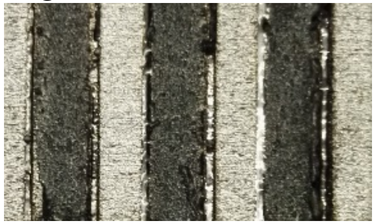
Approach to Make Unsupported Structure by LENS

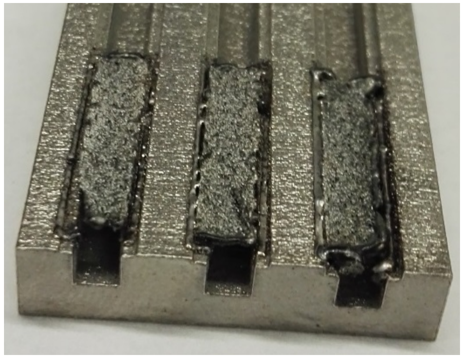
* Suitable for casted blades

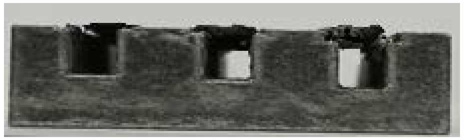
1. Fill grooves with powder



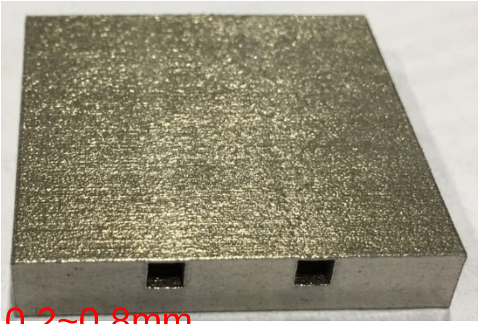
2.Sinter the top layer by one scanning

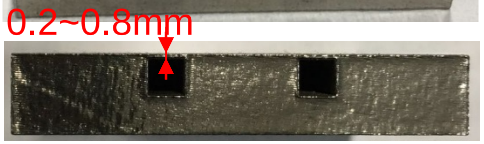


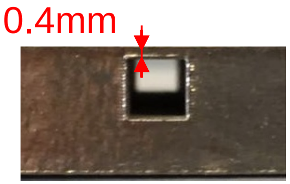


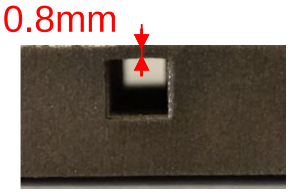


Overhangs and Unsupported Bridges by EOS



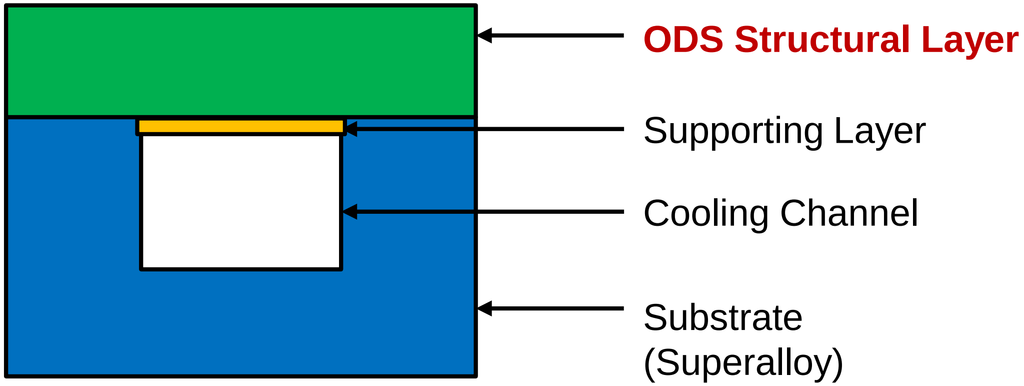




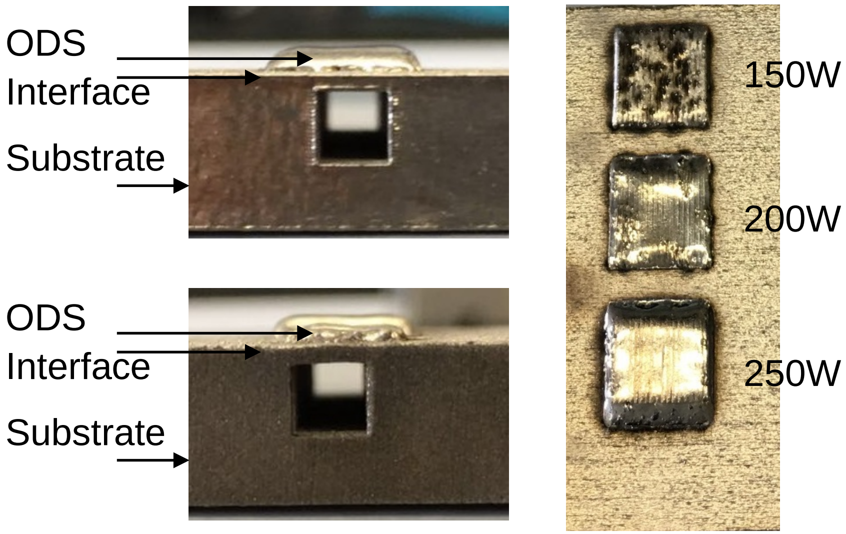


Additive Manufactured ODS Coated Cooling Channels

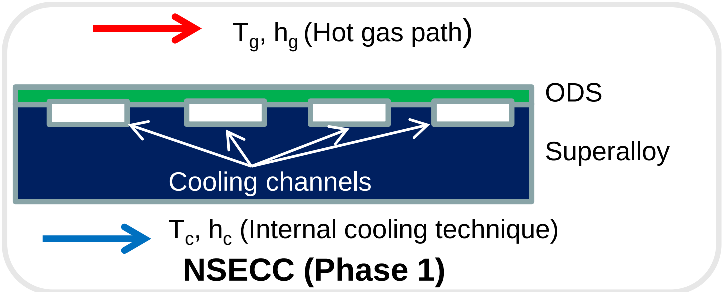
Objective: Produce a series of test coupon with densified ODS layer atop of grooved single crystal substrate to form cooling channels.



NSECC manufacturing Approach



ODS Coupons with Rectangular Cooling Channels



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- *Introduction and Background*
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- *Tasks*
  1. *Advanced Impingement*
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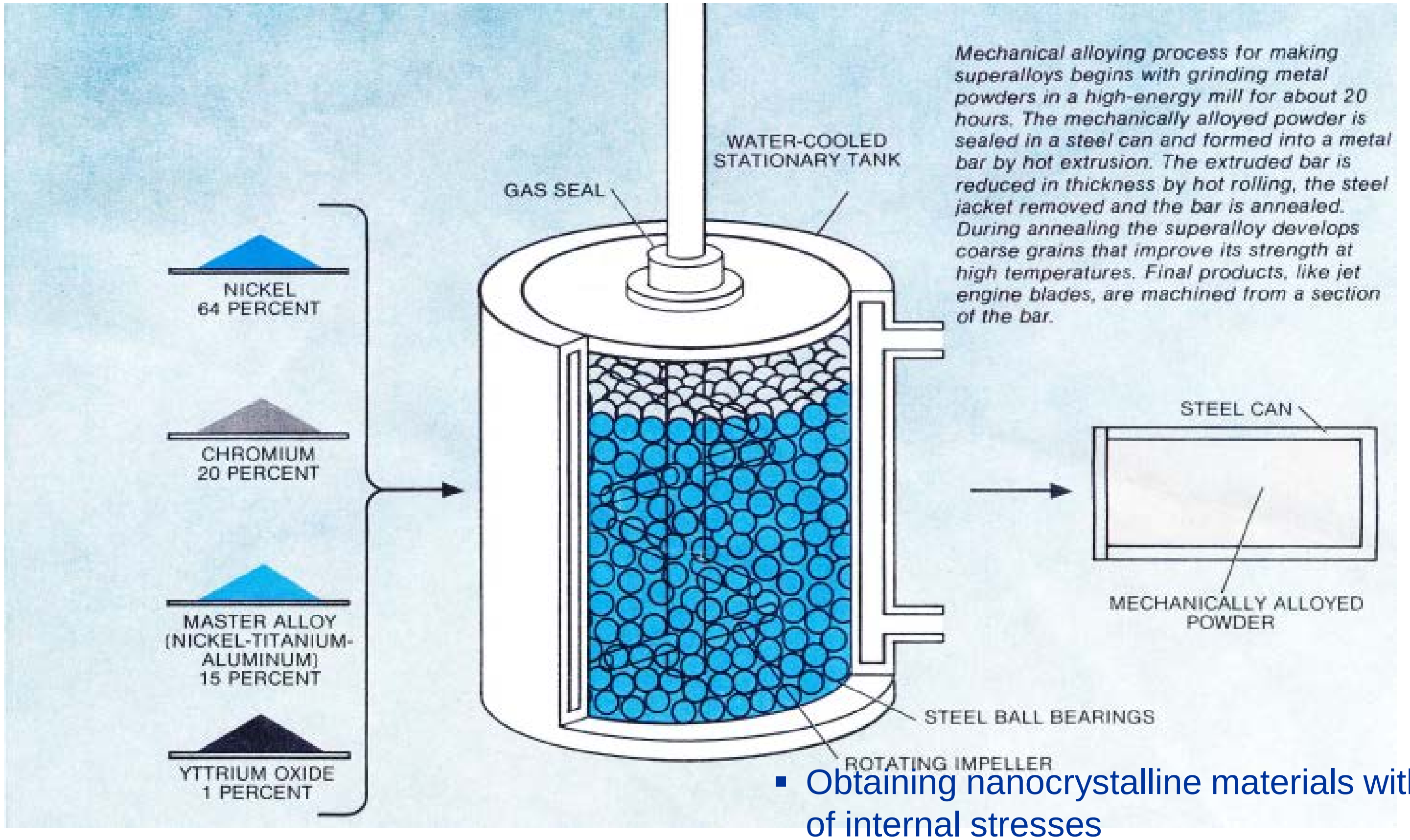
  3. ***ODS Powders Fabrication and Characterization***
  4. *Microstructural and Mechanical Properties Characterization*
  5. *Detailed Experimental Measurement and Validation*

Mechanical Alloying/Ball Milling (Traditional ODS Powder Fabrication)

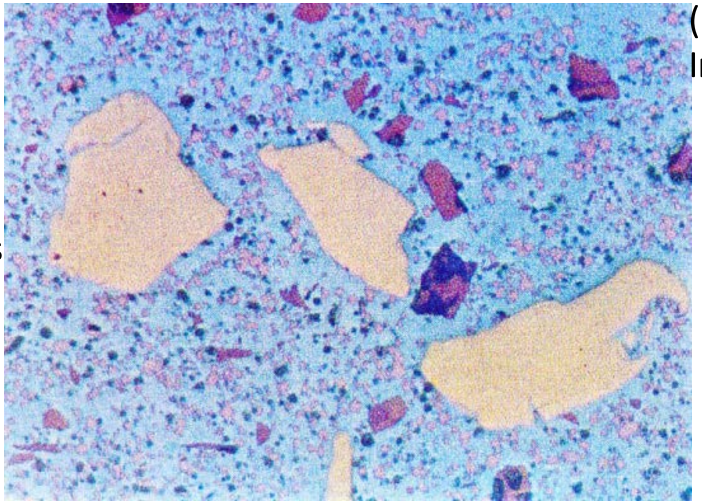


(From Huntington Alloy Inc., Huntington, WV)

- Obtaining nanocrystalline materials with very high concentrations of internal stresses
- Obtaining metastable and nonequilibrium states
- Reactive Powder
- Improved dispersion homogeneity

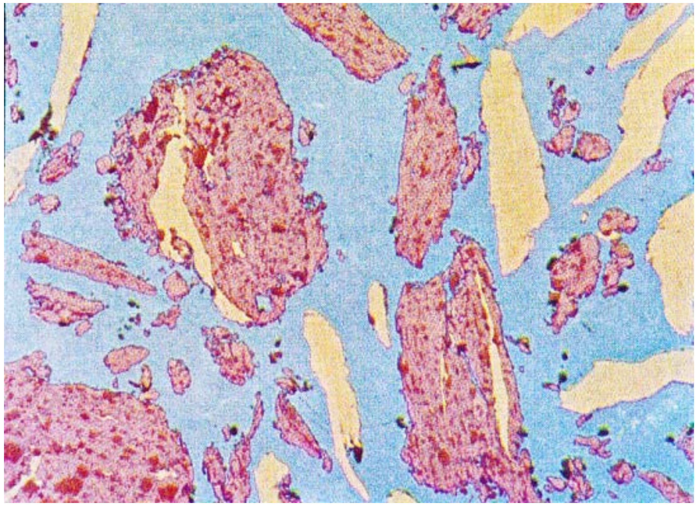
Mechanical Alloying/Ball Milling (Traditional ODS Powder Fabrication)

Raw Powders

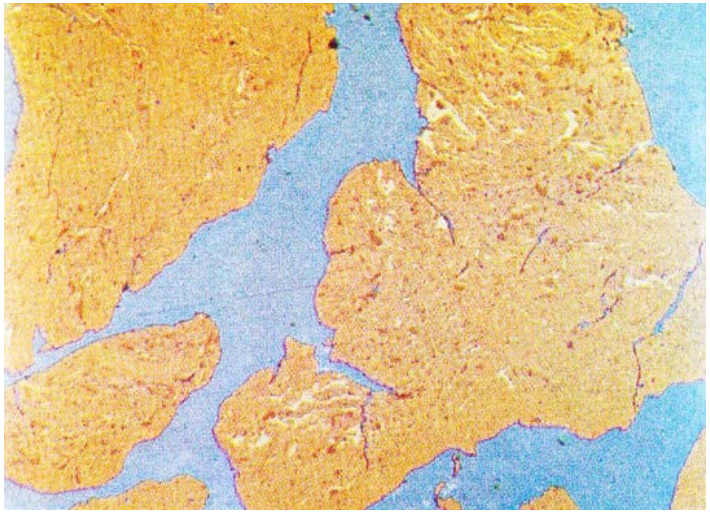


(From Huntington Alloy Inc., Huntington, WV)

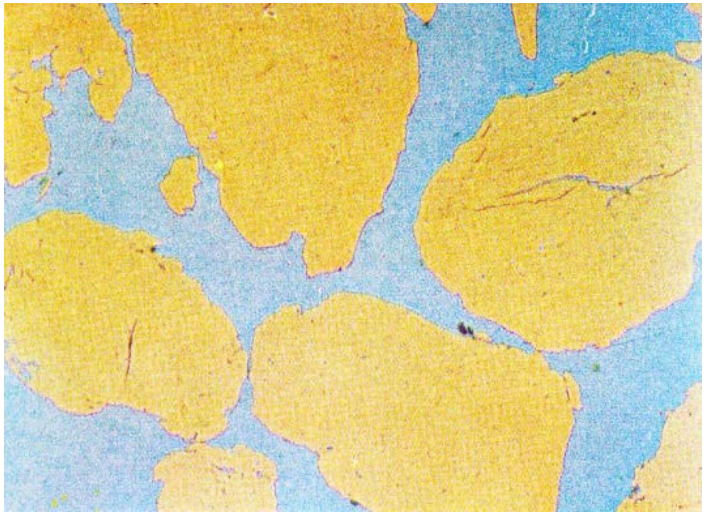
30 min.



4 hrs



10 hrs



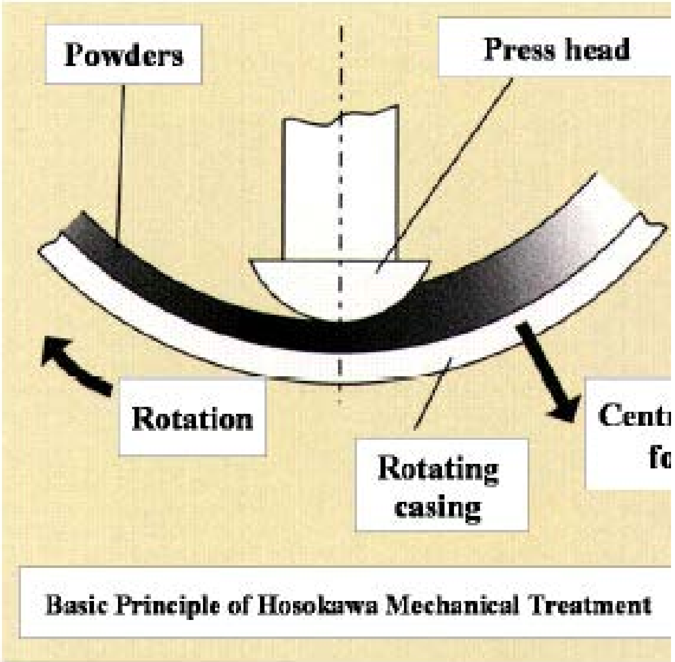
ODS Powders Fabrication and Characterization

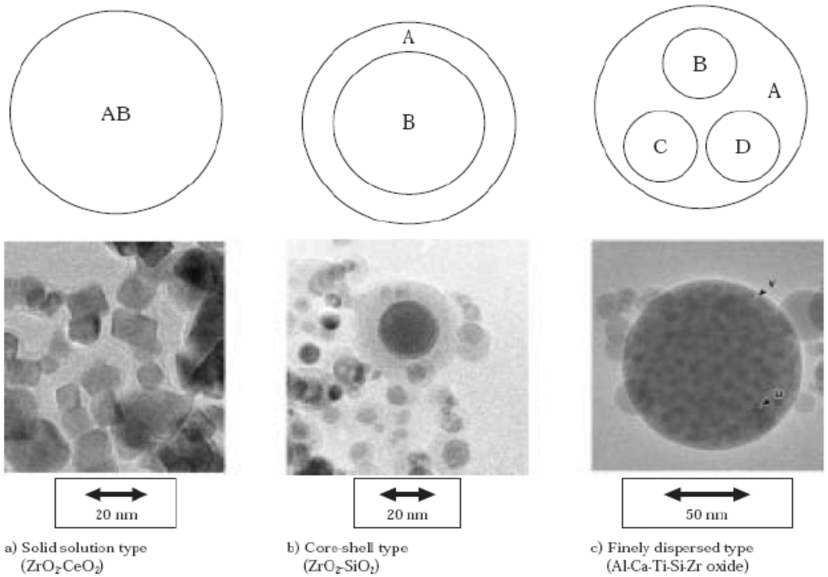
Objective: Develop and optimize ODS fabrication process for additive manufacturing (AM) applications

Approach

➢ **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**)
- Enable particles to be dispersed uniformly and bonded onto base(host) particles without using binders. Improved particle sphericity



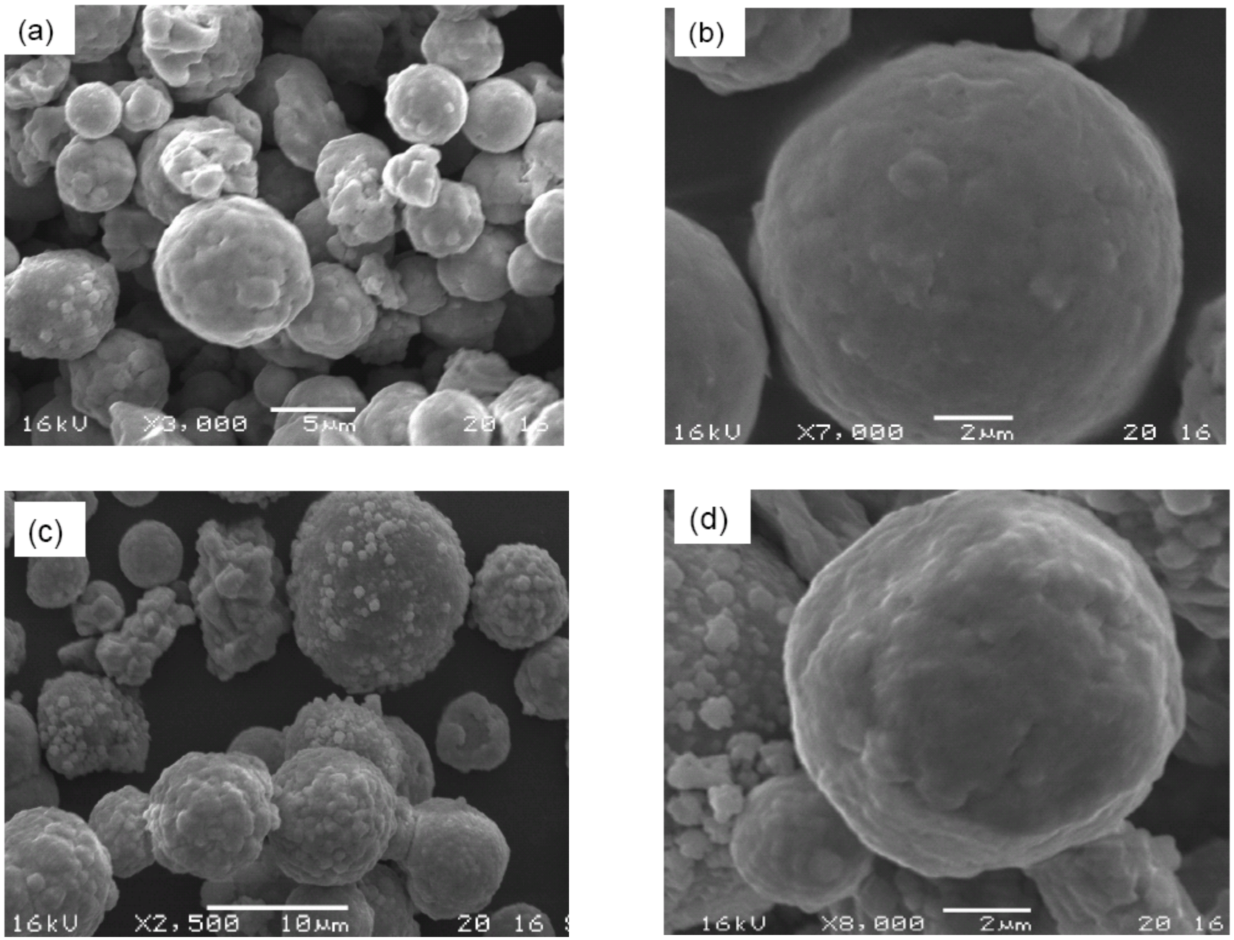


Structural patterns of nanocomposite particles
[T. Yokoyama and C. C. Huang, KONA No.23 (2005)]

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 %)

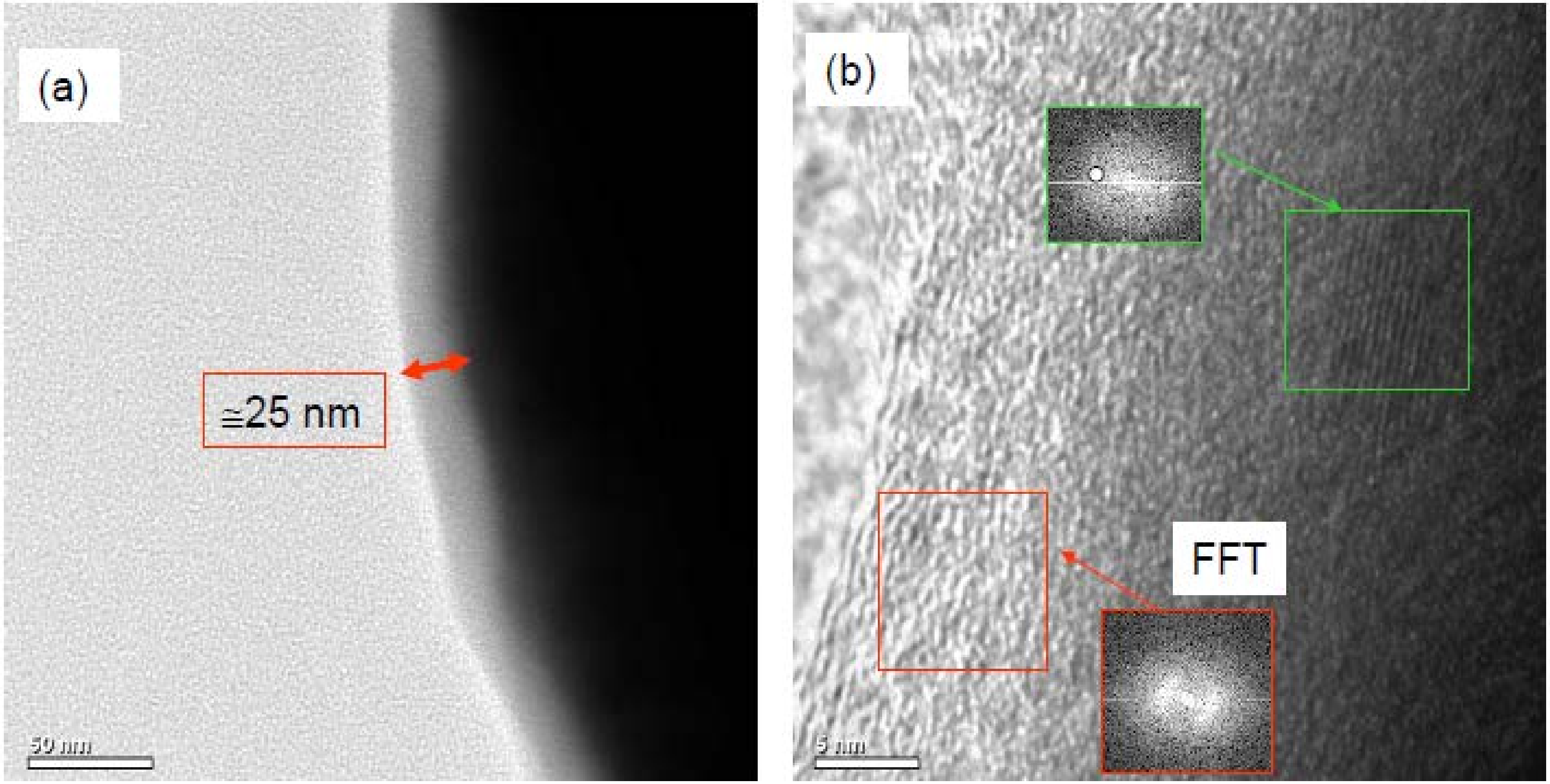
	Cr (7.5~10 µm)	Al (4.5 ~ 7 µm)	Y_2O_3 < 50nm	W (~1 µm)	Ni (4 ~ 8 µm)
A1	20	5	1.5	0	73.5
A2	20	5	1.5	3	70.5



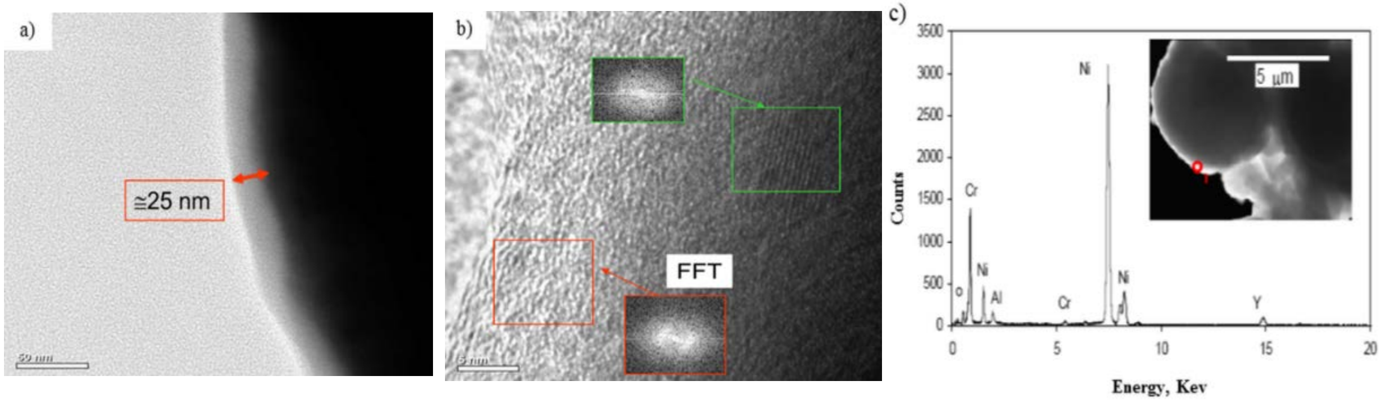
SEM micrographs of MCB processed powder sample A1 and A2
(a). Sample A1; (b) close view of (a); (c) sample A2; (d): close view of (c)

ODS Powder Characterization

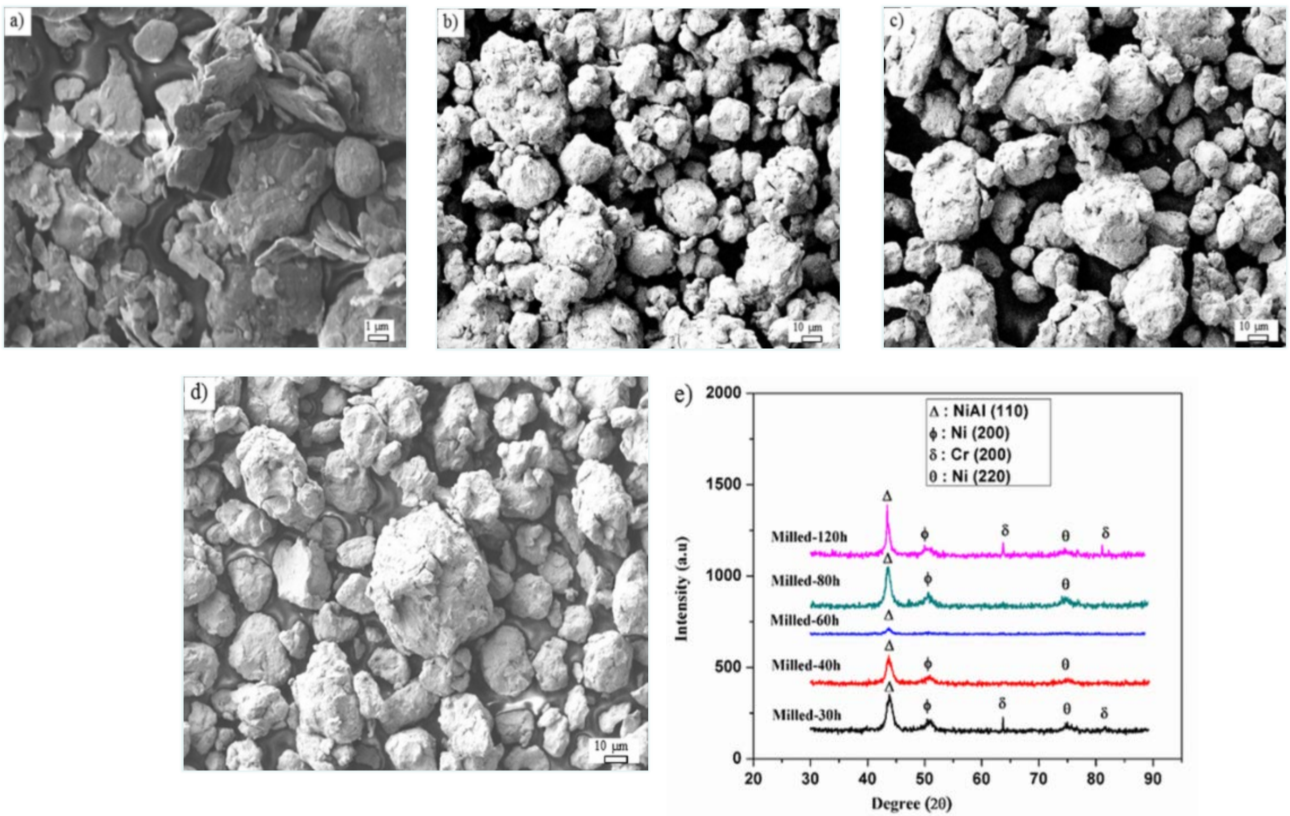
TEM BF and HREM imaging – A1 Sample



- 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.



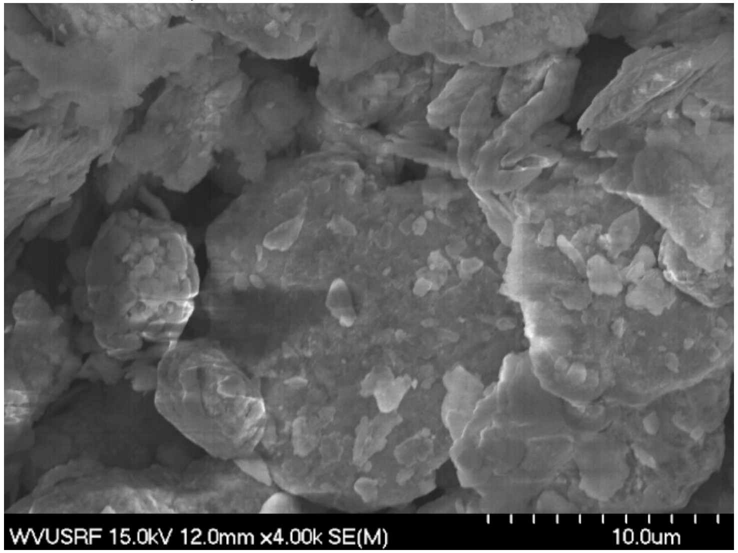
MCB processed ODS powders images, (a) TEM BF, (b) HR TEM, (c) STEM EDX



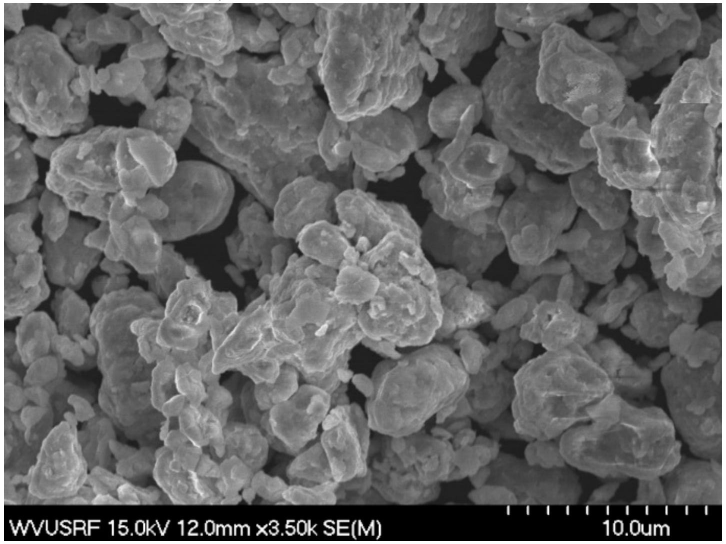
SEM micrographs of milled ODS powders for (a) 5 hrs, (b) 40 hrs, (c) 60 hrs, (d) 120 hrs, and (e) XRD spectrum.

ODS Powder Fabrication Optimization

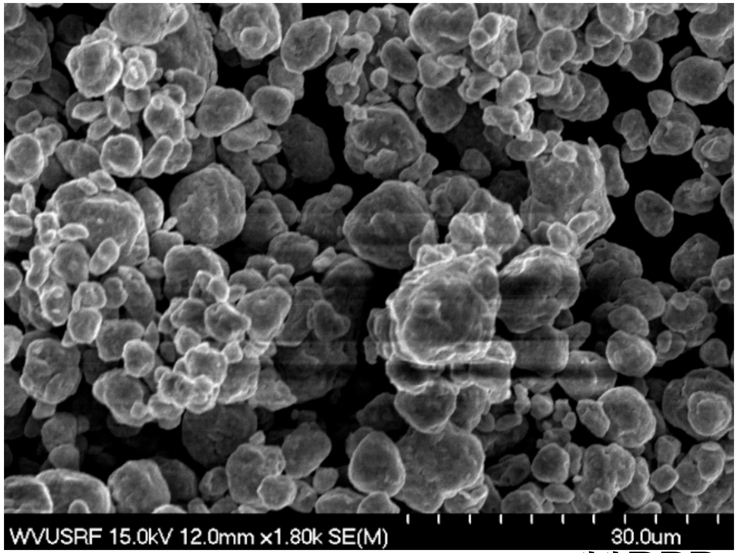
BPR: 10, MCB + 25 hours BM



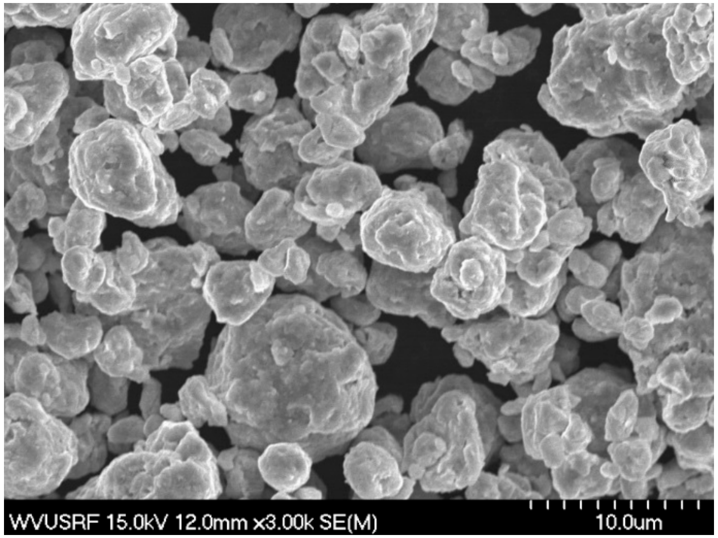
BPR: 15, MCB + 15 hours BM



BPR: 30, MCB + 45 hours BM

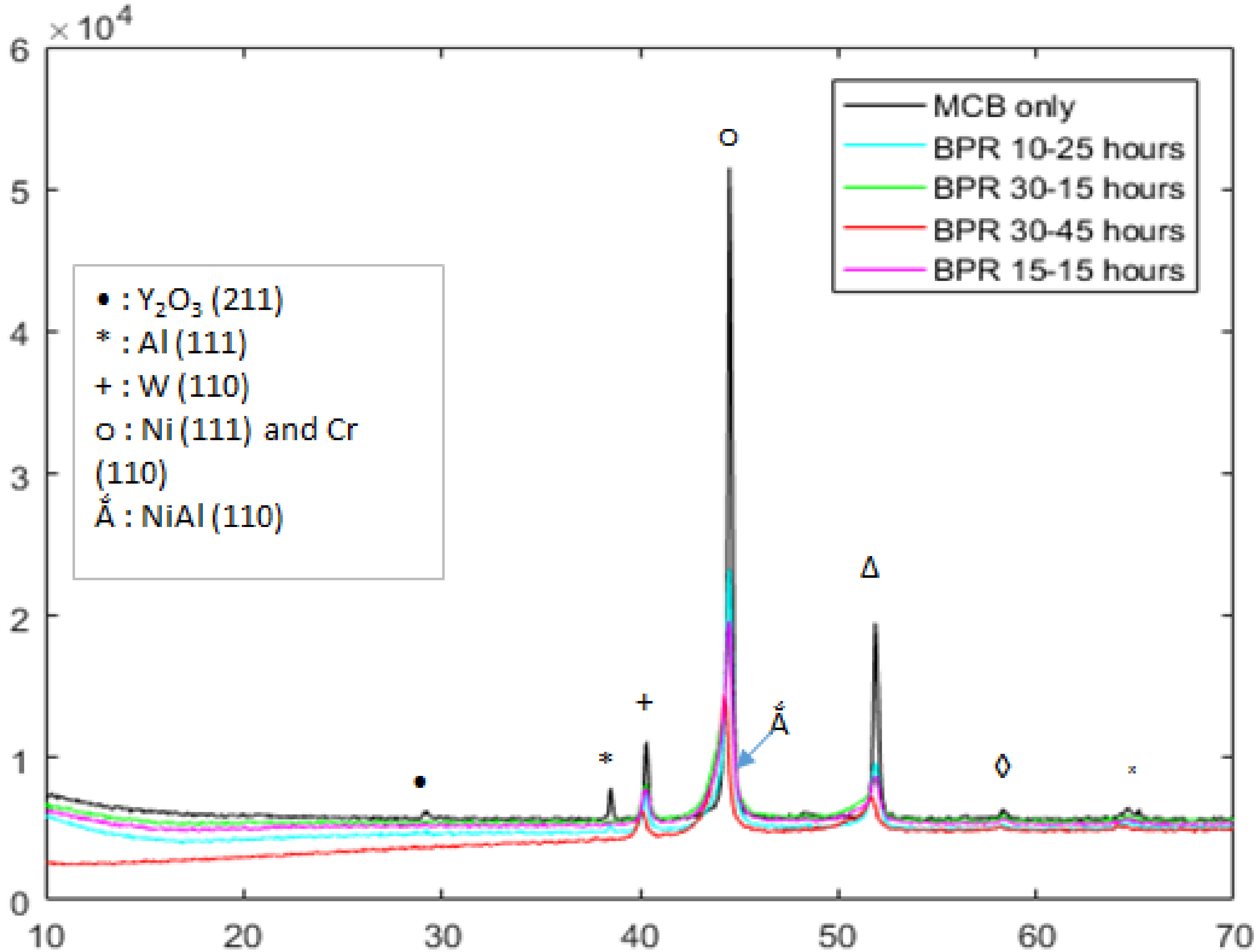


BPR:30, MCB + 15 hours BM



*****BPR: Ball to Powder Ratio***

XRD Characterization – Effect of BPR and Time



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Task 4: Microstructural and Mechanical Properties Evaluations

Objective: Characterize the microstructural and mechanical properties of ODS coating under high temperature condition

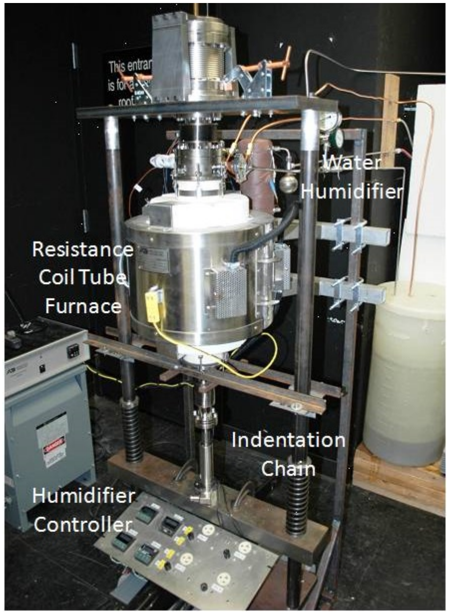
Approach

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

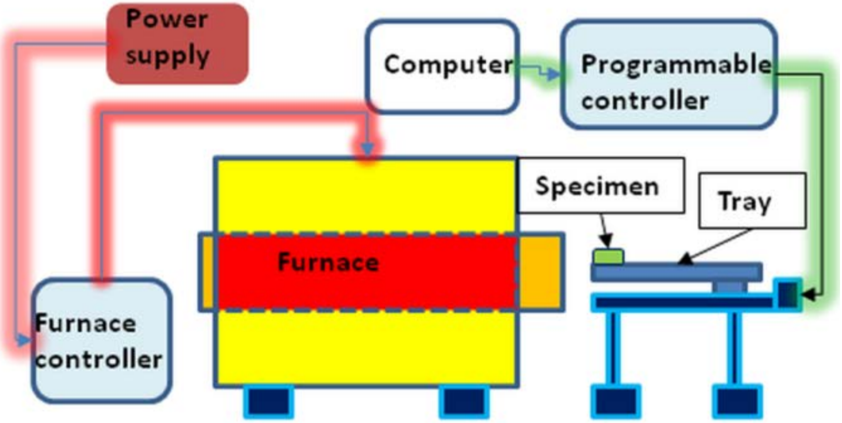
Sample

- ODS Coating layers on flat plate substrates

Gridding and Cutting of ODS Coated Coupons



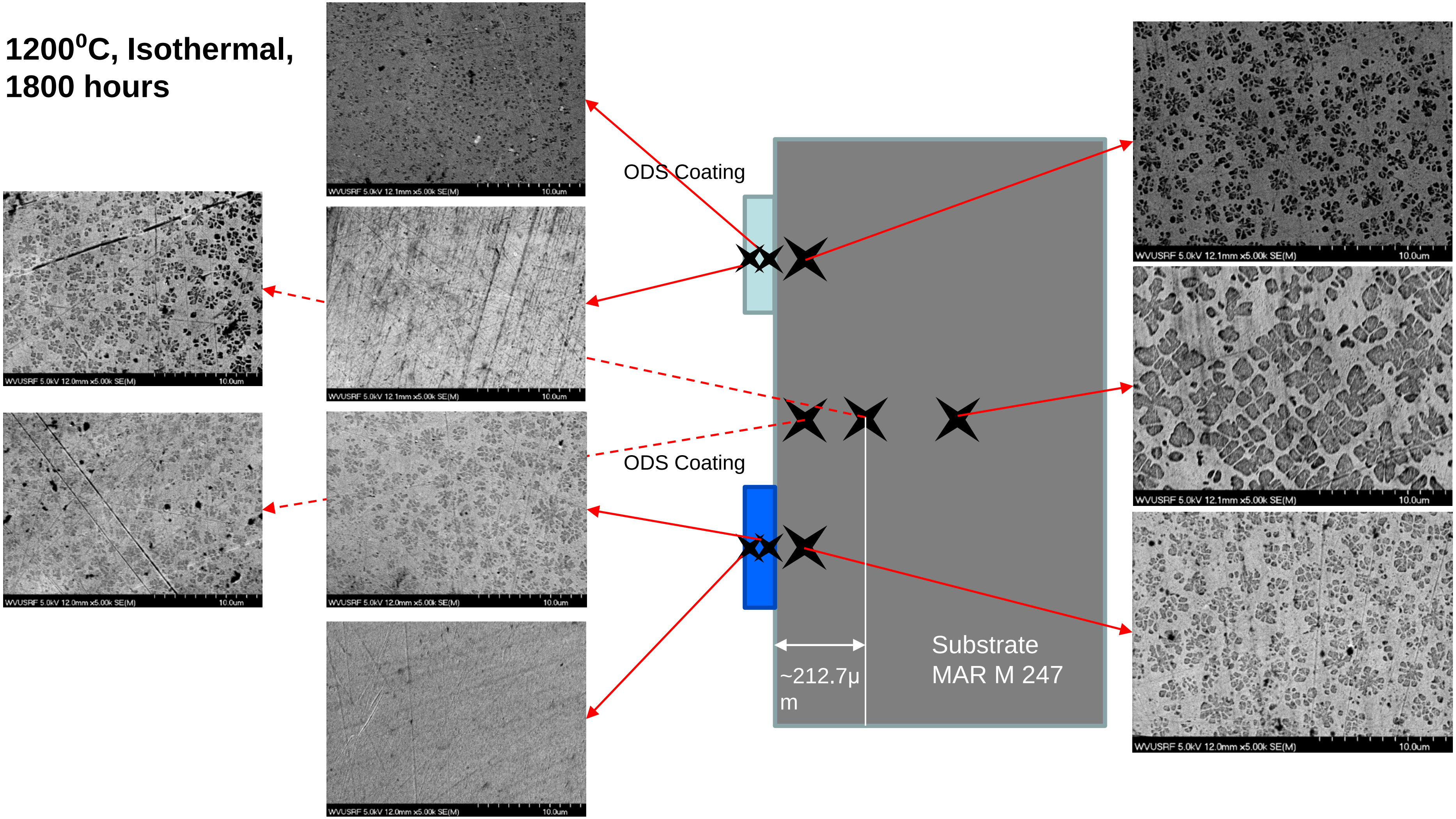
Controlled environment high temperature micro-indentation system (WVU)



Schematic of the cyclic thermal exposure apparatus setup (WVU)

Isothermal Oxidation Testing

1200^{0}C, Isothermal, 1800 hours

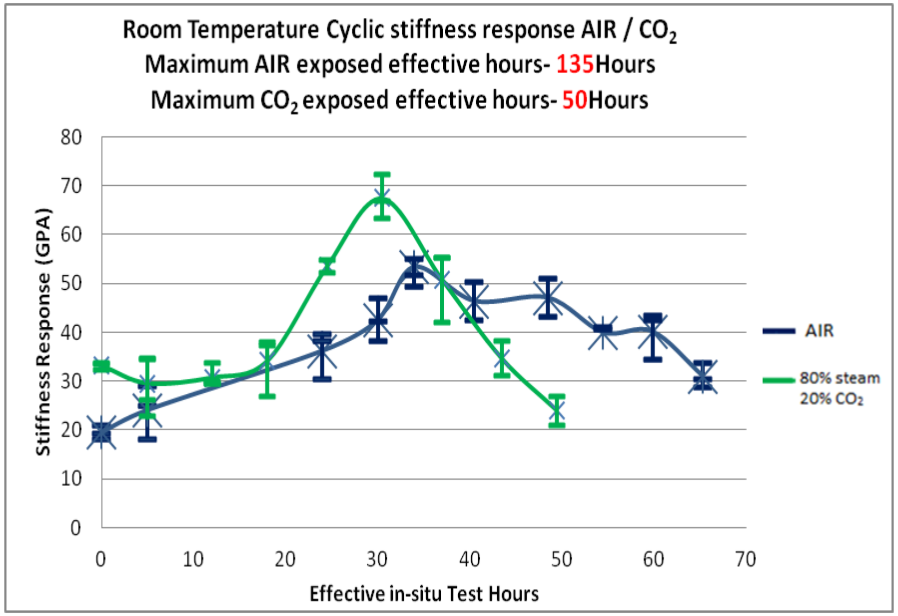


***Gamma Prime (γ'): This phase constitutes the precipitate used to strengthen the alloy. It is an intermetallic phase based on Ni3(Ti,Al) which have an ordered FCC L12 structure*

Thermal Cyclic Testing**
Comparison of Measured Surface Mechanical Property (Young's modulus)

AM-assisted ODS coating on M247 superalloy substrate

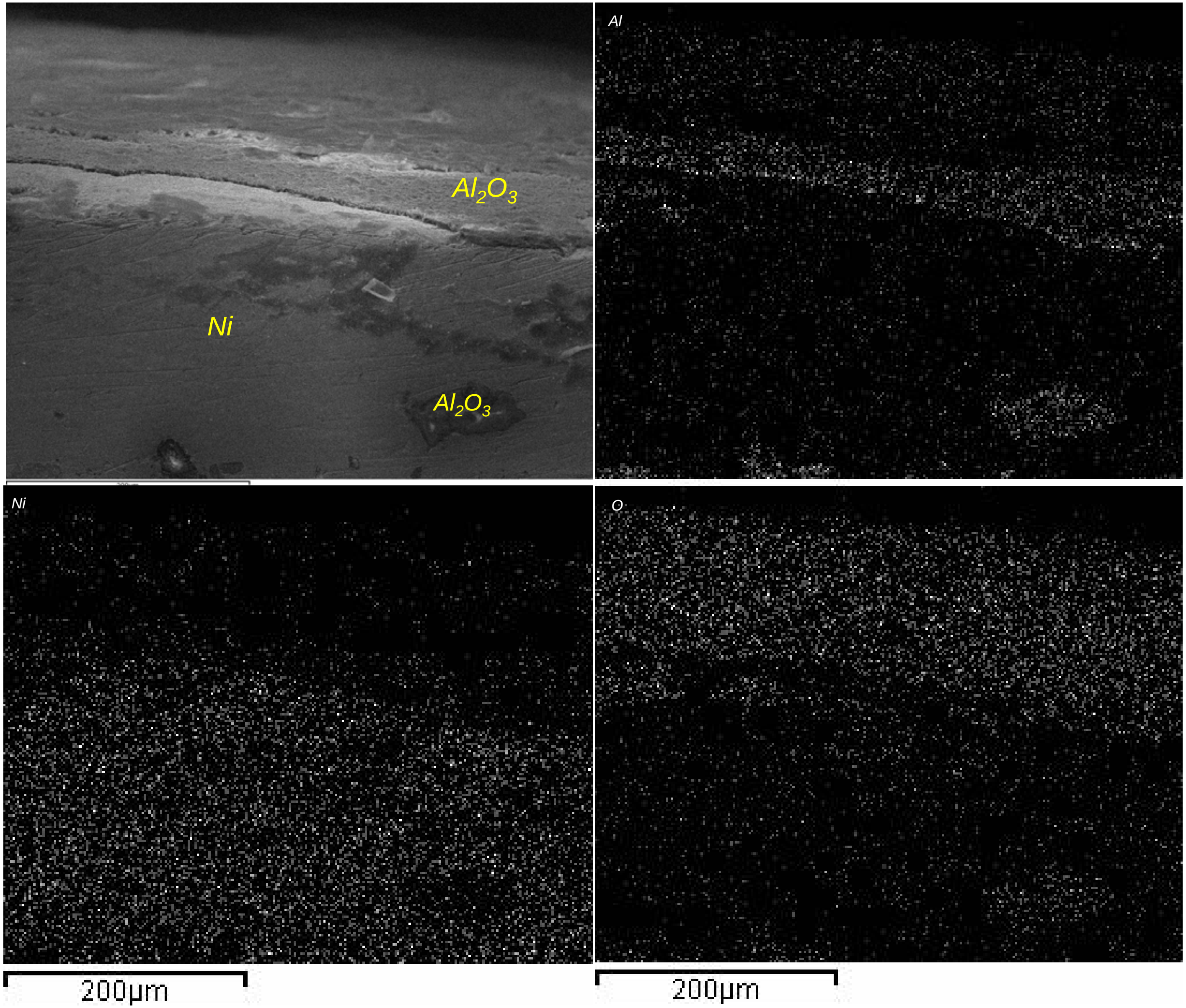
	200 W	150 W	100 W	Substrate
As-received	174.4	173.8	227.6	126.5
15 cycles	141.5	80.9		100.2
40 cycles	132.1	85.5		109.1
	143.0	86.8		
80 cycles	113.2	59.4	57.3	58.7
	113.0	58.4	57.4	61.0
				56.2
160 cycles	110.3	68.8	62.4	
	135.4	65.4	61.2	
	118.2			
240 cycles	210.0	72.0		
	213.5	88.8		
360 cycles	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	59.0	141.7
600 cycles	183.0	84.7	163.6	124.6
	225.0	96.5	139.0	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



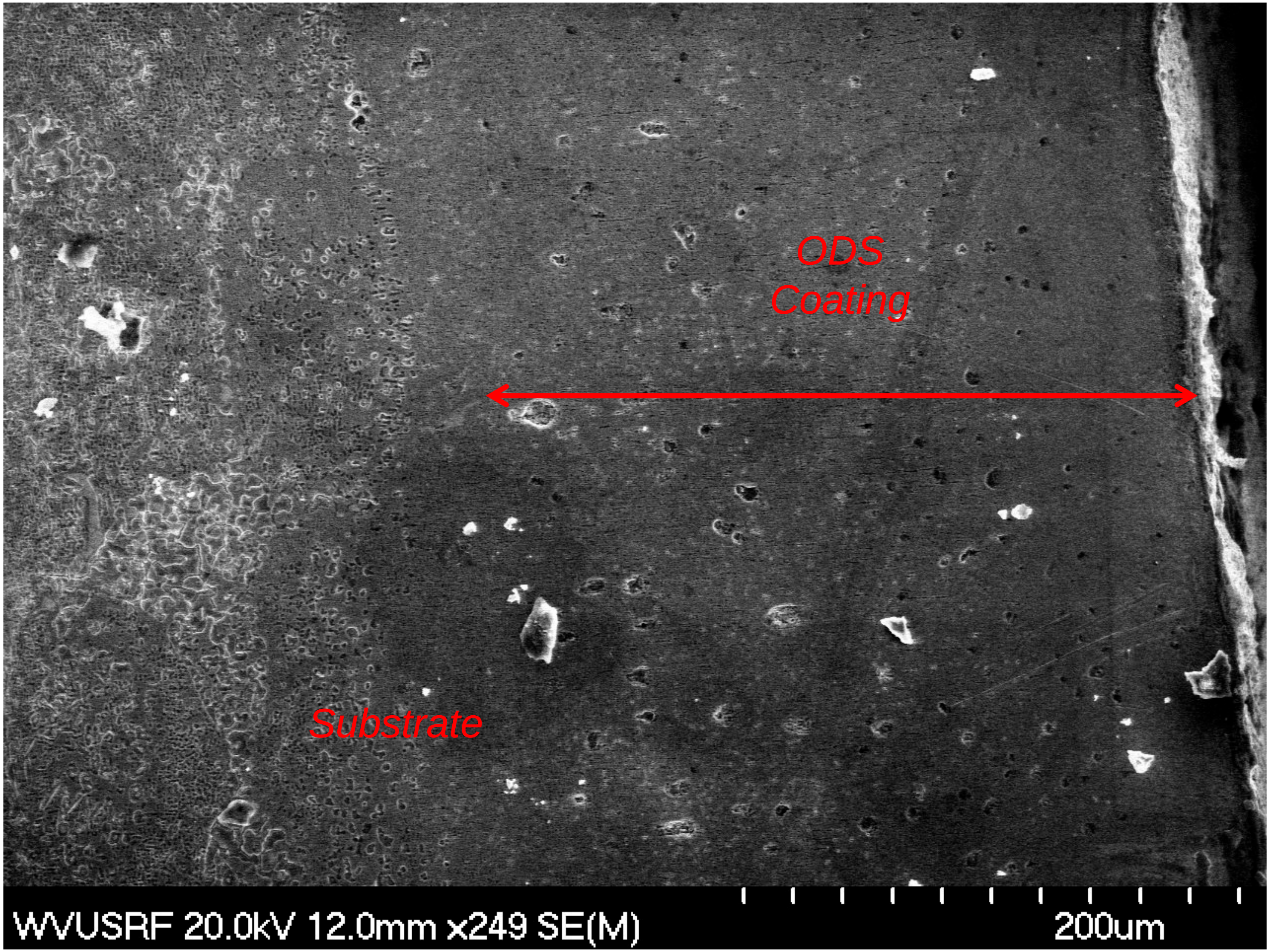
In-situ micro-indentation stiffness response of APS/MCrAlY/RenéN5 coupon under cyclic oxidation room to 1100°C under air and wet (80% steam/20% CO_2) conditions

*** 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.***

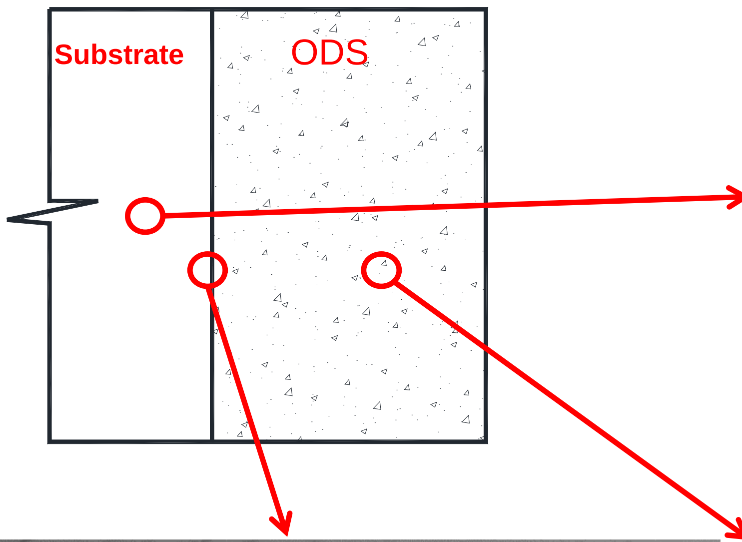
Stable alpha Al_2O_3 oxide layer at 240 cycles

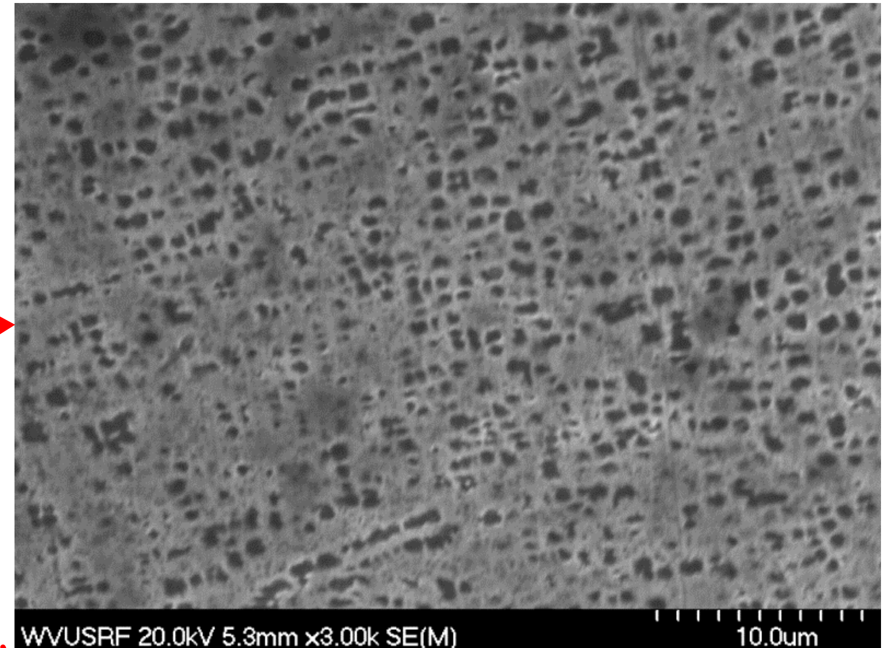


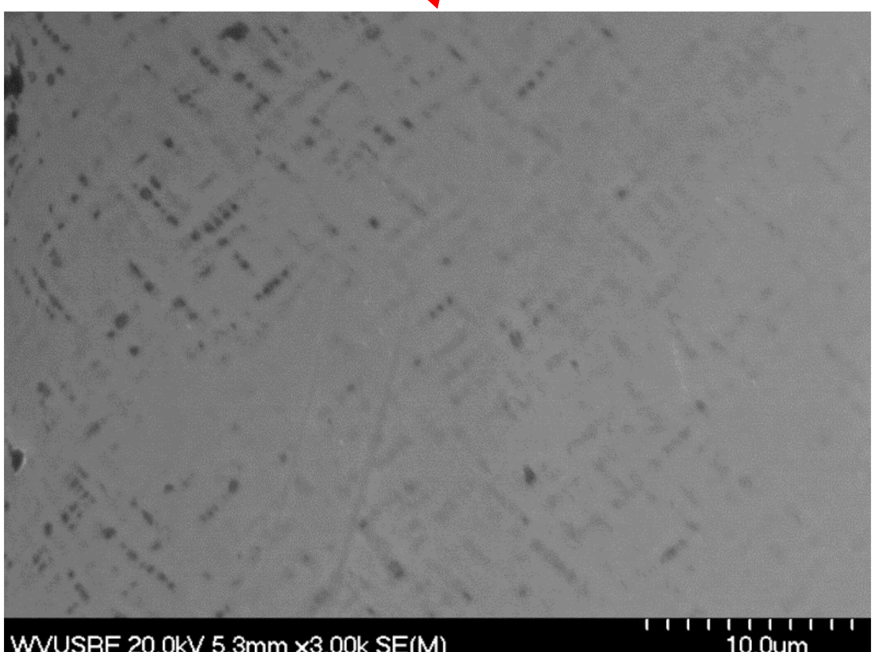
200w – 1040 thermal cycles

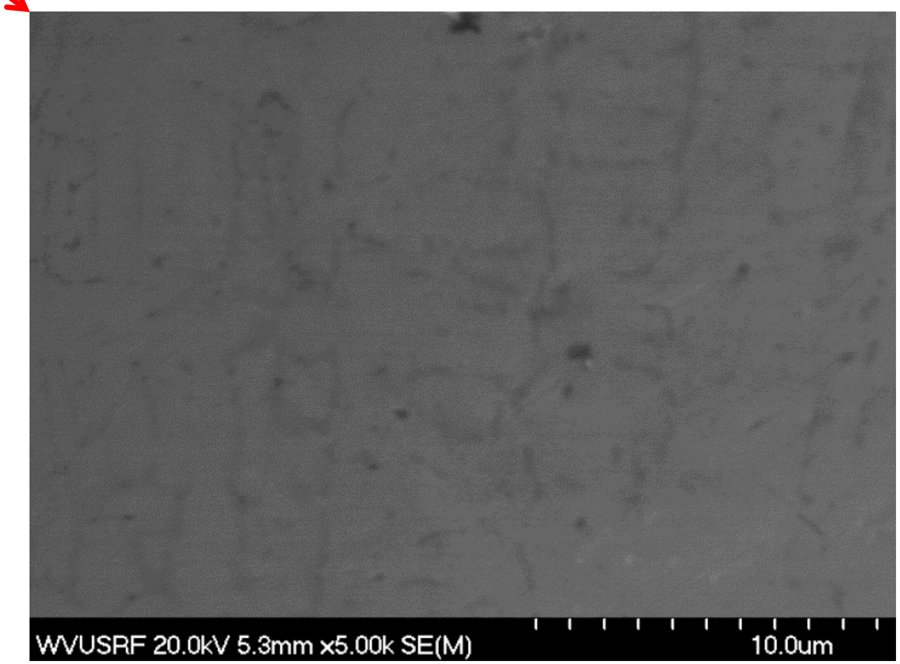


275W – 0 thermal cycles

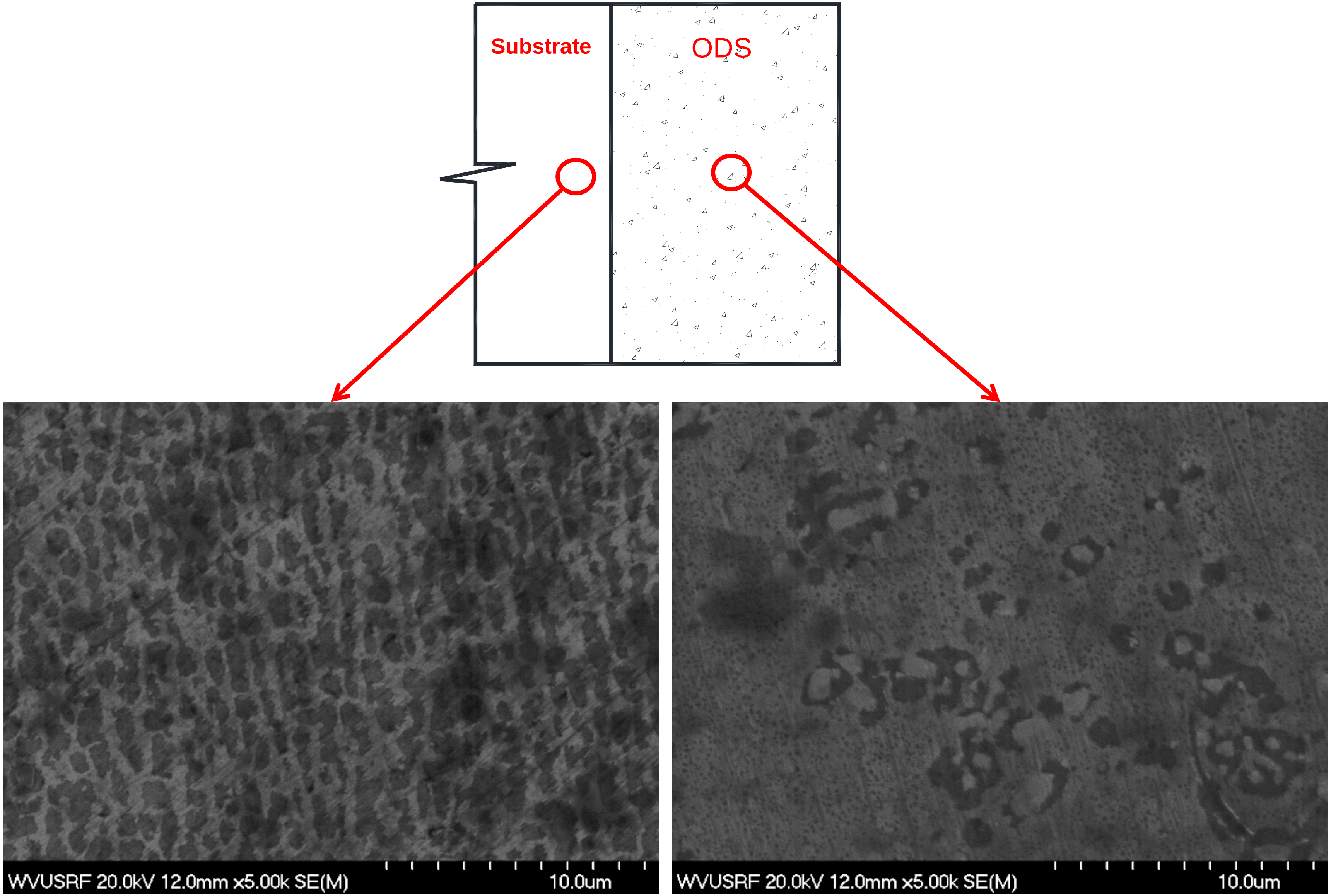




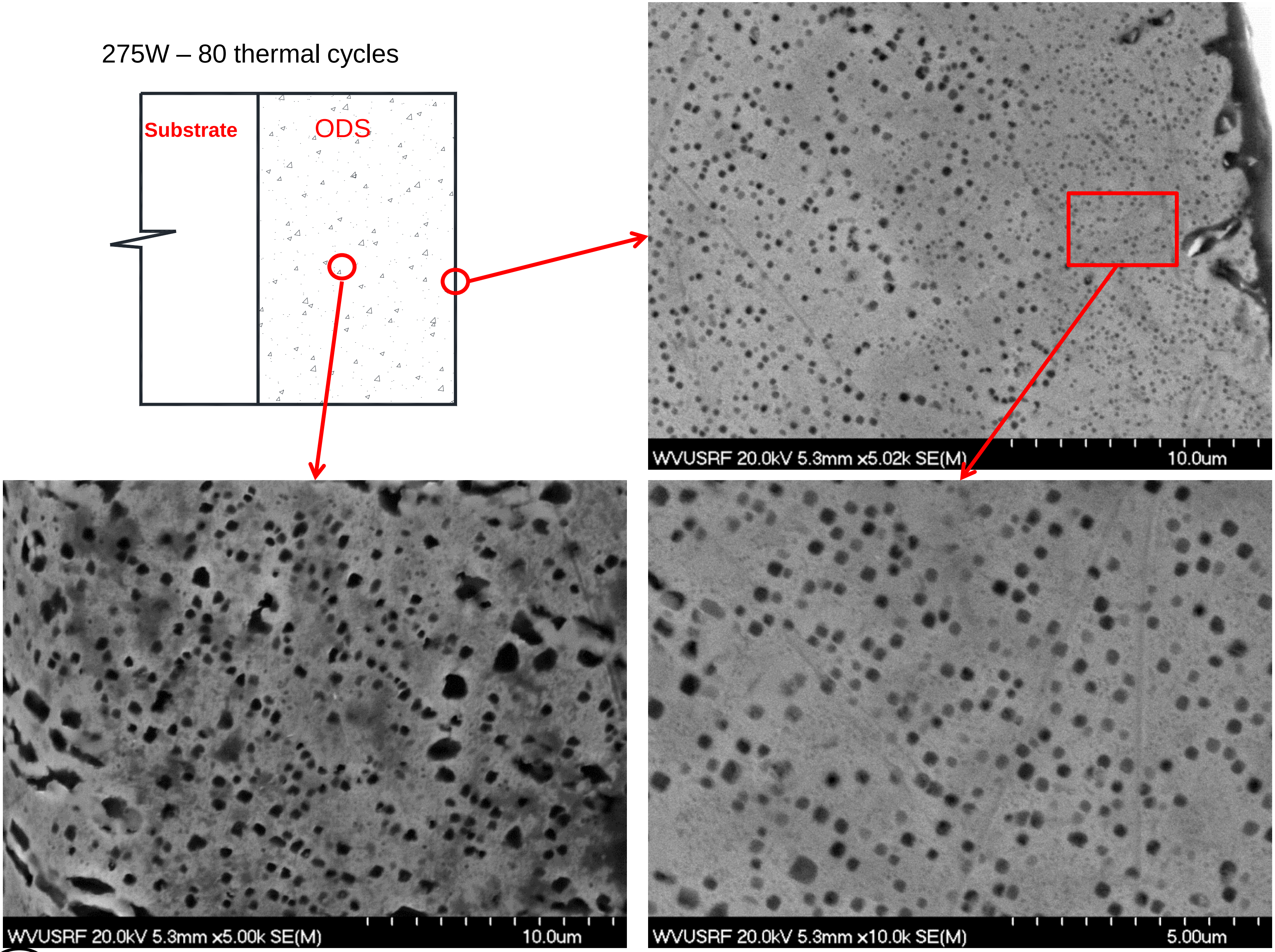




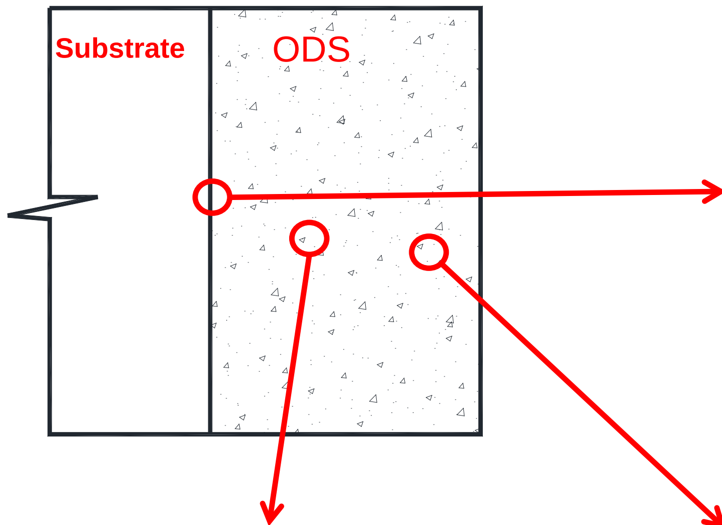
275W – 40 thermal cycles

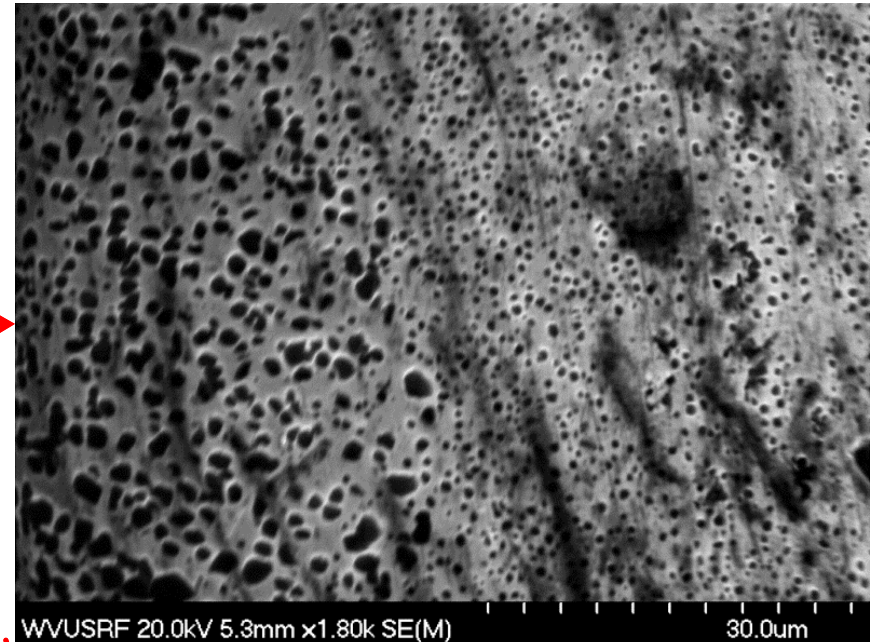


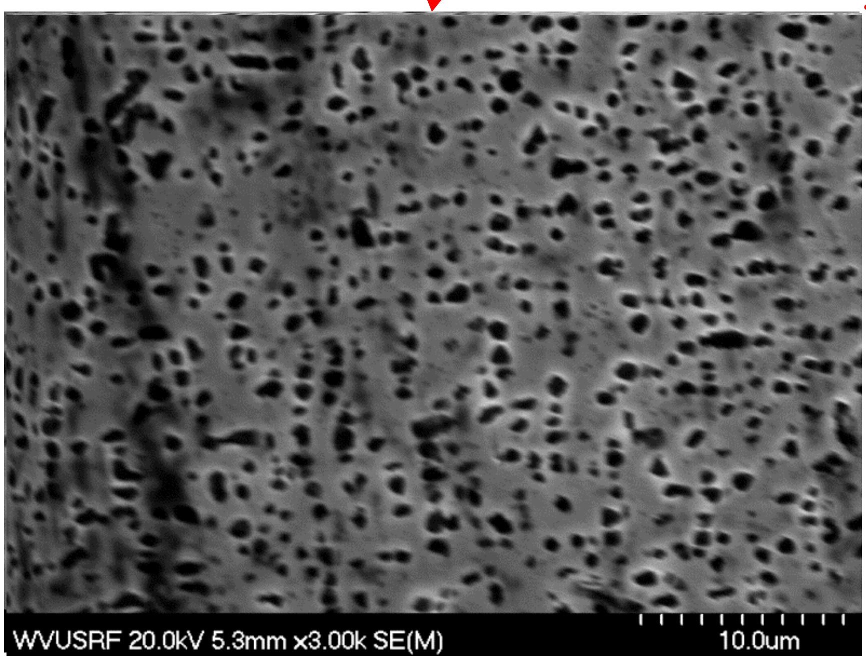
275W – 80 thermal cycles

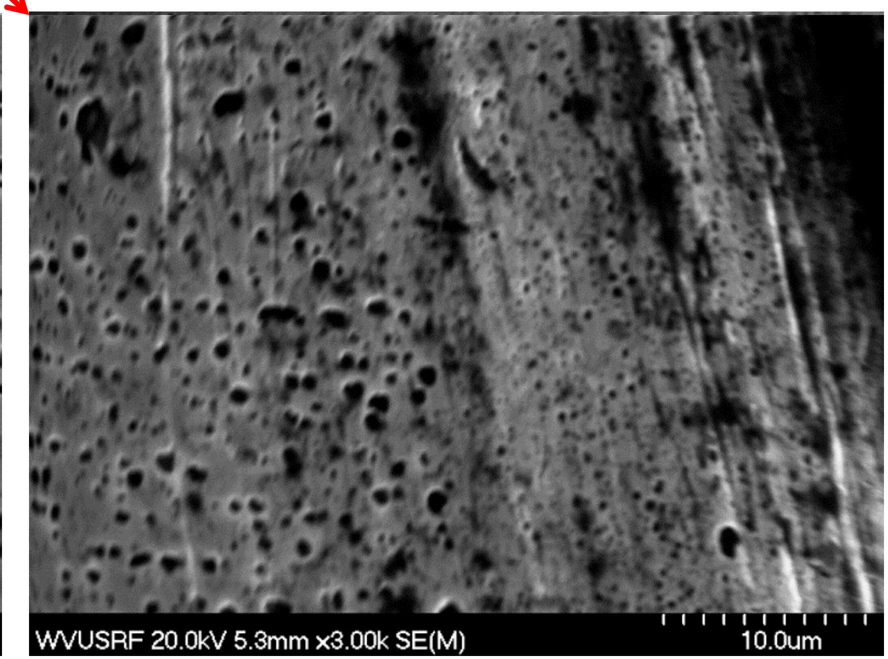


100W – 1080 thermal cycles

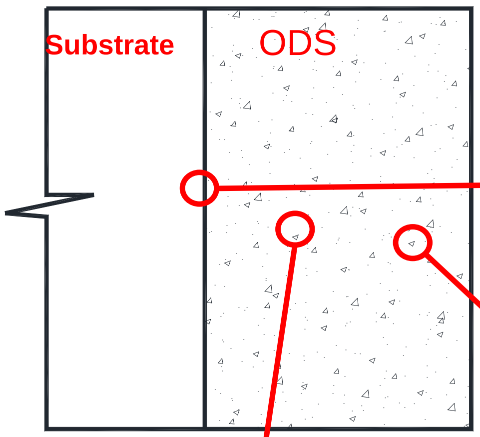


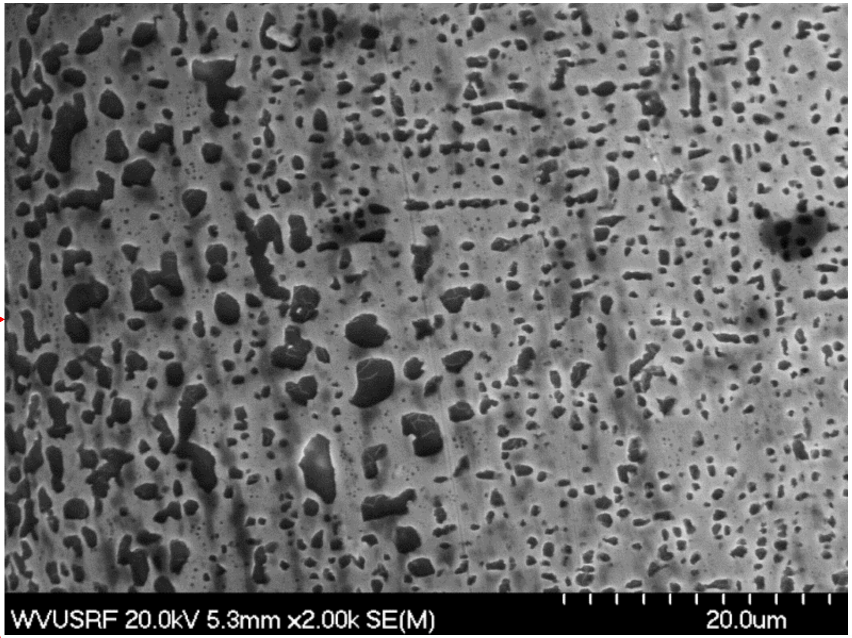


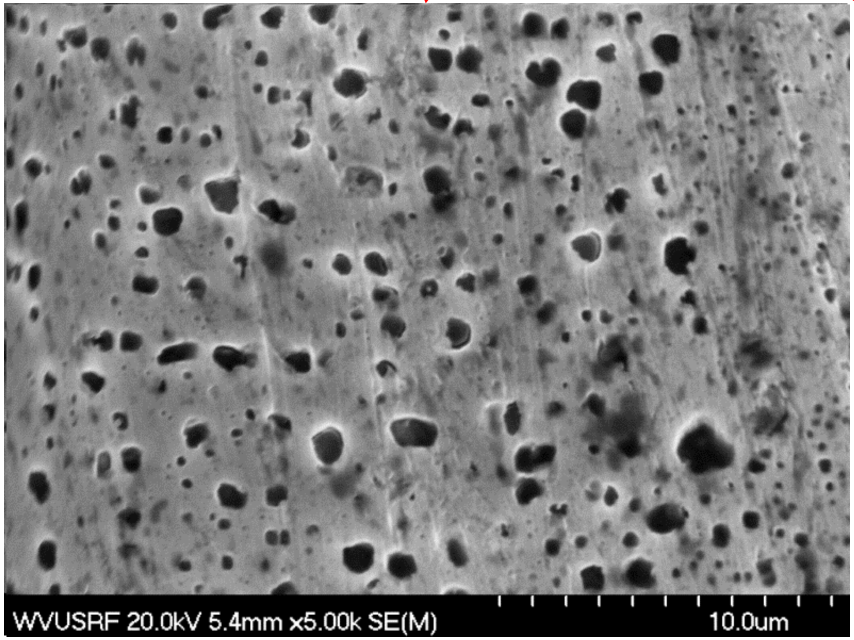


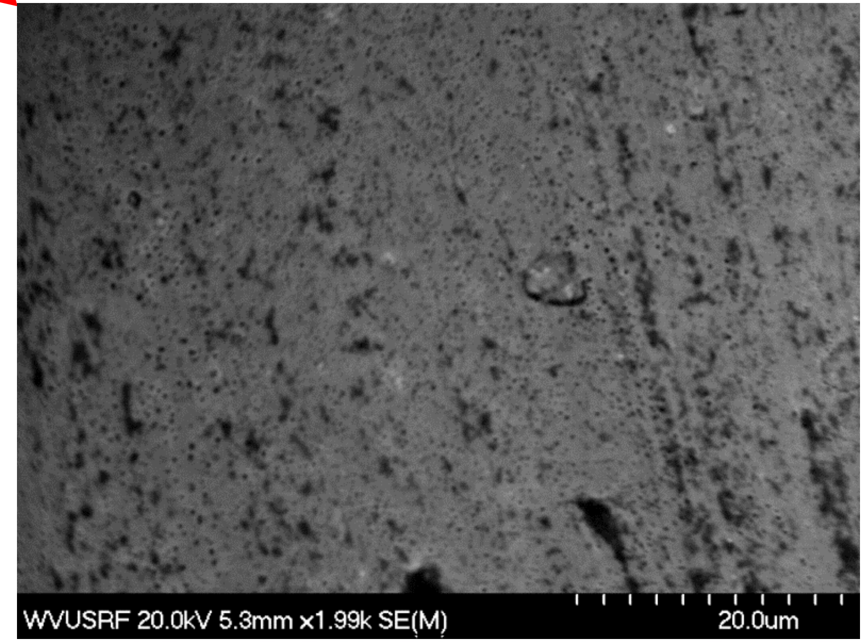


150W – 1080 thermal cycles

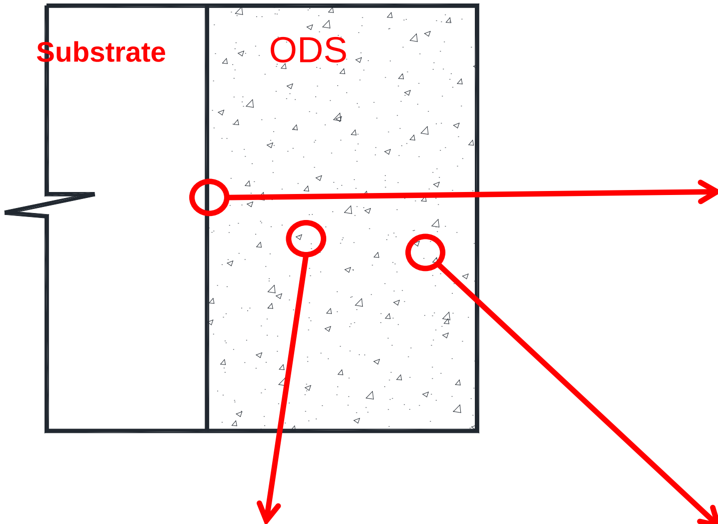


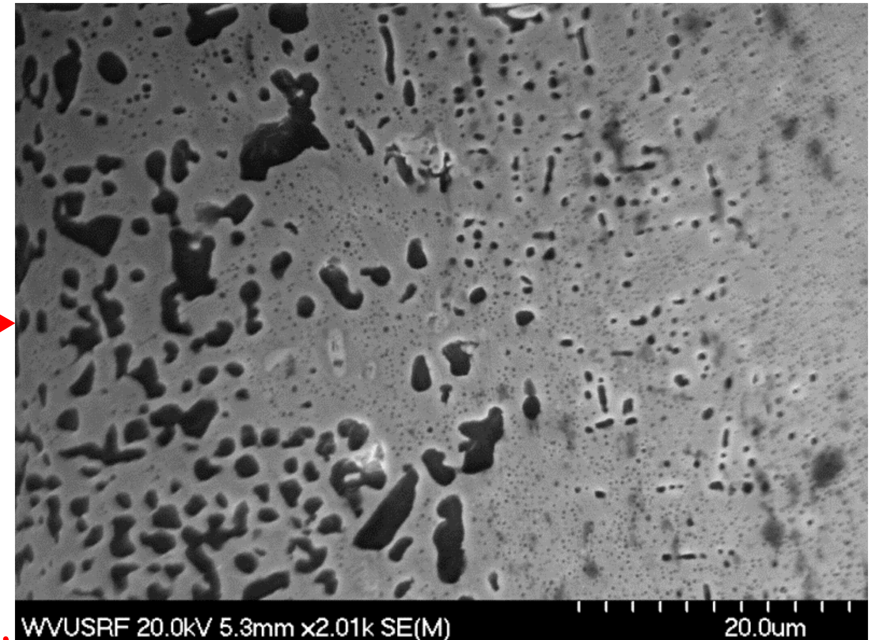


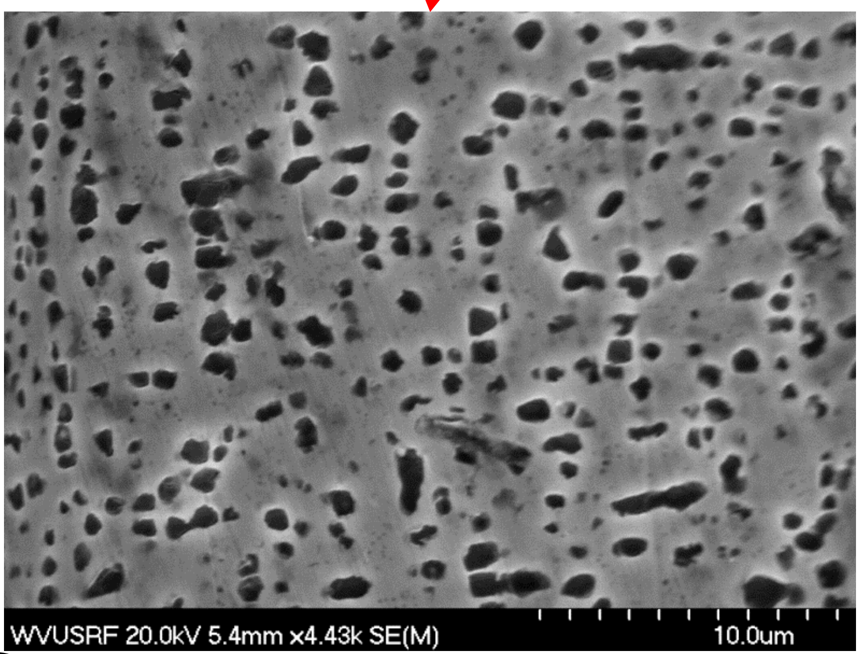


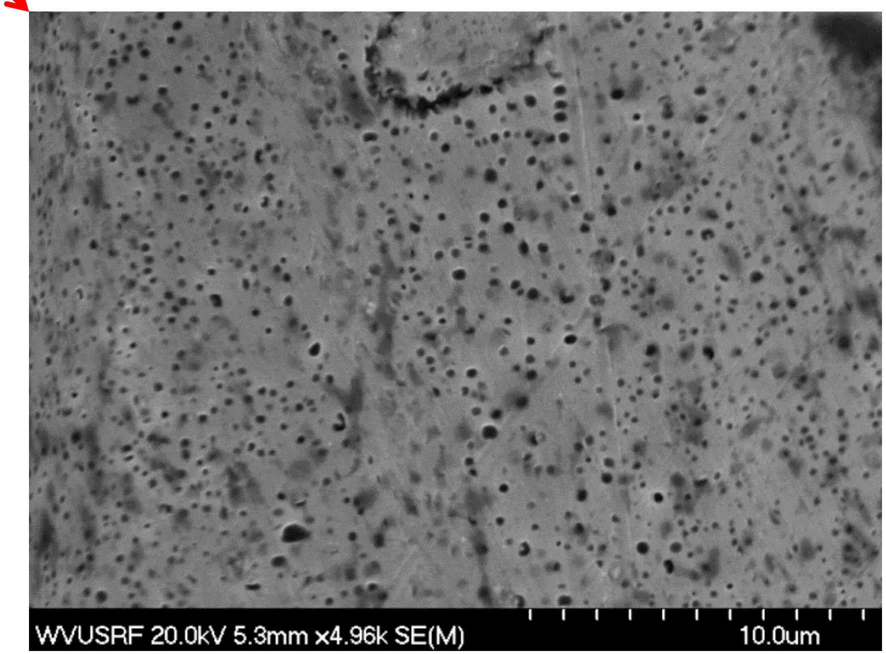


200W – 1080 thermal cycles









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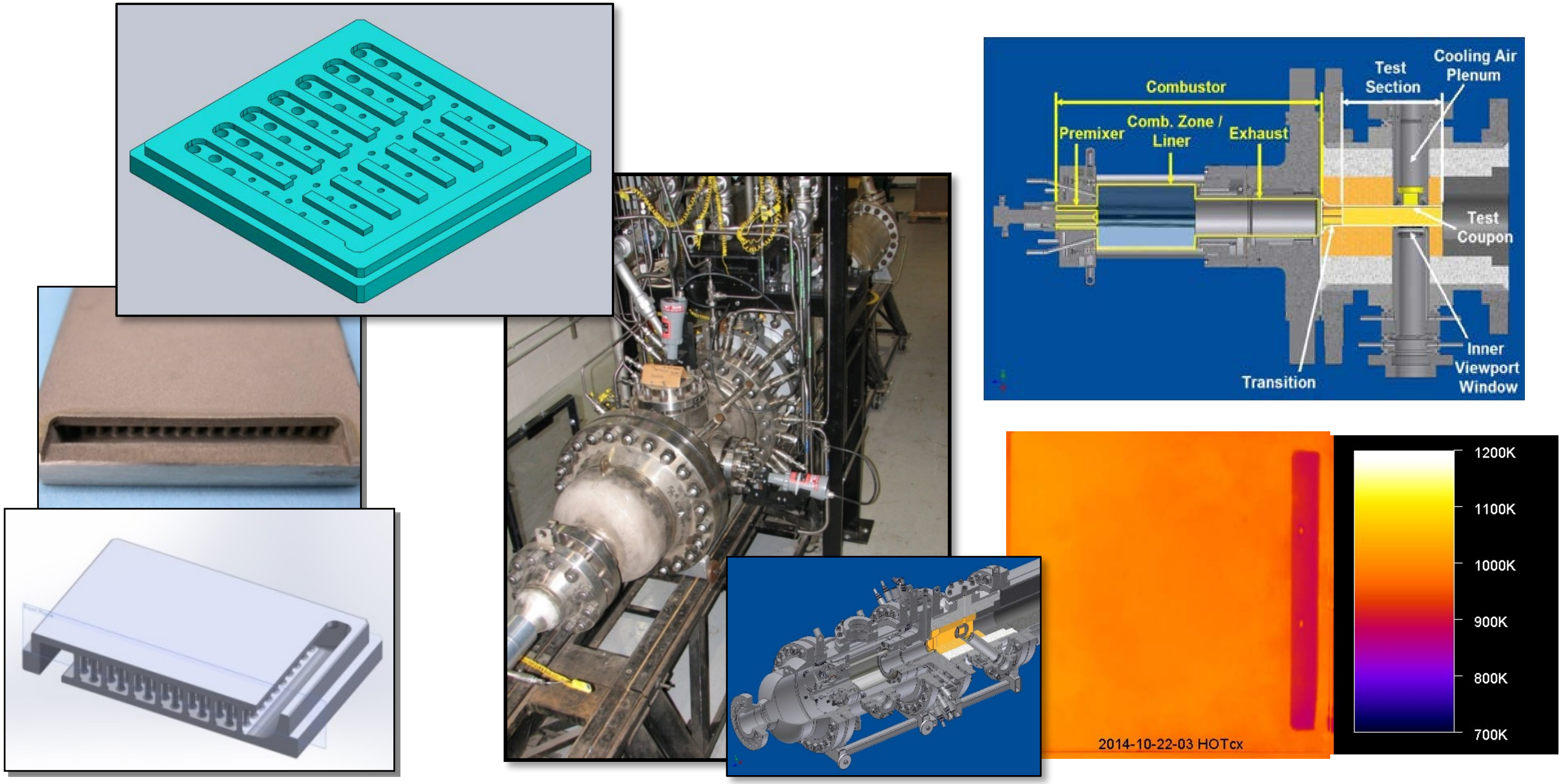
Task 5: Detailed Experimental Measurements and Validation



- ➢ 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

Summary

- ***Reporting period (10/01/2015-10/31/2016)***

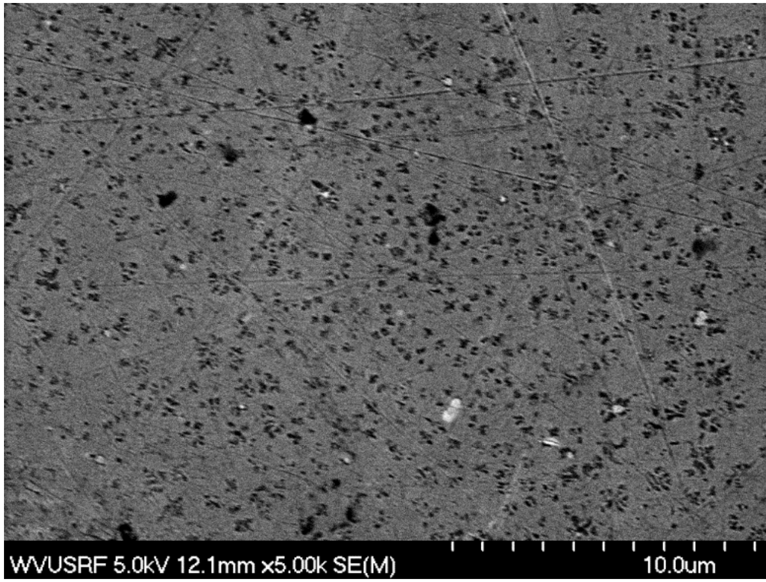
- ***A batch of near surface embedded cooling channels (NSECC) were developed and characterized. Complex geometric features fabricated by AM could provide coolant air to near surface regions while significantly enhance the transfer enhancement of internal cooling for turbine blades.***
- ***Long-term isothermal and cyclic thermo-loading tests of AM-assisted ODS coating on MAR 247 substrate were conducted. Existence of gamma prime phase in AM-assisted ODS coating is confirmed. Growth and coarsening of primary and secondary gamma prime phase on the ODS/M247 system were studied. Test results demonstrate that AM-assisted ODS coating can be considered as a structural coating applicable to critical gas turbine components under HT and corrosive environments.***
- ***Further research efforts are needed to cover research issues such as:***

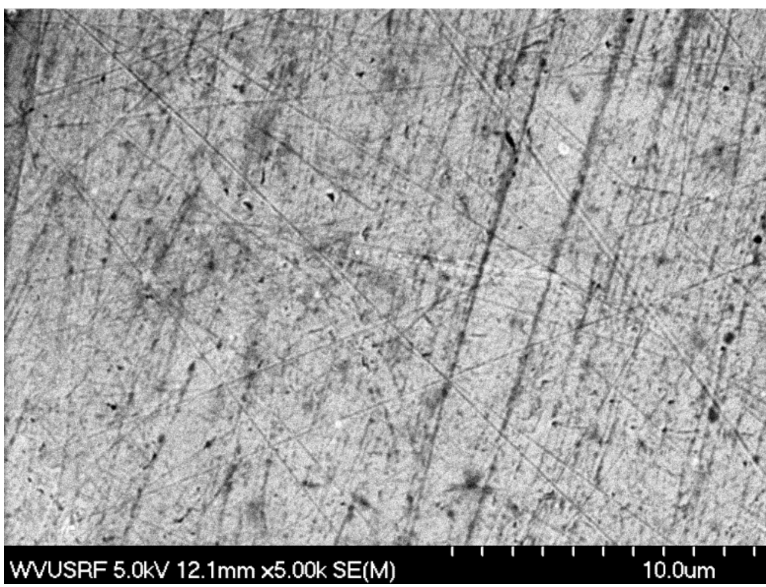
Stable oxide formation mechanism – oxidation kinetics of non-equilibrium material system

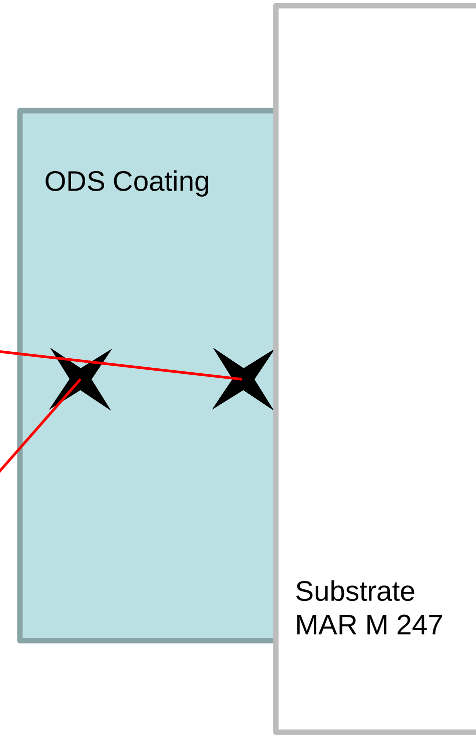
ODS power optimized for AM applications

Model-based AM Processes – 3D manufacturing optimization, scale-up route, cost, etc.

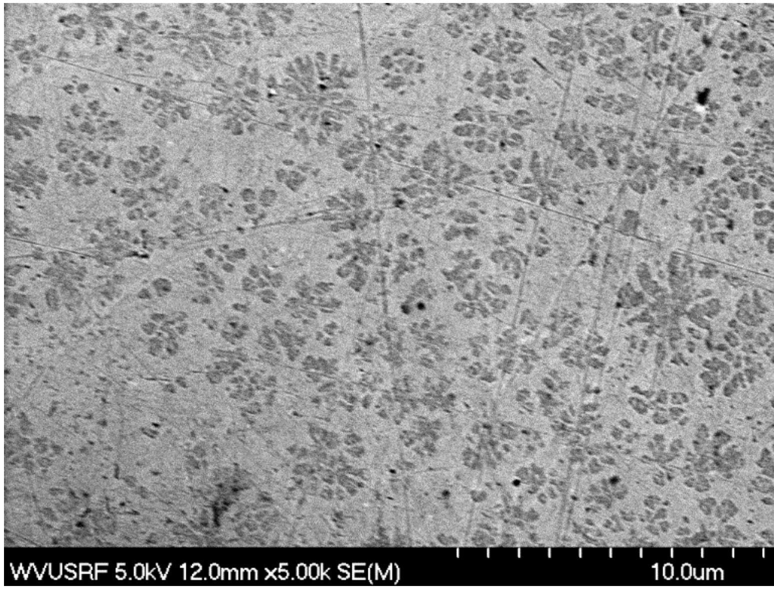
Thank You!

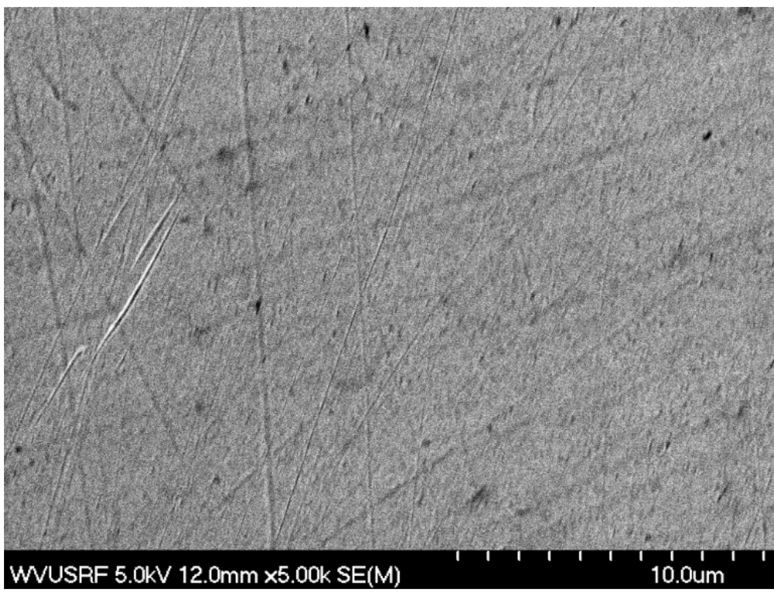


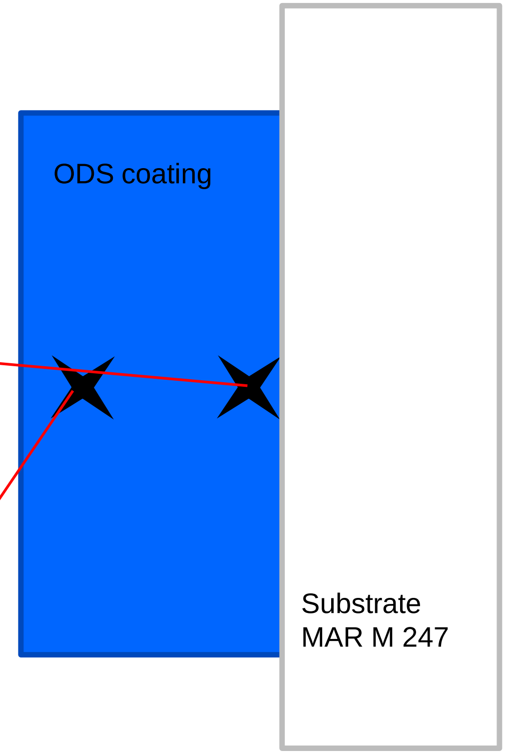




1200^0C, Isothermal,
1800 hours
250W







1200^{0}C, Isothermal,
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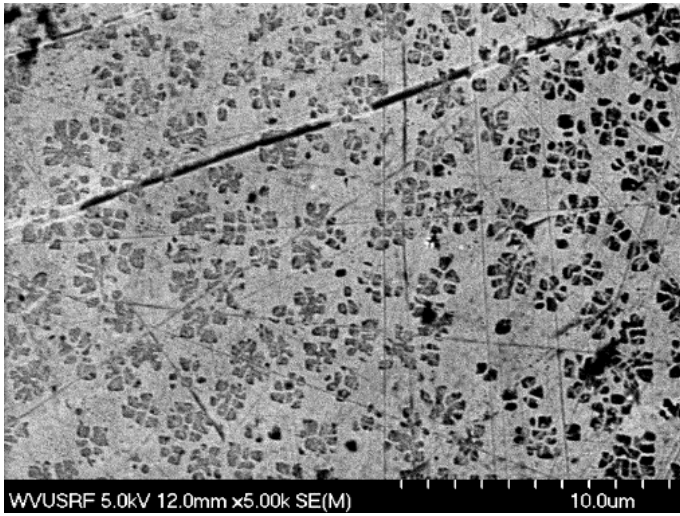
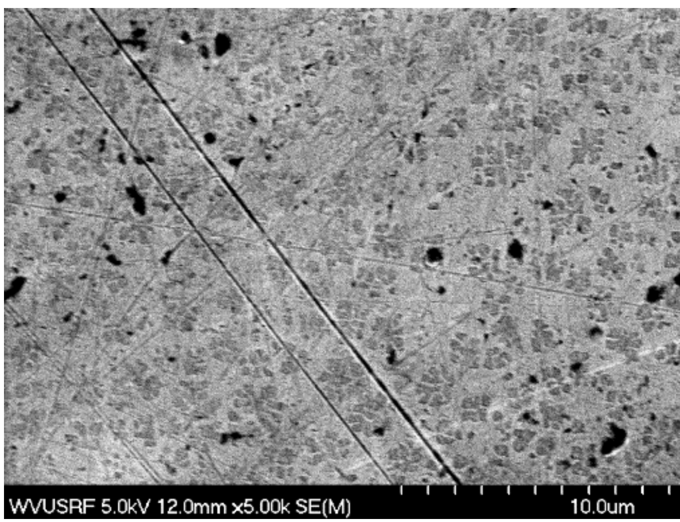
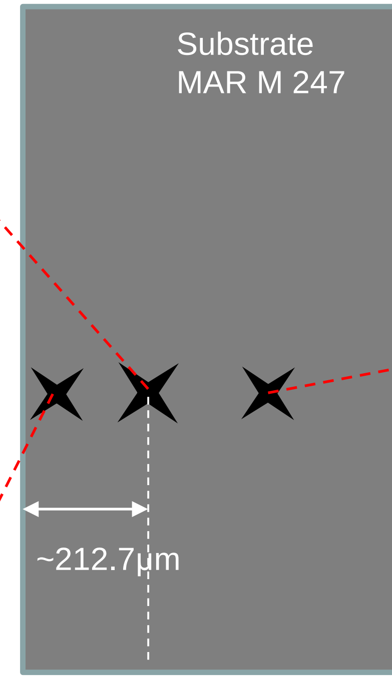
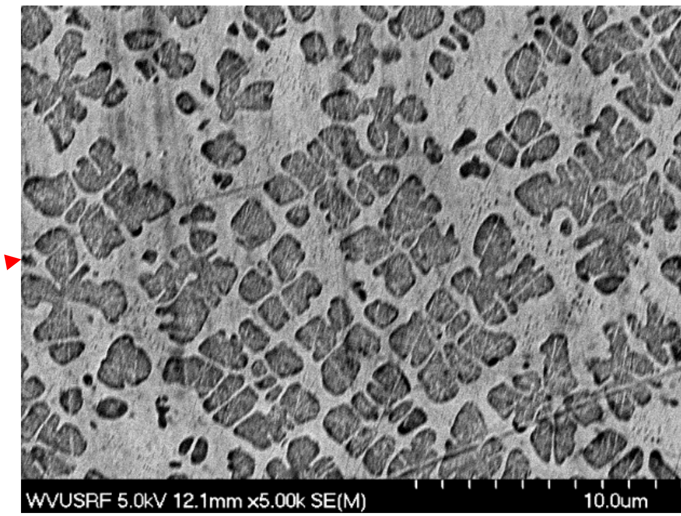
1200^0C, Isothermal,
1800 hours
250W









1200^0C, Isothermal,
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