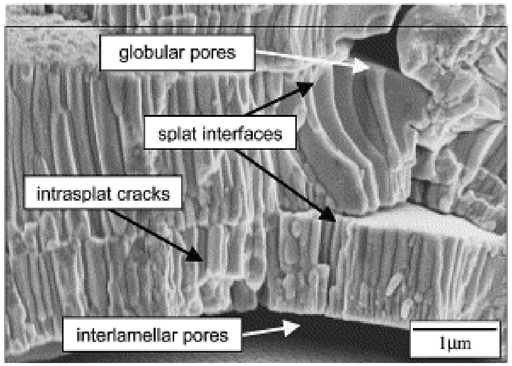
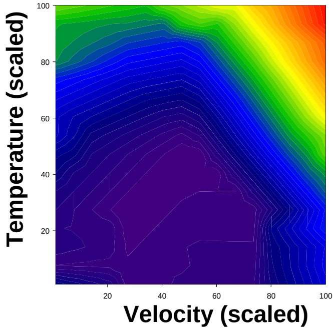
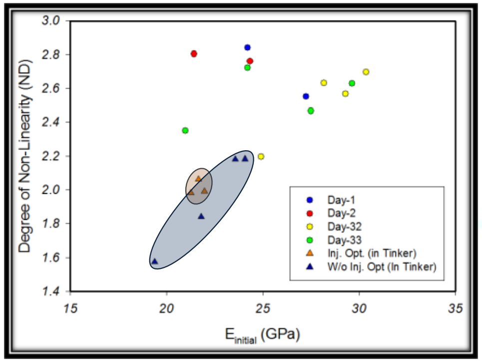
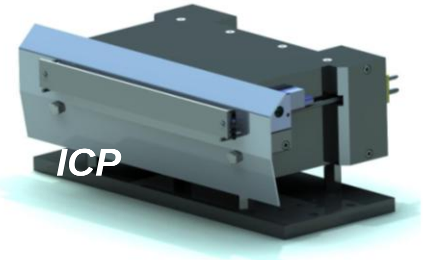
Advanced Thermal Barrier Coatings for Operation in High Hydrogen Content Gas Turbines



Thermal Conductivity







Christopher Weyant, Sanjay Sampath

Center for Thermal Spray Research, Stony Brook University

University Turbine Systems Research Workshop

October 20, 2010

Consortium for Thermal Spray Technology

Consortium is operated by the Center for Thermal Spray Research at Stony Brook University

Research supported by:

DOE NETL UTSR

DOE Office of Fossil Research STTR with Plasma Technology Inc.

AFRL, NSF

Consortium on Thermal Spray Technology

Contributions from faculty colleagues, post-docs, students, national and international collaborators is acknowledged.

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STATE UNIVERSITY OF NEW YORK

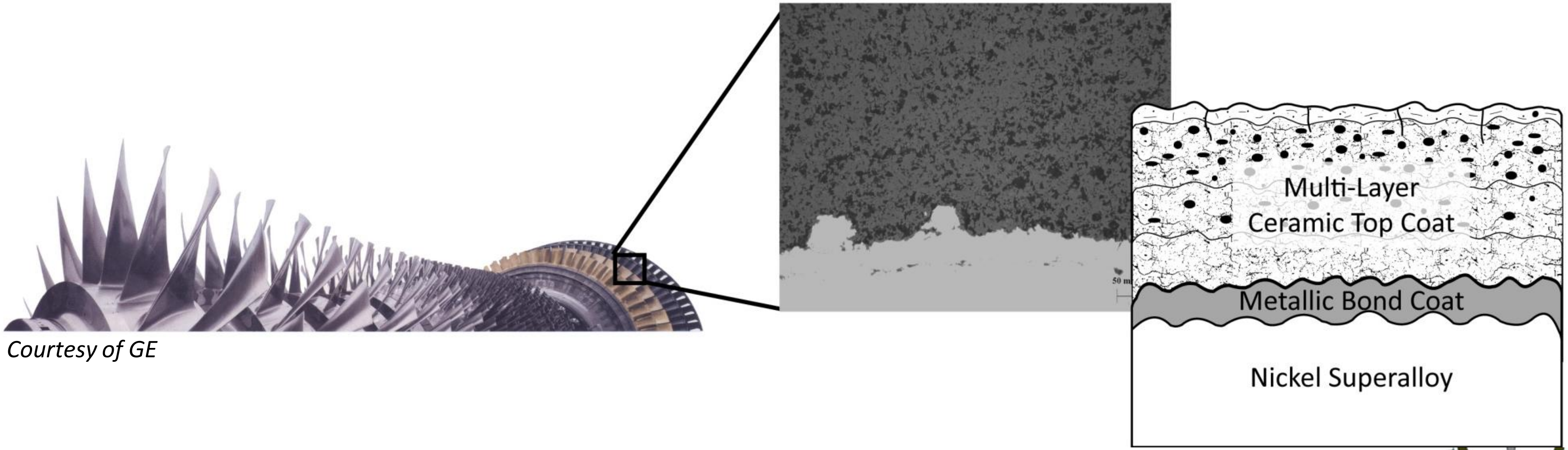
Thermal Barrier Coatings in Hydrogen-Fired IGCC Turbines

***<u>CHALLENGE</u>**: Improved realiability and lifetime of coatings in IGCC gas turbines*

- *Increased mass flow of syngas fuel*
- *Increased heat transfer from water vapor*
- *Impact of water vapor on oxidation*
- *Contaminants*

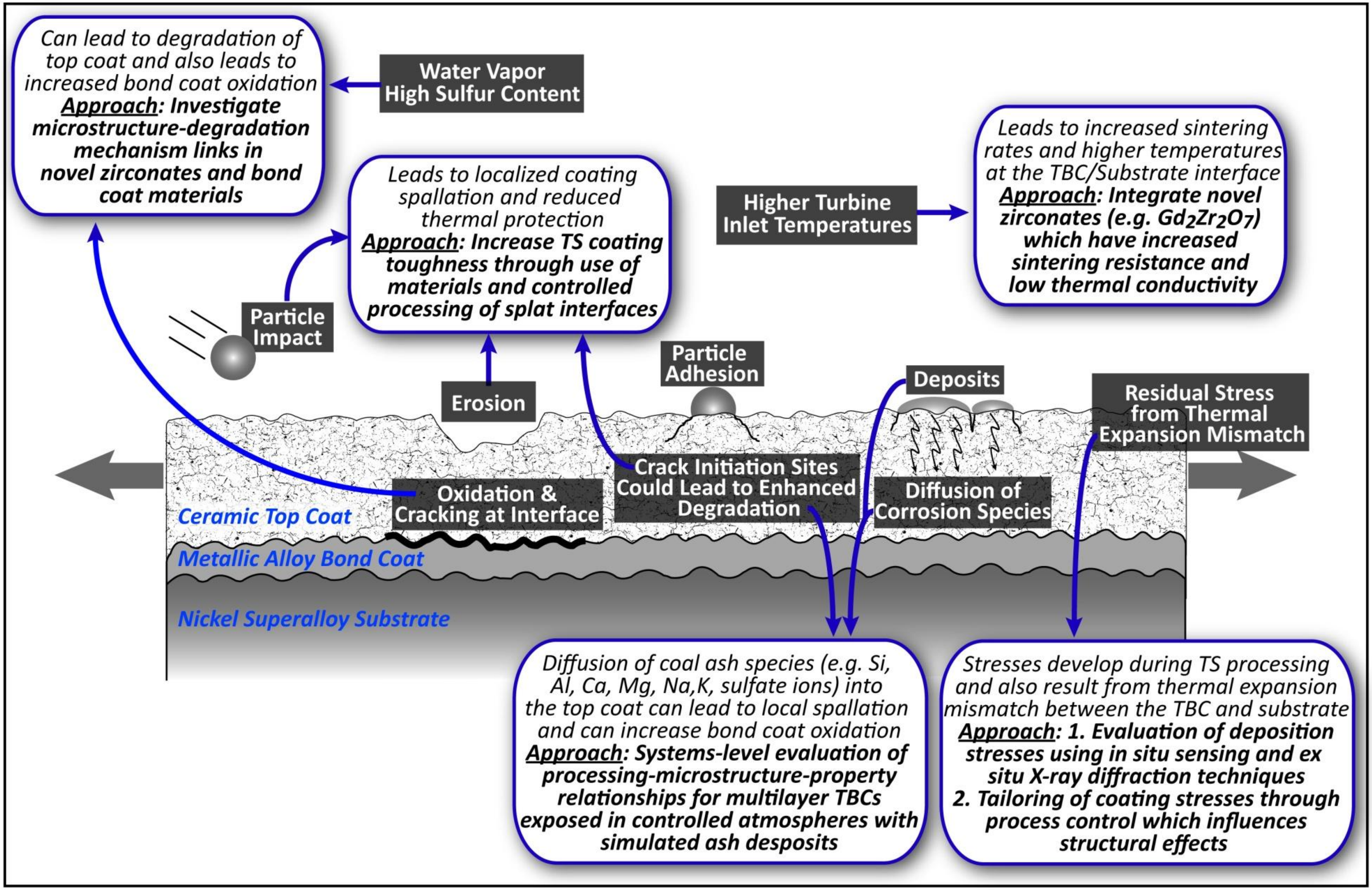
***<u>APPROACH</u>**: Tailored and optimized plasma-sprayed thermal/environmental barrier coating*

- *Material requirements and selection*
- *Processing impacts on microstructure and properties*
- *Iterative coating design and testing*
- *Industry feedback and knowledge transfer*



Courtesy of GE

Degradation in IGCC Gas Turbine TBCs



Can lead to degradation of top coat and also leads to increased bond coat oxidation
***Approach**: Investigate microstructure-degradation mechanism links in novel zirconates and bond coat materials*

Water Vapor
High Sulfur Content

Leads to localized coating spallation and reduced thermal protection
***Approach**: Increase TS coating toughness through use of materials and controlled processing of splat interfaces*

Higher Turbine Inlet Temperatures

Leads to increased sintering rates and higher temperatures at the TBC/Substrate interface
***Approach**: Integrate novel zirconates (e.g. $Gd_2Zr_2O_7$) which have increased sintering resistance and low thermal conductivity*

Particle Impact

Erosion

Particle Adhesion

Deposits

Residual Stress from Thermal Expansion Mismatch

Crack Initiation Sites Could Lead to Enhanced Degradation

Oxidation & Cracking at Interface

Diffusion of Corrosion Species

Ceramic Top Coat

Metallic Alloy Bond Coat

Nickel Superalloy Substrate

Diffusion of coal ash species (e.g. Si, Al, Ca, Mg, Na,K, sulfate ions) into the top coat can lead to local spallation and can increase bond coat oxidation
***Approach**: Systems-level evaluation of processing-microstructure-property relationships for multilayer TBCs exposed in controlled atmospheres with simulated ash desposits*

Stresses develop during TS processing and also result from thermal expansion mismatch between the TBC and substrate
***Approach**: 1. Evaluation of deposition stresses using in situ sensing and ex situ X-ray diffraction techniques*
2. Tailoring of coating stresses through process control which influences structural effects

Proposed IGCC Coating Architecture

Development/ Evaluation Plan

Performances Attributes

Layer Microstructures

Erosion Resistant Top Coat

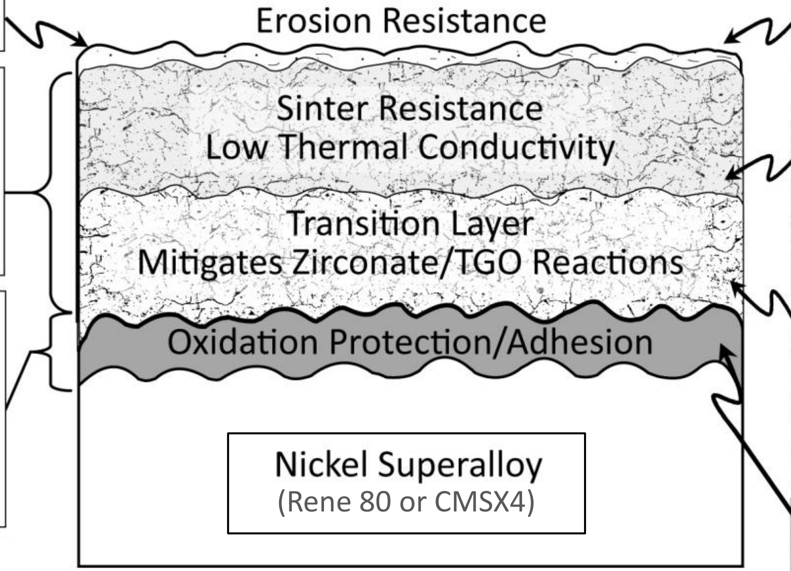
- Produce dense YSZ and $Gd_2Zr_2O_7$ top coat layers
- Evaluate erosion resistance of dense materials
- Develop density-graded structure for top coat

Thermal Barrier Layers

- Determine $Gd_2Zr_2O_7$ properties (thermal/ mechanical) under thermal gradients
- Assess IGCC enviromental effects on degradation of zirconates

Bond Coat

- Evaluate processing (HVOF/LPPS + anneal) effects on microstructure and phase composition of MCrAlY (where M = Ni, Co, Si, Hf, and/or La)
- Determine IGCC environmental effects on long-term oxidation of bond coat materials



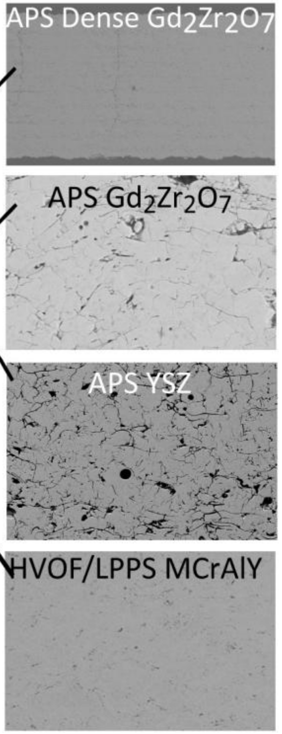
Erosion Resistance

Sinter Resistance
Low Thermal Conductivity

Transition Layer
Mitigates Zirconate/TGO Reactions

Oxidation Protection/Adhesion

Nickel Superalloy
(Rene 80 or CMSX4)



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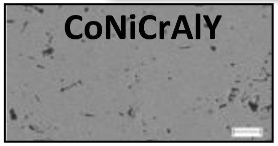
Overall UTSR Program Approach

Advanced Thermal Spray TBCs for IGCC Turbine Systems

Bond Coat



Materials: MCrAlY
M = Ni, Co, Si, Hf, La

Processing Effects on Microstructure (HVOF/LPPS/Anneal)

Isothermal Exposures in water vapor

Property Evaluation: Oxidation behavior in high temperature water vapor

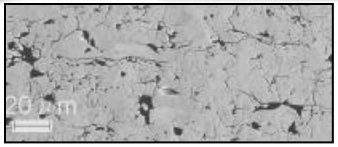
System Level

Rig Testing: Thermal gradient exposure with water vapor

Isothermal Exposures with ash deposits

Property Evaluation: Bond coat oxidation, through-thickness residual stress and composition, erosion

Top Coat



Materials:
YSZ, $Gd_2Zr_2O_7$

Processing Effects on Microstructure (APS)

Isothermal Exposures in water vapor

Property Evaluation: Thermal conductivity, sintering, compliance, erosion, thermal expansion

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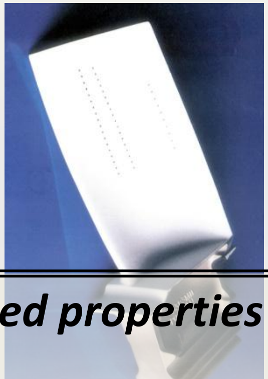
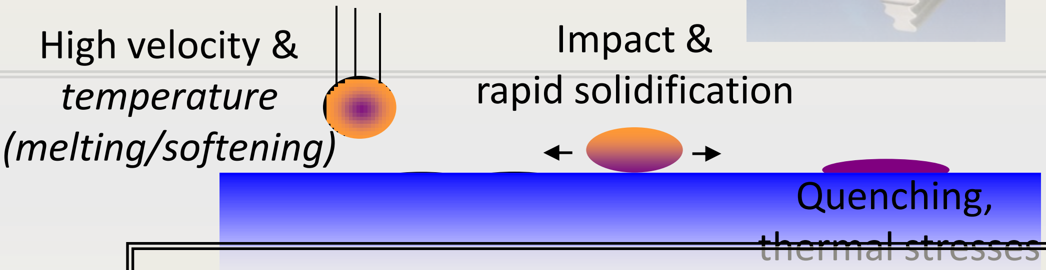
Thermal spray is a complex process

Melting, quenching and consolidation in single process



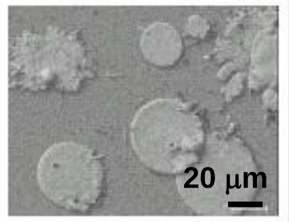
Splat based build-up and state induced properties



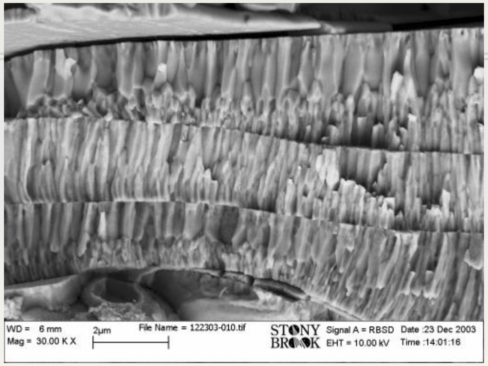
High velocity &
temperature
(melting/softening)

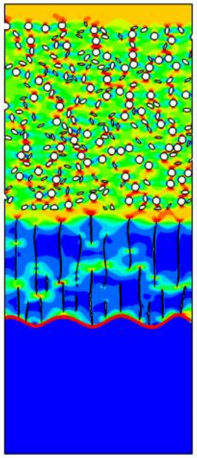
Impact &
rapid solidification

Quenching,
thermal stresses

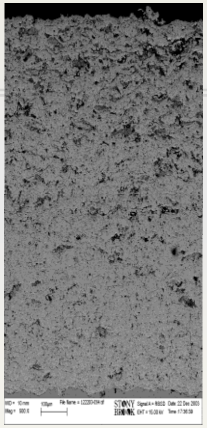


Layered and graded architectures through successive splat quenching



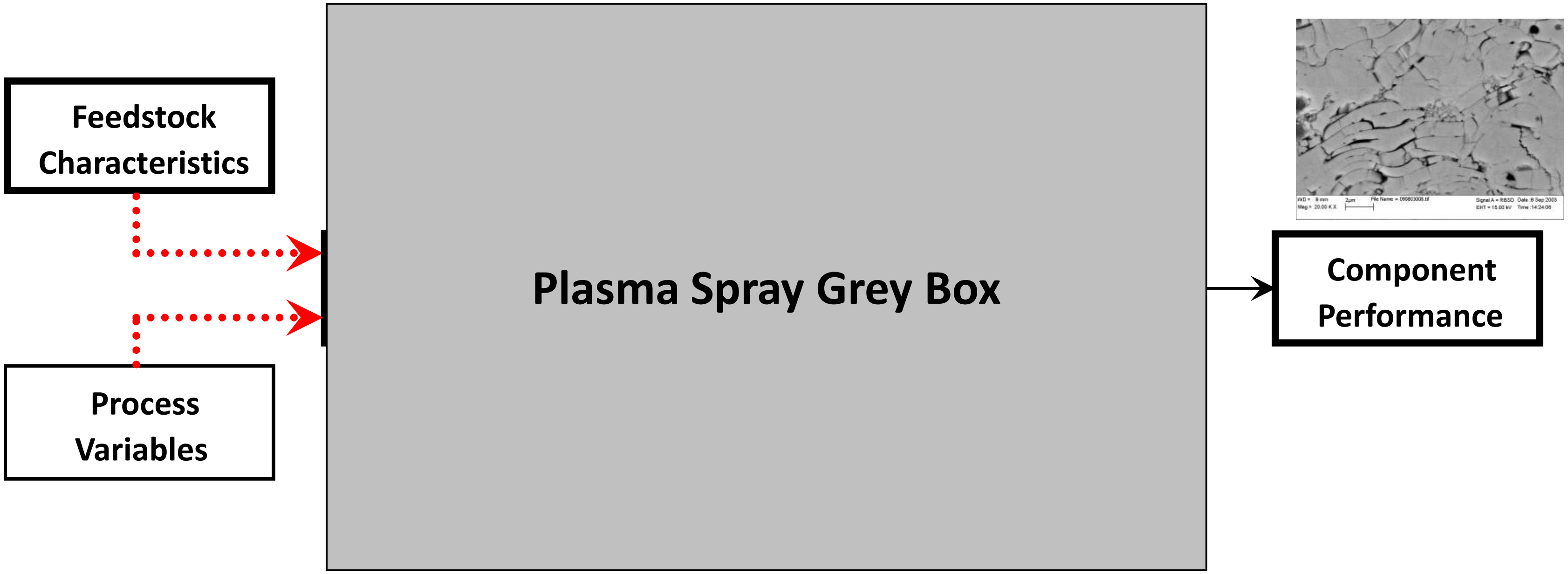


Layered
Thick
Films



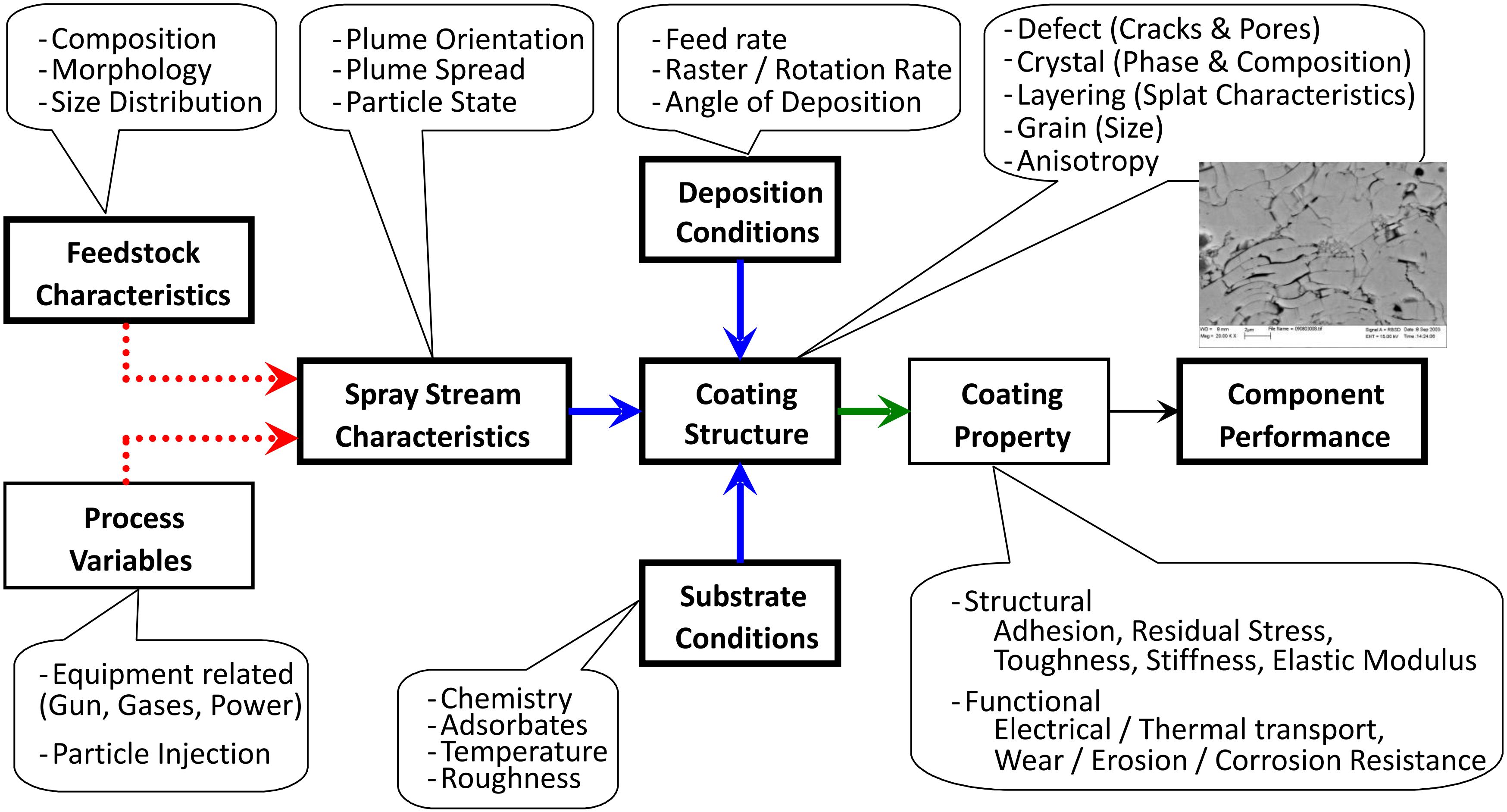
Graded
Porosity
In ceramics

Common Approach for TBC Manufacturing



Lee *et al.*, *J. Europ. Cer. Soc.* 25(10):1705-1715 (2005).

CTSR Approach for TBC Development



Feedstock Characteristics
- Composition
- Morphology
- Size Distribution

Process Variables
- Equipment related (Gun, Gases, Power)
- Particle Injection

Spray Stream Characteristics
- Plume Orientation
- Plume Spread
- Particle State

Deposition Conditions
- Feed rate
- Raster / Rotation Rate
- Angle of Deposition

Substrate Conditions
- Chemistry
- Adsorbates
- Temperature
- Roughness

Coating Structure
- Defect (Cracks & Pores)
- Crystal (Phase & Composition)
- Layering (Splat Characteristics)
- Grain (Size)
- Anisotropy

Coating Property
- Structural
  Adhesion, Residual Stress, Toughness, Stiffness, Elastic Modulus
- Functional
  Electrical / Thermal transport, Wear / Erosion / Corrosion Resistance

Component Performance

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Lee *et al.*, *J. Europ. Cer. Soc.* 25(10):1705-1715 (2005).

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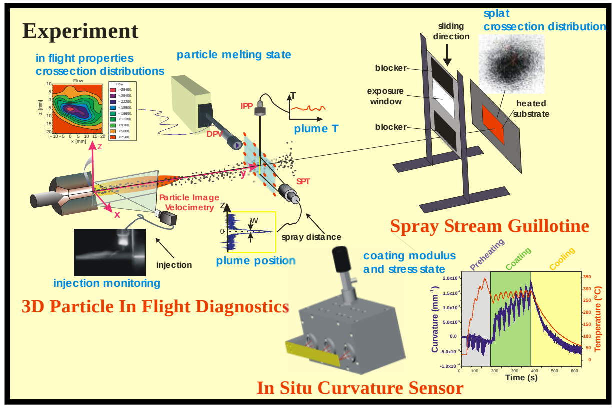
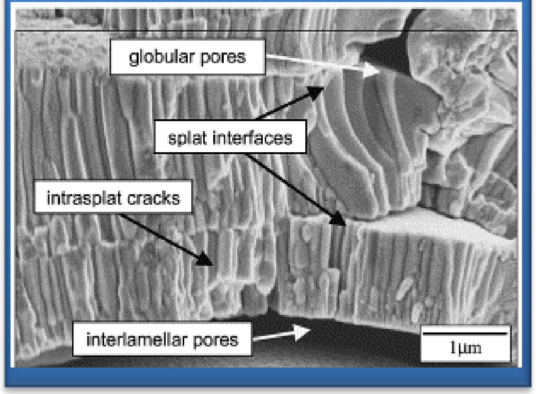
How can modern TS science enhance TBC requirements?

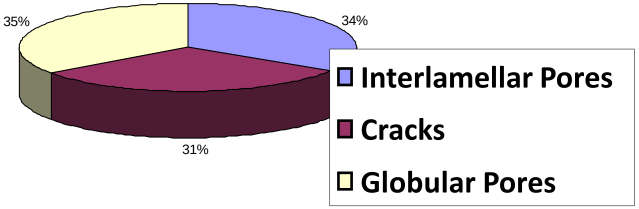
Integrated Process Diagnostics



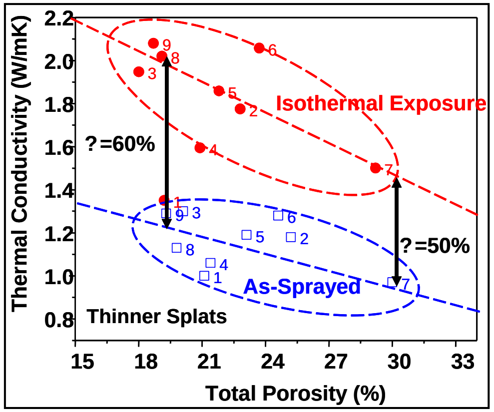
Properties dominated by defects, nanoscale grains, splats interfaces and interphases



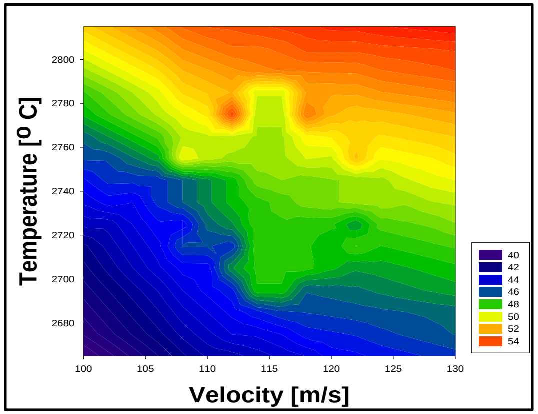
Neutron-based Assessment of Pore Distribution (3D)



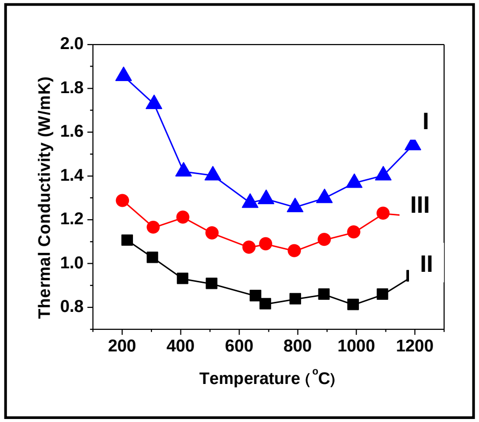
Thermal Aging Effects on Properties



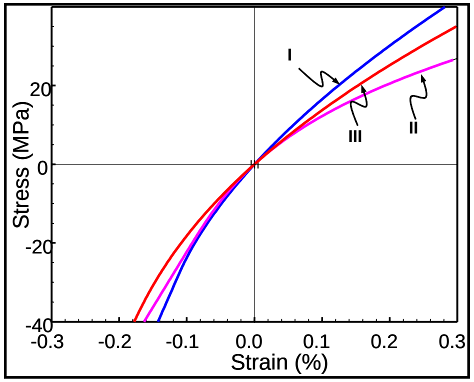
2nd Order Process Map
Elastic Modulus Contours



Temperature-Dependent Thermal Conductivity



Nonlinear Stress-Strain



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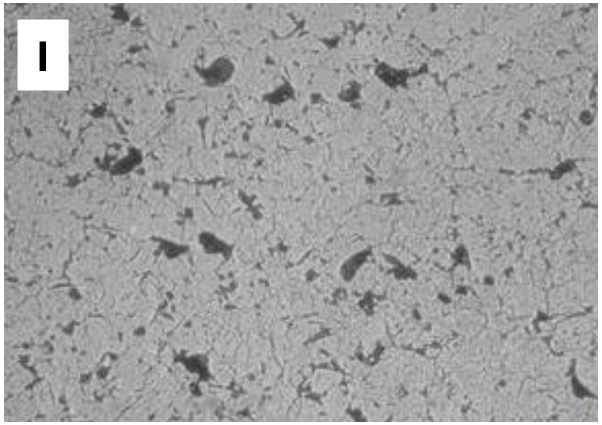
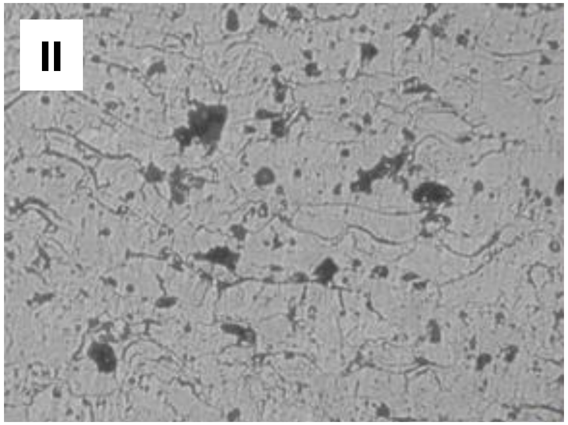
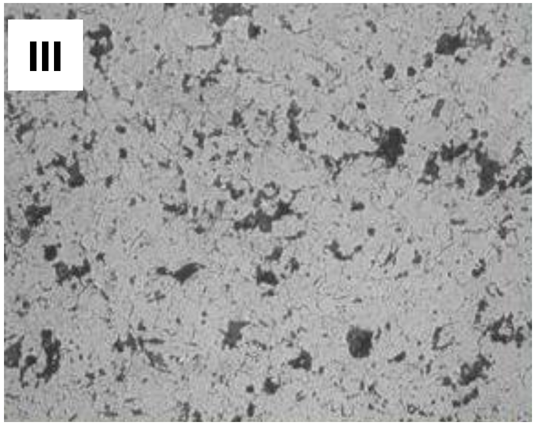
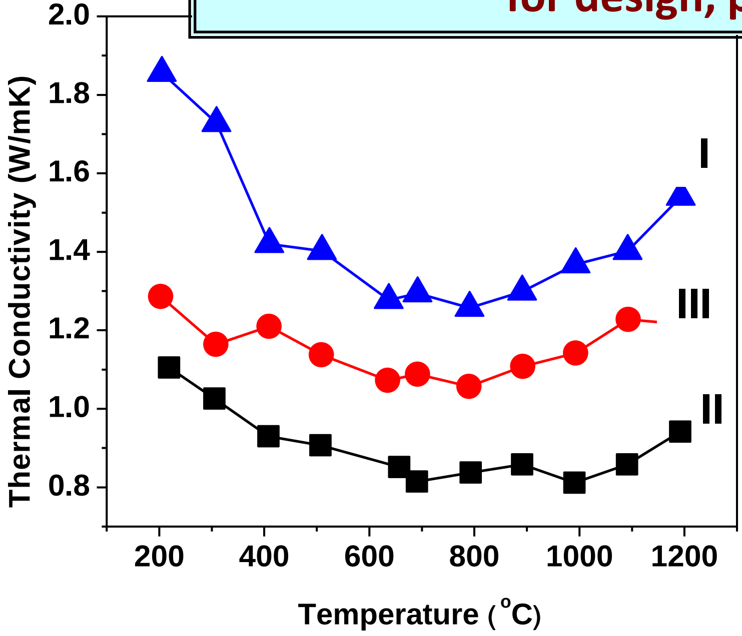
What is the difference in these TBC coatings?

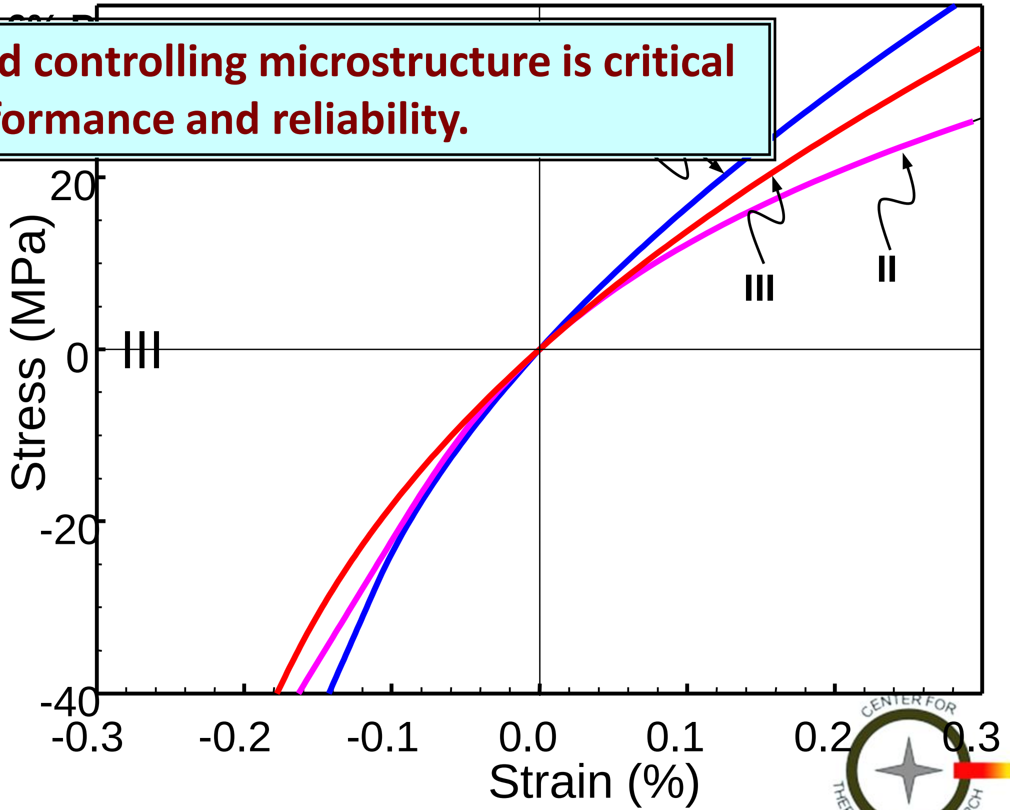




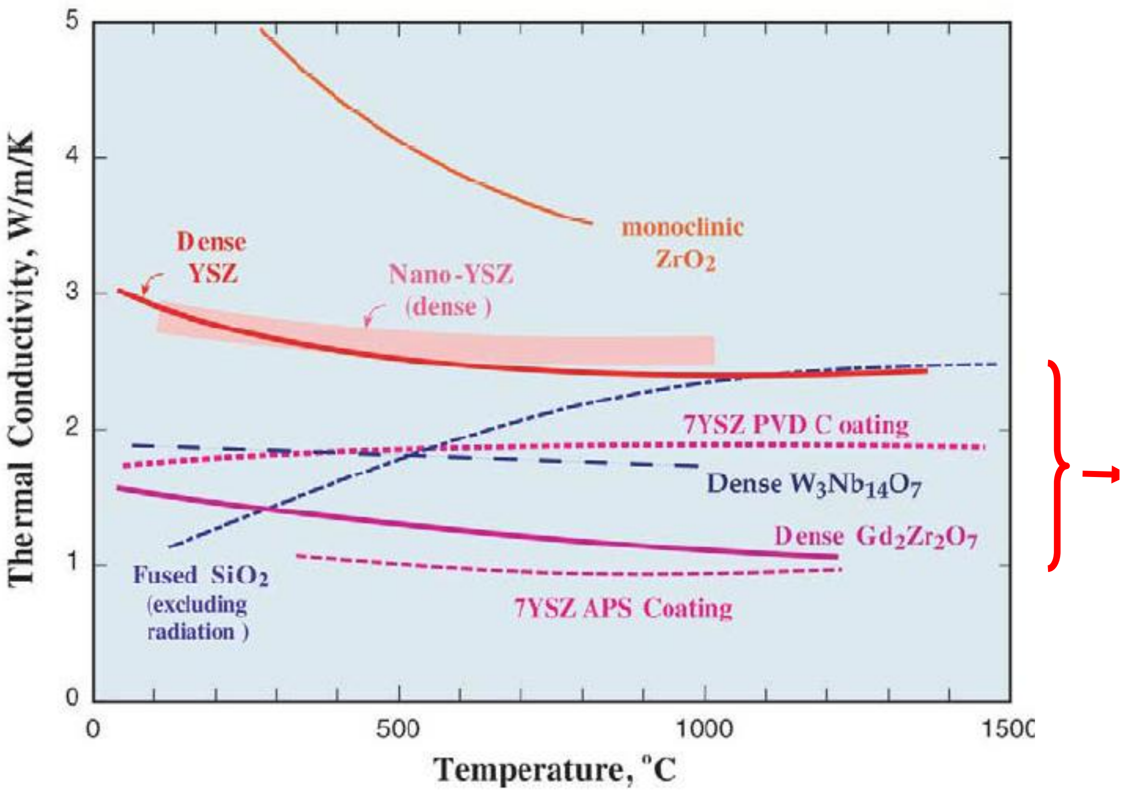


Understanding, optimizing and controlling microstructure is critical for design, performance and reliability.

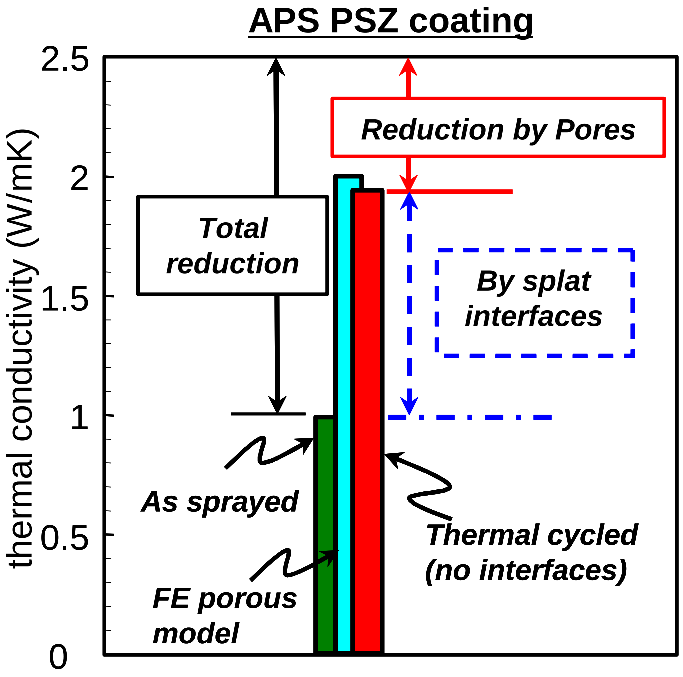




Implications on Properties: Thermal Conductivity



Clarke and Levi, Ann. Rev. Materials, 2003
Clarke and Phillpot, Materials Today, June 2005



Nakamura et al., Acta Met, 2004

Thermal spray microstructure has significant influence on material properties

Integrated Study of Thermal Spray TBCs

- Understand and control the plasma spray process to tailor and optimize the microstructure
- Develop methodologies for diagnostics, control, microstructure and property quantification
- Establish correlations among process-microstructure-properties so as to affect
  - Microstructure, thermal conductivity and compliance
- Achieve repeatability and reliability in microstructure and properties
- Assess changes in properties at time and temperature

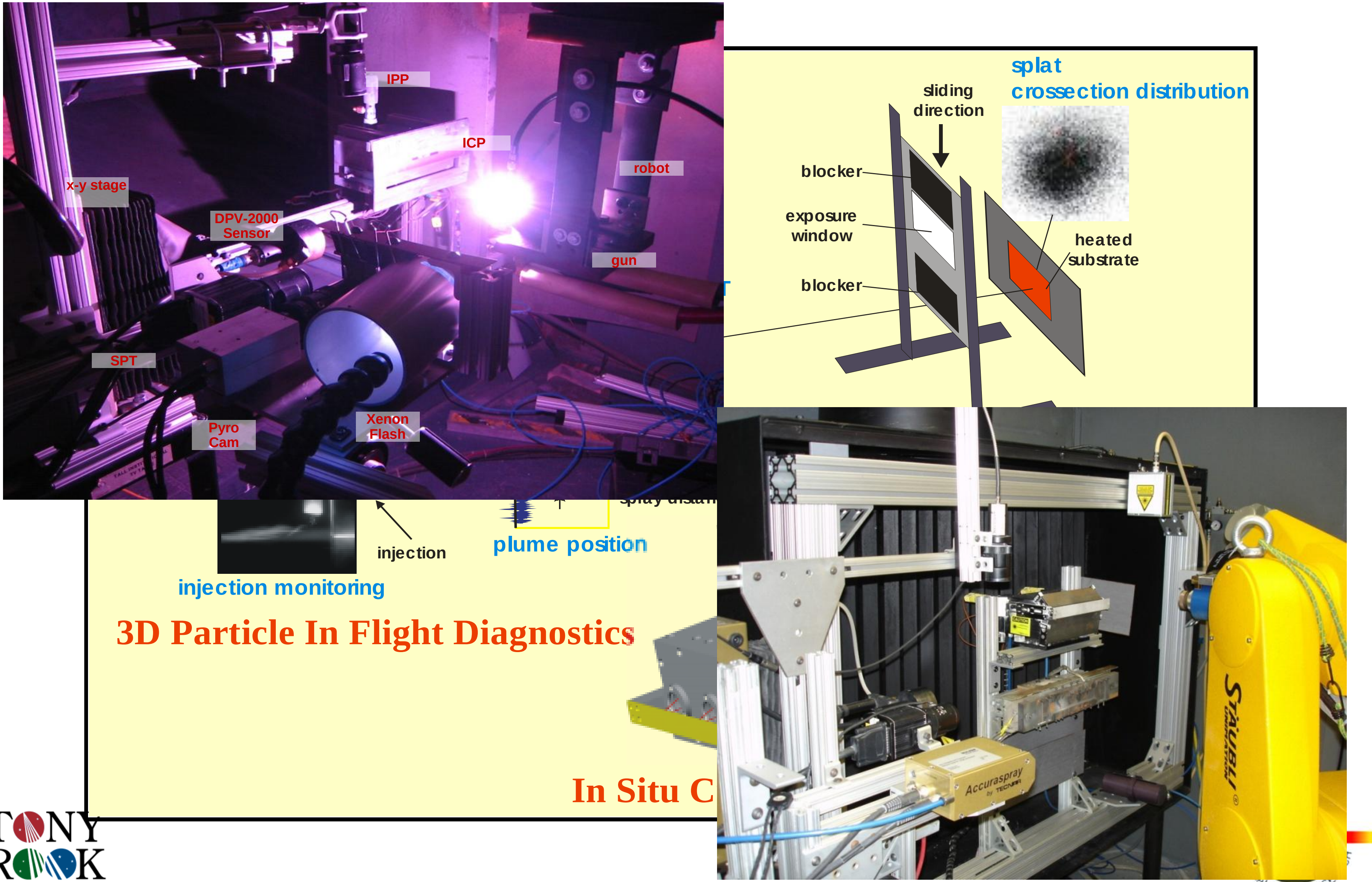
⇒ Provide input for design

⇒ Reduce infant mortality and improve reliability

⇒ Quantify microstructure evolution for life prediction

Integrated Studies of TS Coatings Including TBCs

- ***Fundamental process science and property evaluation at CTSR***



Integrated Studies of TS Coatings Including TBCs

- ***Fundamental process science and property evaluation at CTSR***
- ***Collaborative studies with Consortium members including field trips to industrial sites***

T-800, Stellite 6
WC-CoCr, WC-18Co
Ni20Cr,
CoNiCrAlY,
JK-3000

WC-12Co,
Ni20Cr, YSZ,
Abradables,
CrC-NiCr.
Guns:
Woka Star
Guns,
Triplex, Cold Spray

Inconel, CrC-NiCr, NiCrAlY
Max-phase
Guns: DJ

YSZ, CoNiCrAlY
Guns: F4,
JP-5000

Inconel, WC-Co
YSZ
Guns: JK, F4
testing:
Repeatability and injection optimization

YSZ, WC-Co
Guns: DJ, F4
testing:
Repeatability and injection optimization

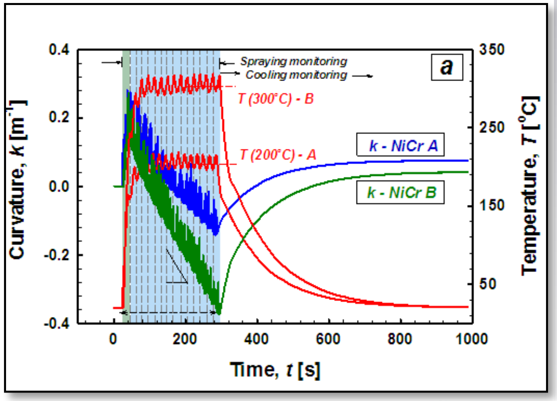
CrC-NiCr
JP-5000
JK-3000
testing: Feedrate, SD, pass rate, parameters

T-800, WC-CoCr,
Ni20Cr,
CoNiCrAlY,
CrC-NiCr.
JP-5000

Volvo Sweden Field Trip

Residual Stress and Evolution
Coating Modulus Evaluation
Diagnostics
Coatings Characterization

Stony Brook-Caterpillar Team

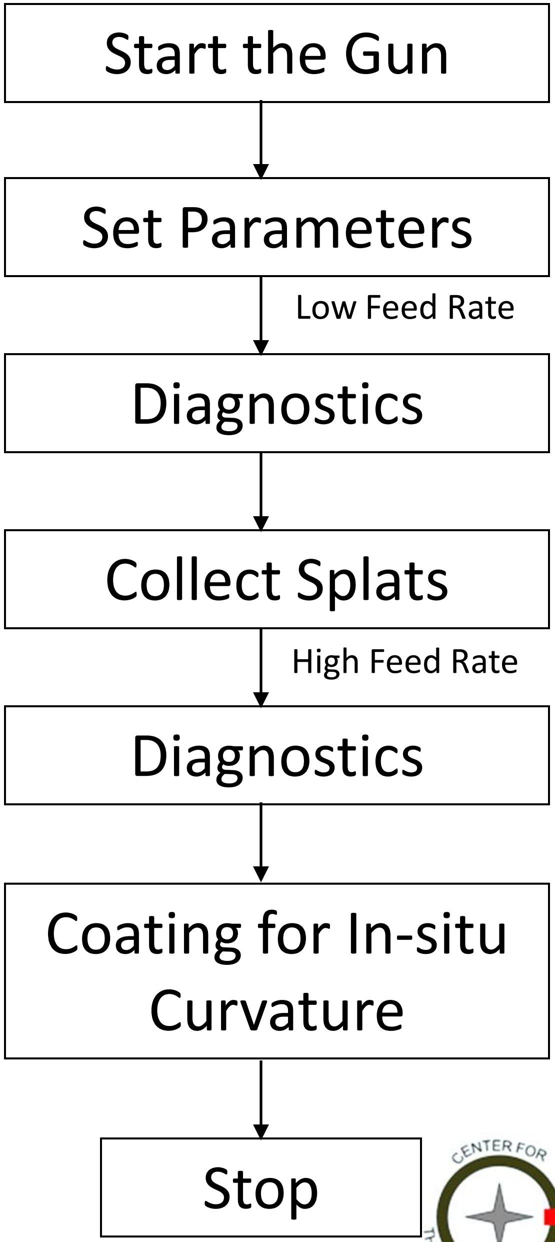


Many parameters can be considered for tailoring a microstructure

- Starting powder morphology
- Particle size distribution
- Particle injection
- Plasma torch, power and gases
- Substrate temperature
- Particle flux
- Robot motion

+ Pore Architecture
Modulus (two orientations)
Indentation
Stress-Strain
Thermal Conductivity
(in-plane and through-thickness)

- Examine process/coating repeatability
- Examine testing repeatability



Start the Gun

Set Parameters

Low Feed Rate

Diagnostics

Collect Splats

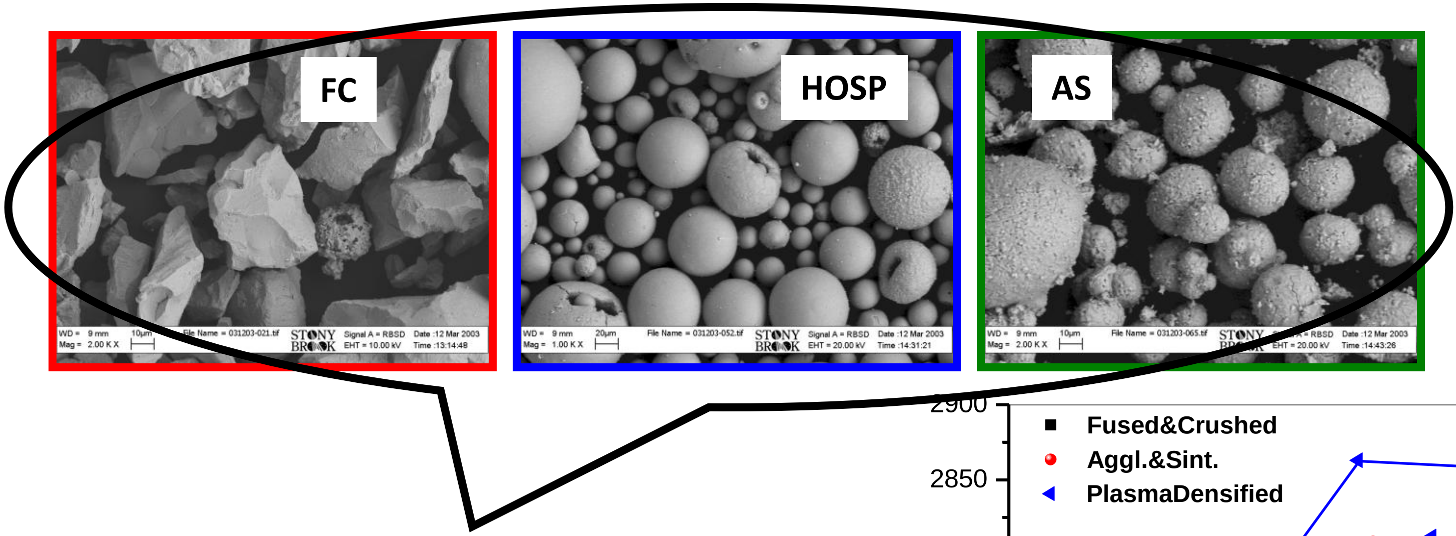
High Feed Rate

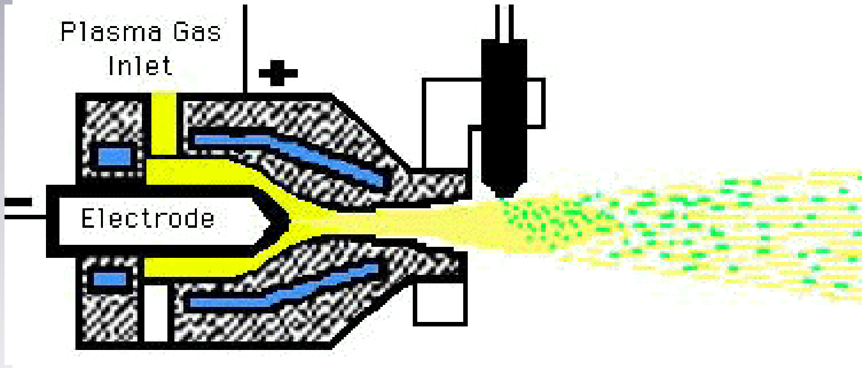
Diagnostics

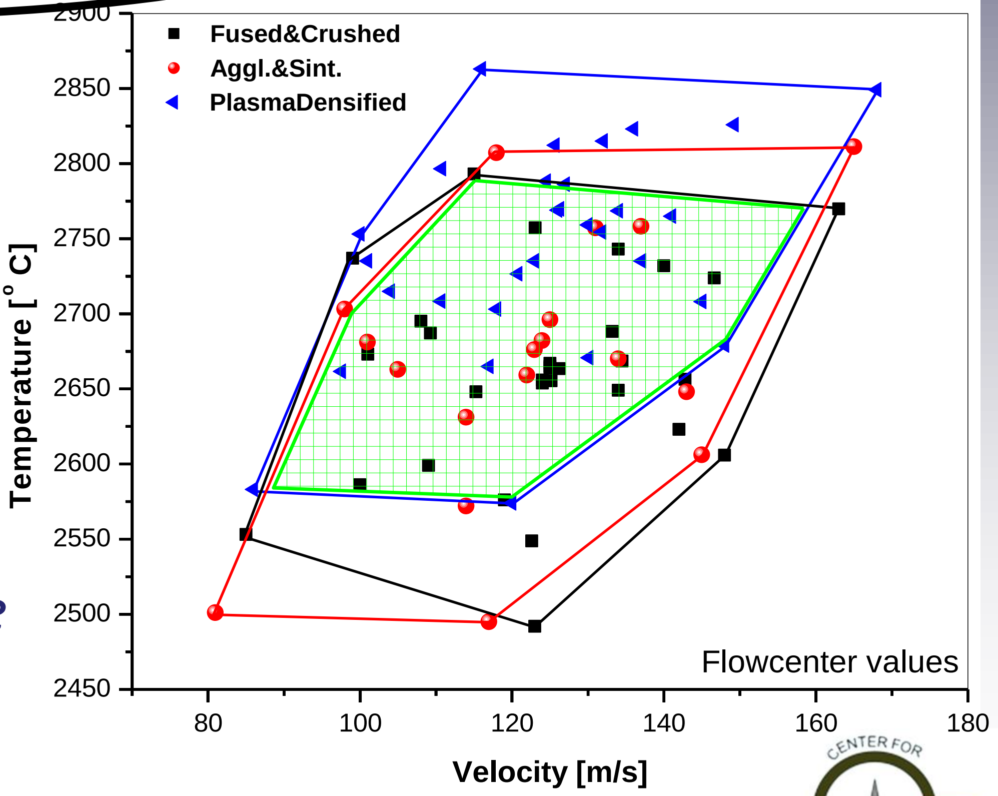
Coating for In-situ Curvature

Stop

Example 1: Effect of Starting Powder Morphology







Each Powder Optimized to Produce the Same ***Average*** *T & V*

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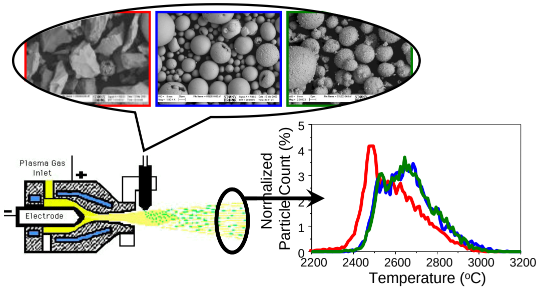
Example 1: Effect of Starting Powder Morphology

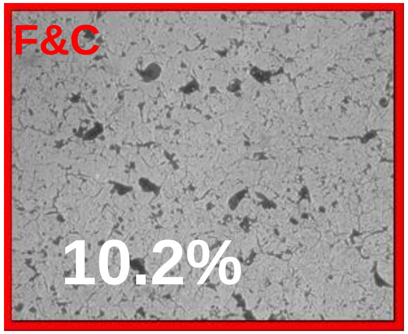


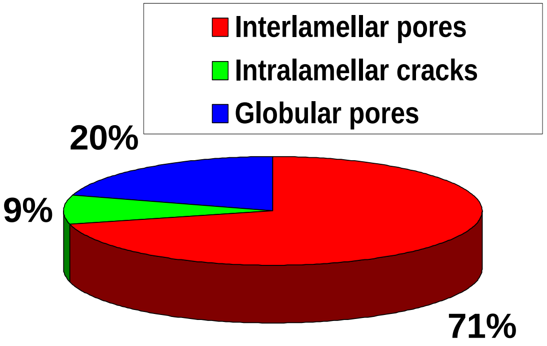
Each Powder Optimized to
Produce the Same **Average** T & V

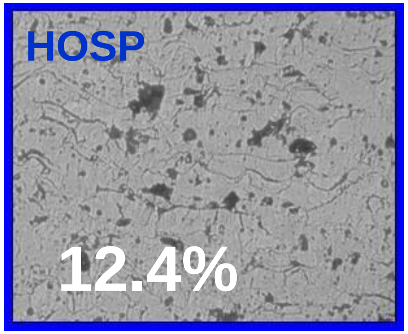
Similar Total Porosity

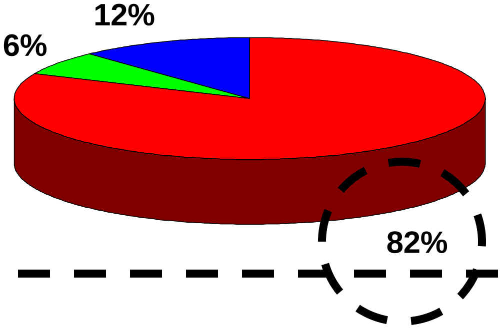
and

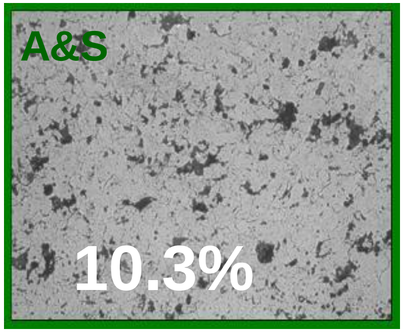
Higher % ILP

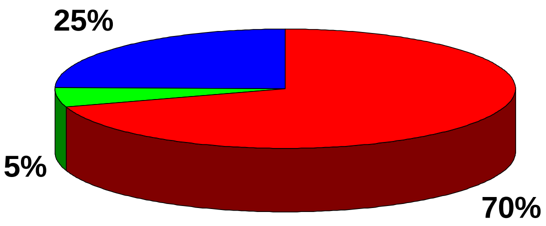




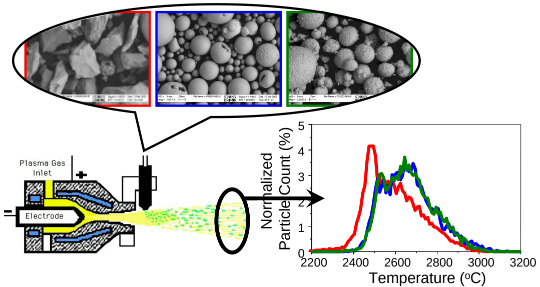




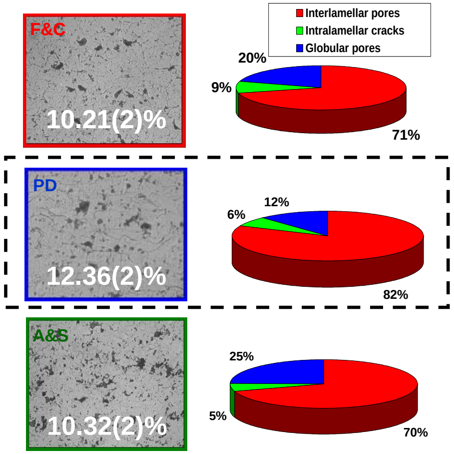


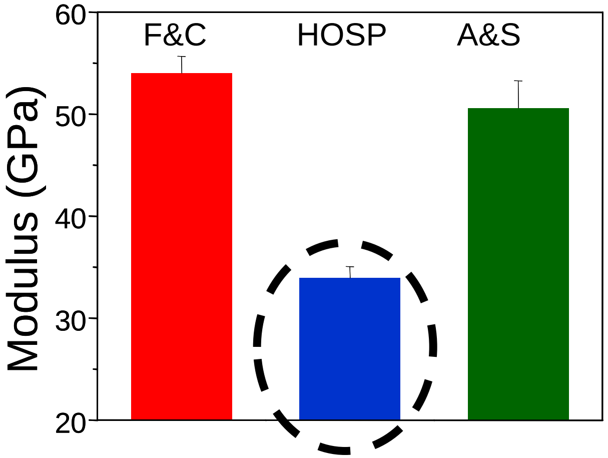


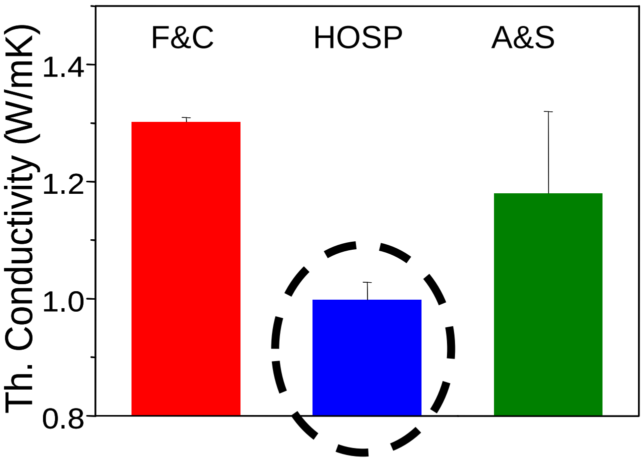
Example 1: Effect of Starting Powder Morphology



Each Powder Optimized to
Produce the Same **Average** T & V

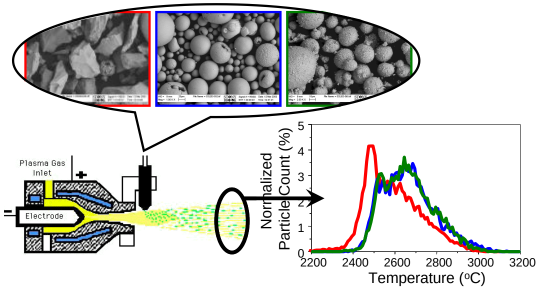




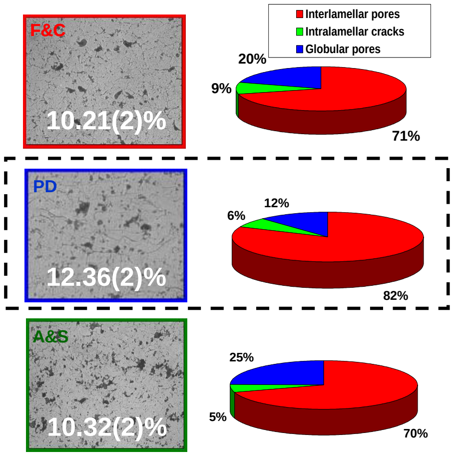


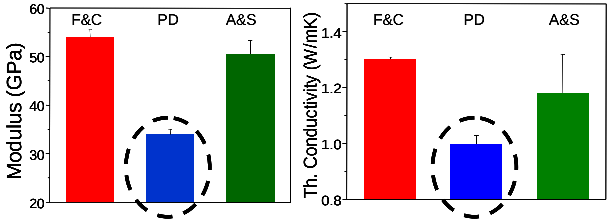
HOSP
shows
consistently
lower E and K

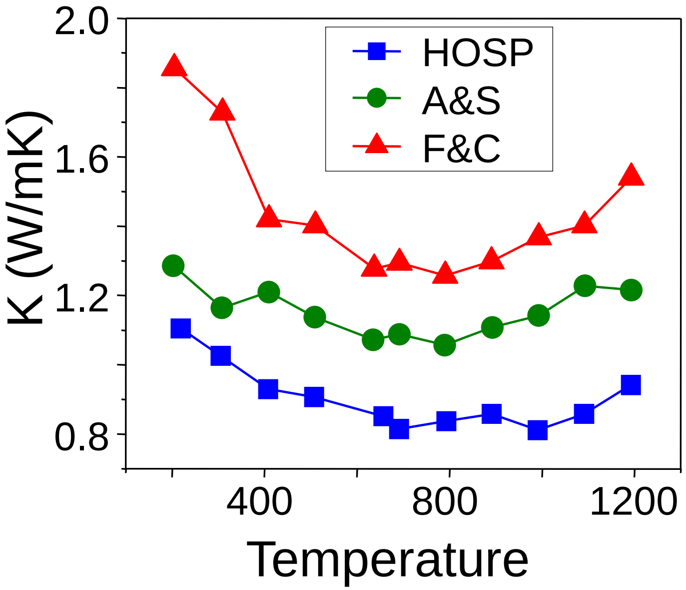
Example 1: Effect of Starting Powder Morphology

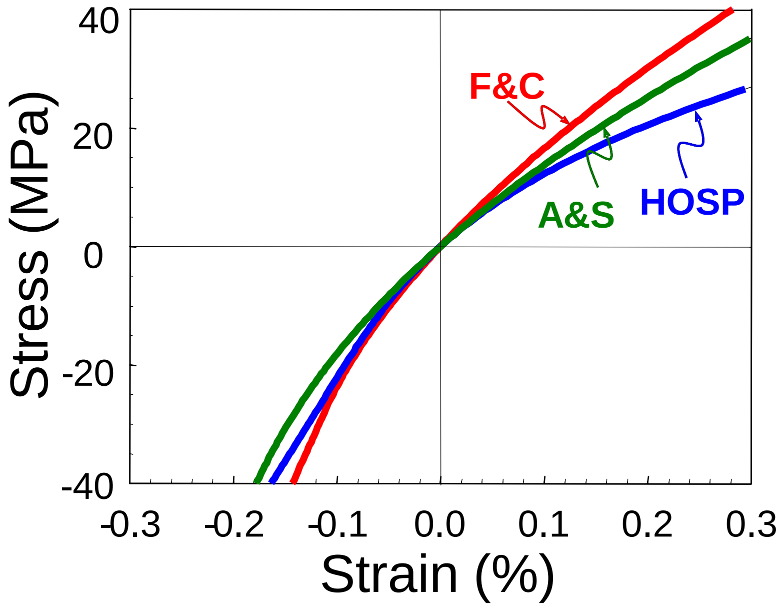


Each Powder Optimized to
Produce the Same **Average** T & V



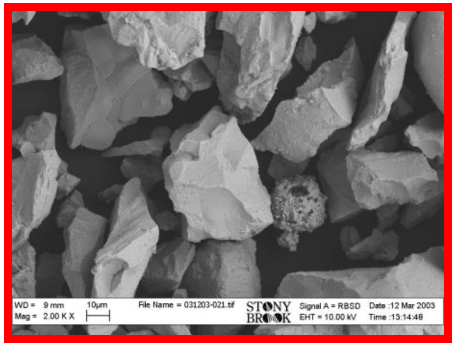


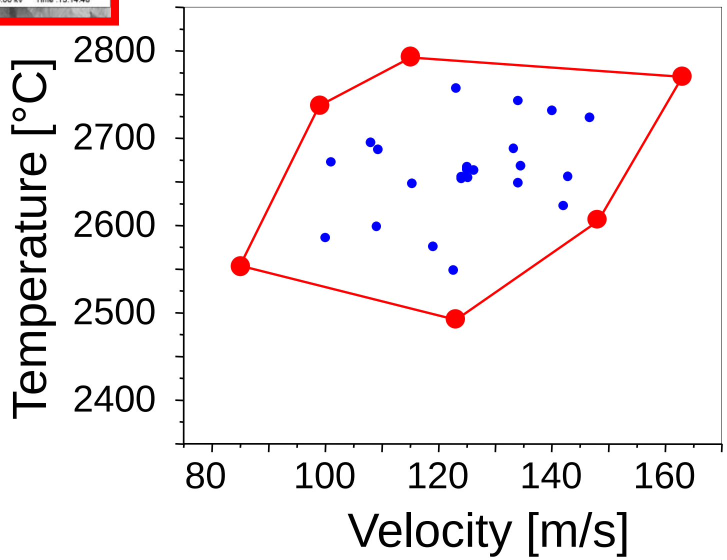




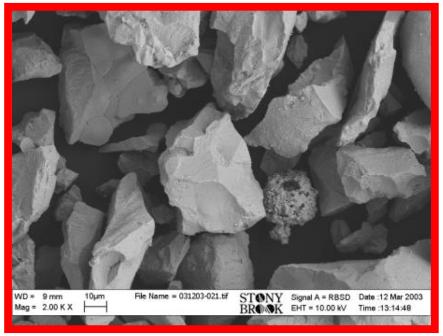
Temperature-dependent K and mechanical behavior differences are observed.

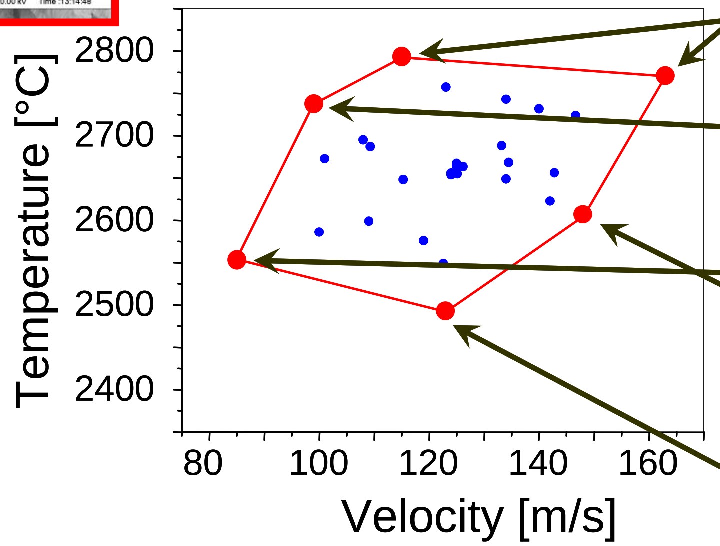
Example 2: Changing T-V process space via torch parameters

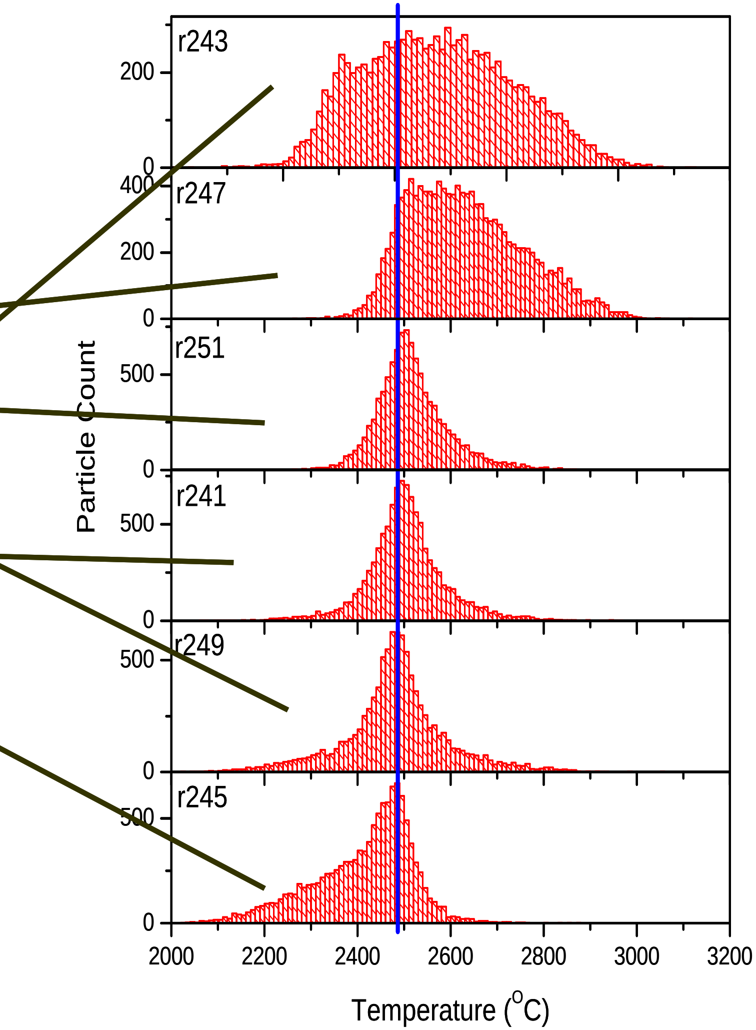




Example 2: Changing T-V process space via torch parameters

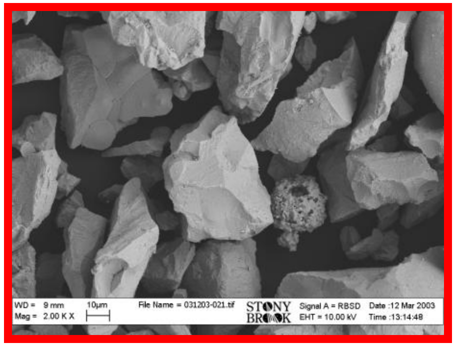


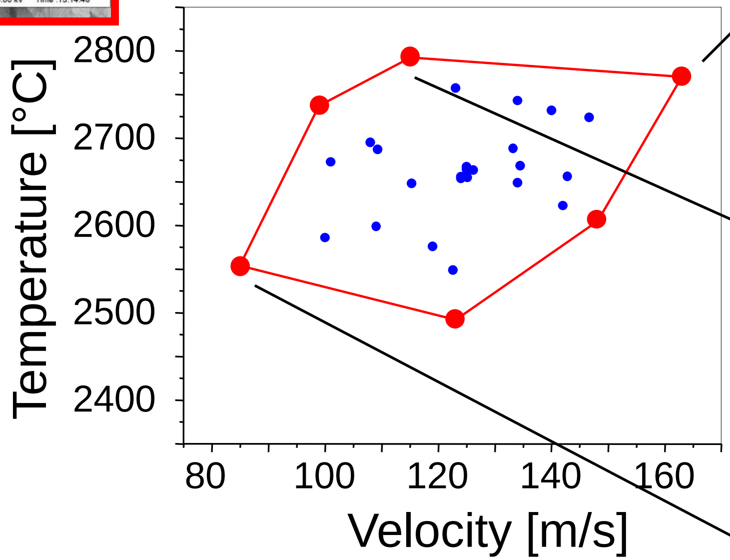




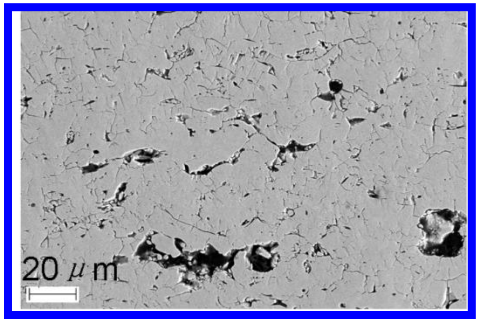
Changing torch parameters effects particle temperature distribution

Example 2: Changing T-V process space via torch parameters

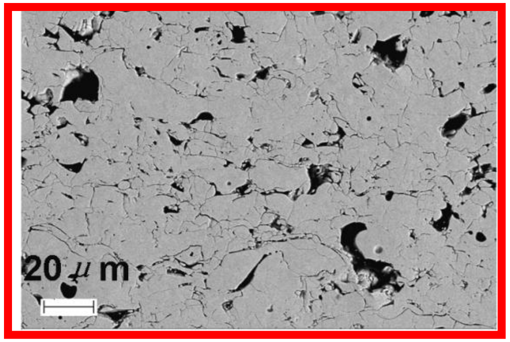




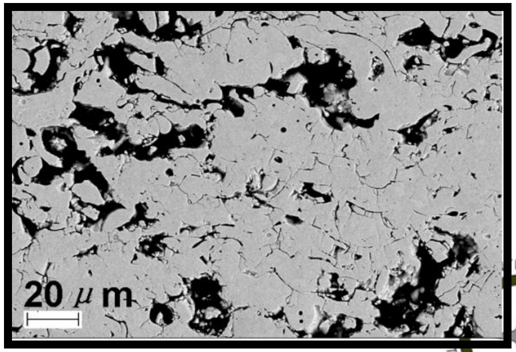
67 GPa **1.3 W/mK**



51 GPa **1.13 W/mK**

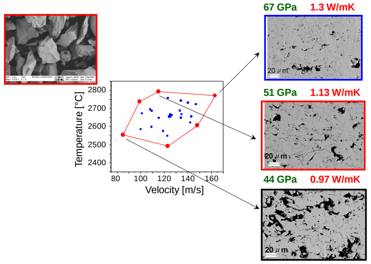


44 GPa **0.97 W/mK**

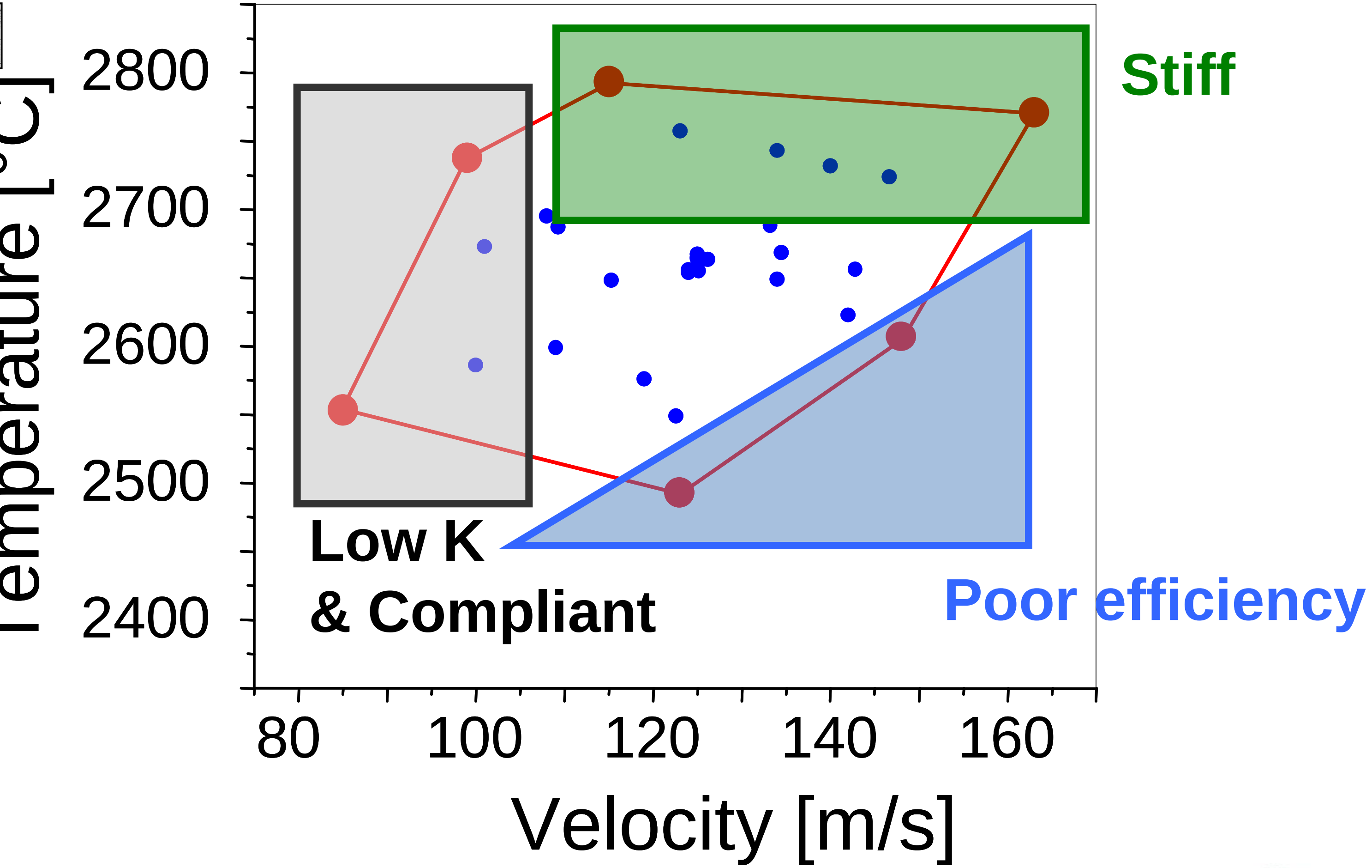


Changing torch parameters effects microstructure, elastic modulus and thermal conductivity.

Example 2: Changing T-V process space via torch parameters

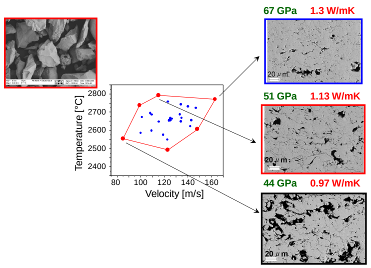


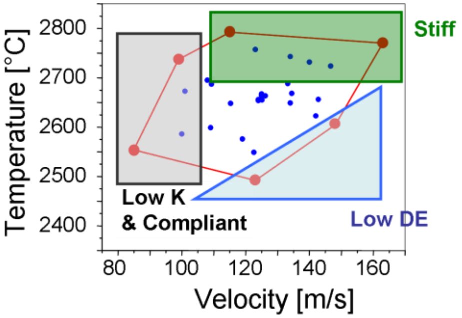
2nd Order Process Map

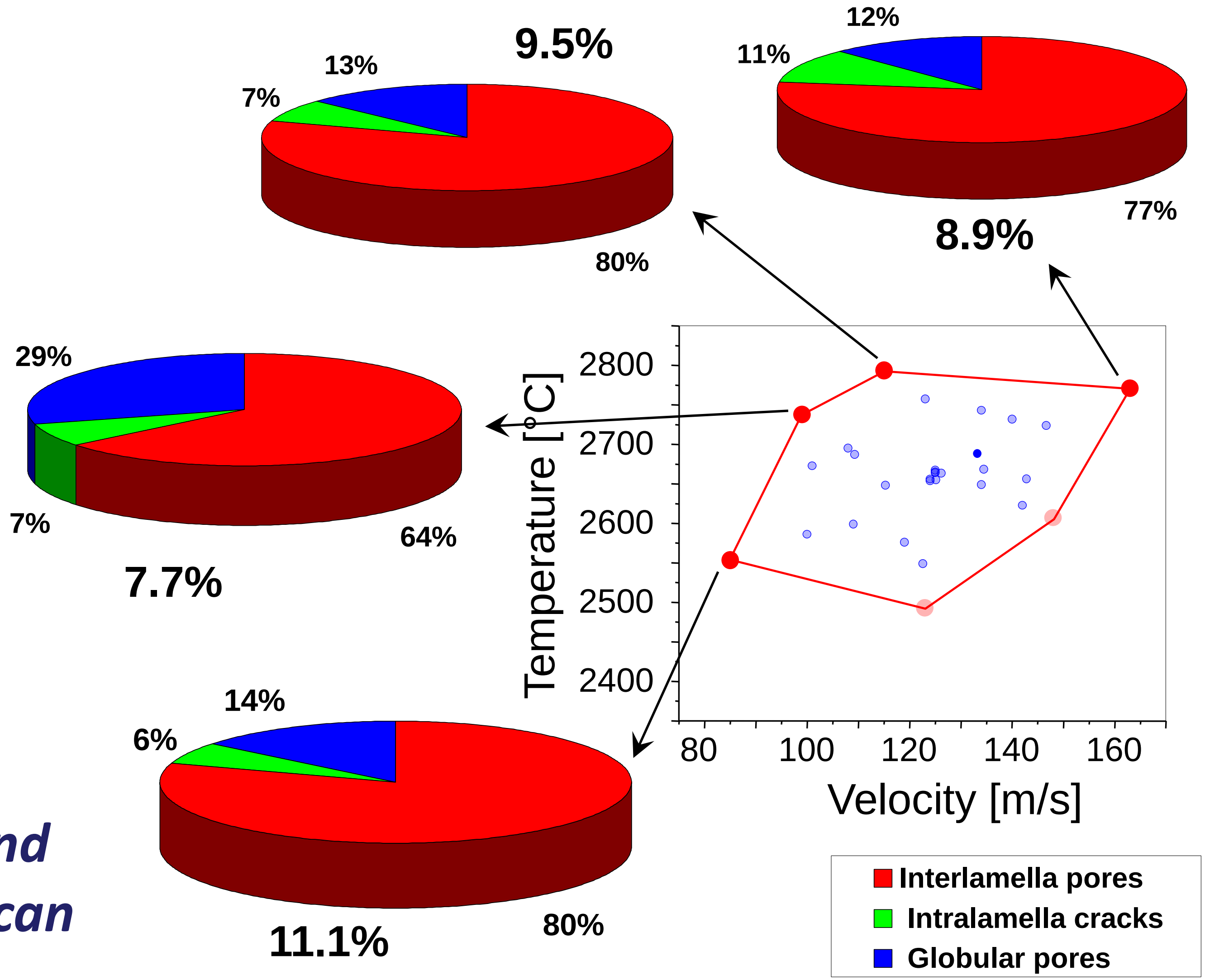


Process map allows for distinguishing processing effects

Example 2: Changing T-V process space via torch parameters

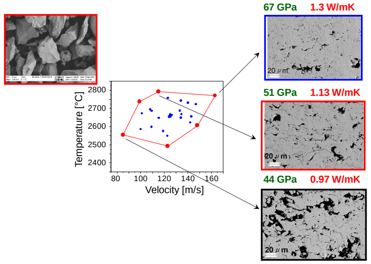


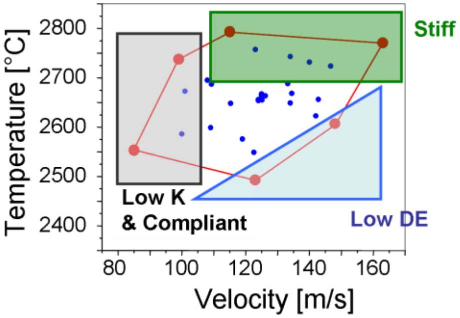


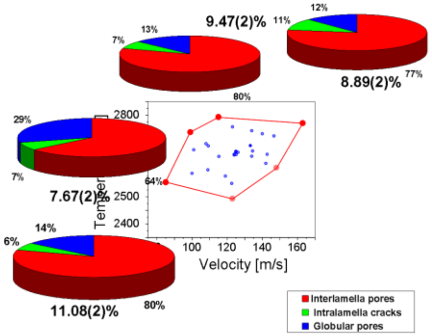


Total amount and type of porosity can be controlled

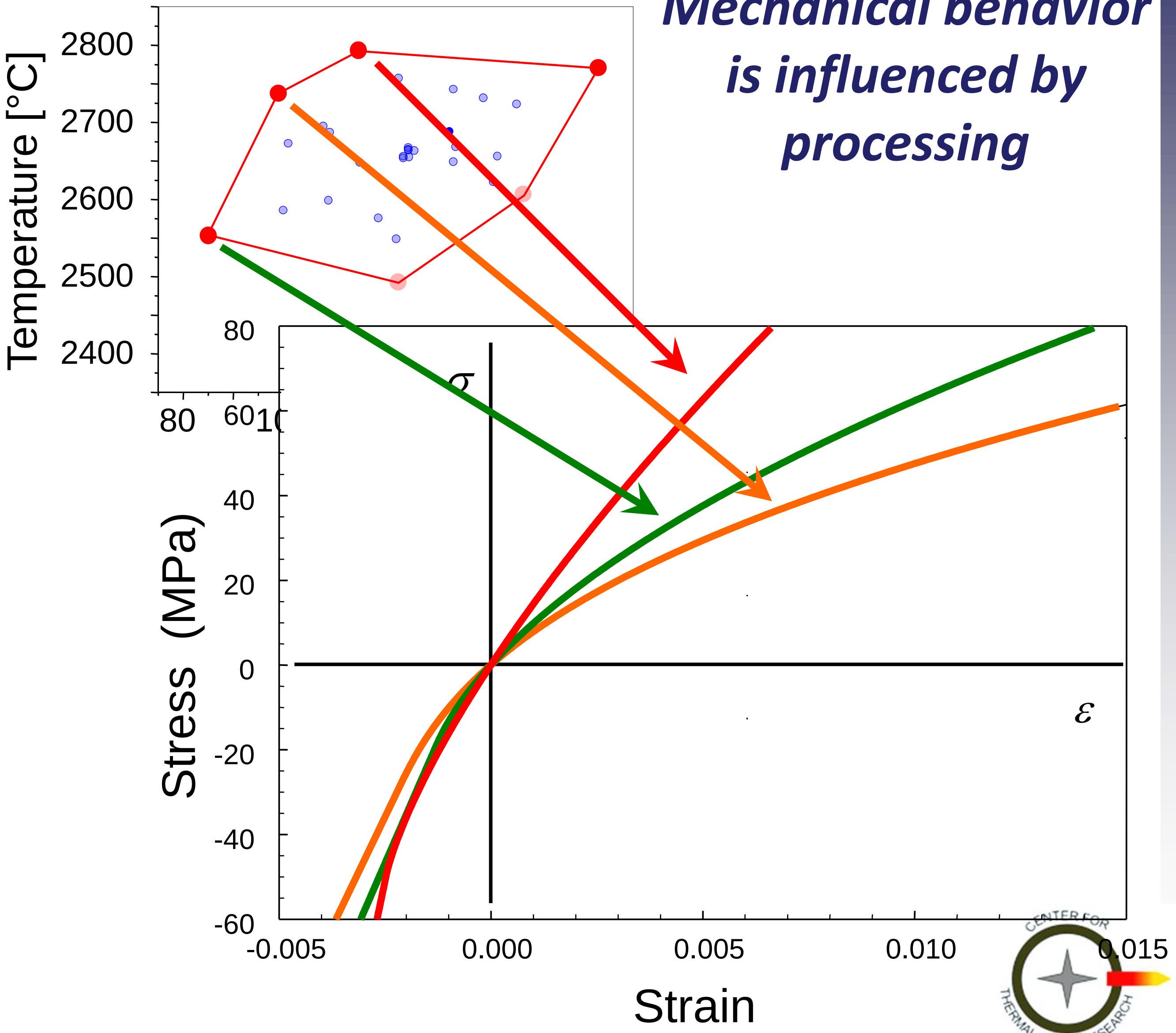
Example 2: Changing T-V process space via torch parameters







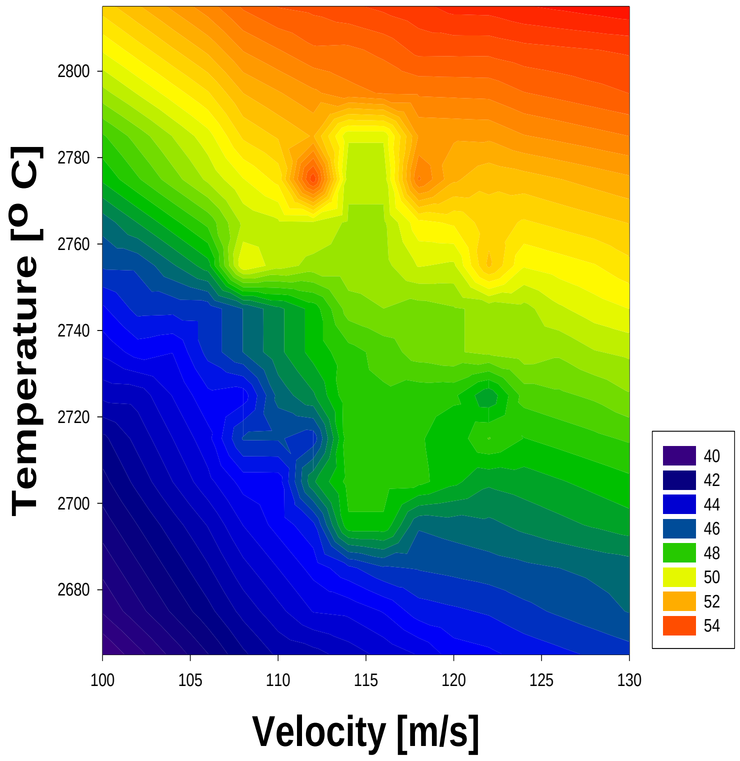
Mechanical behavior is influenced by processing



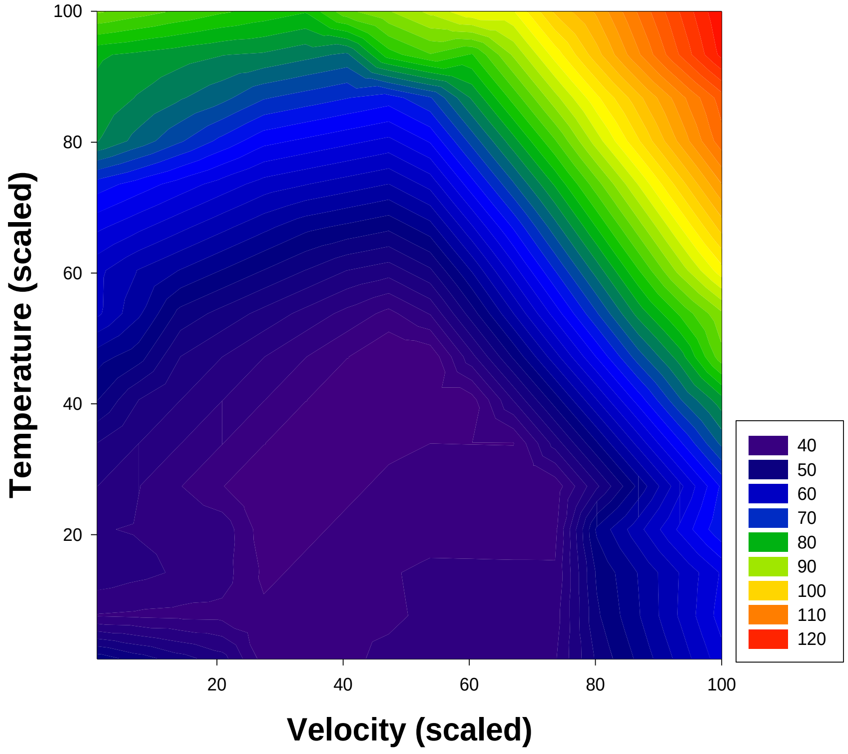
Example 2: Changing T-V process space via torch parameters

Detailed process maps can be created for use by process and design engineers

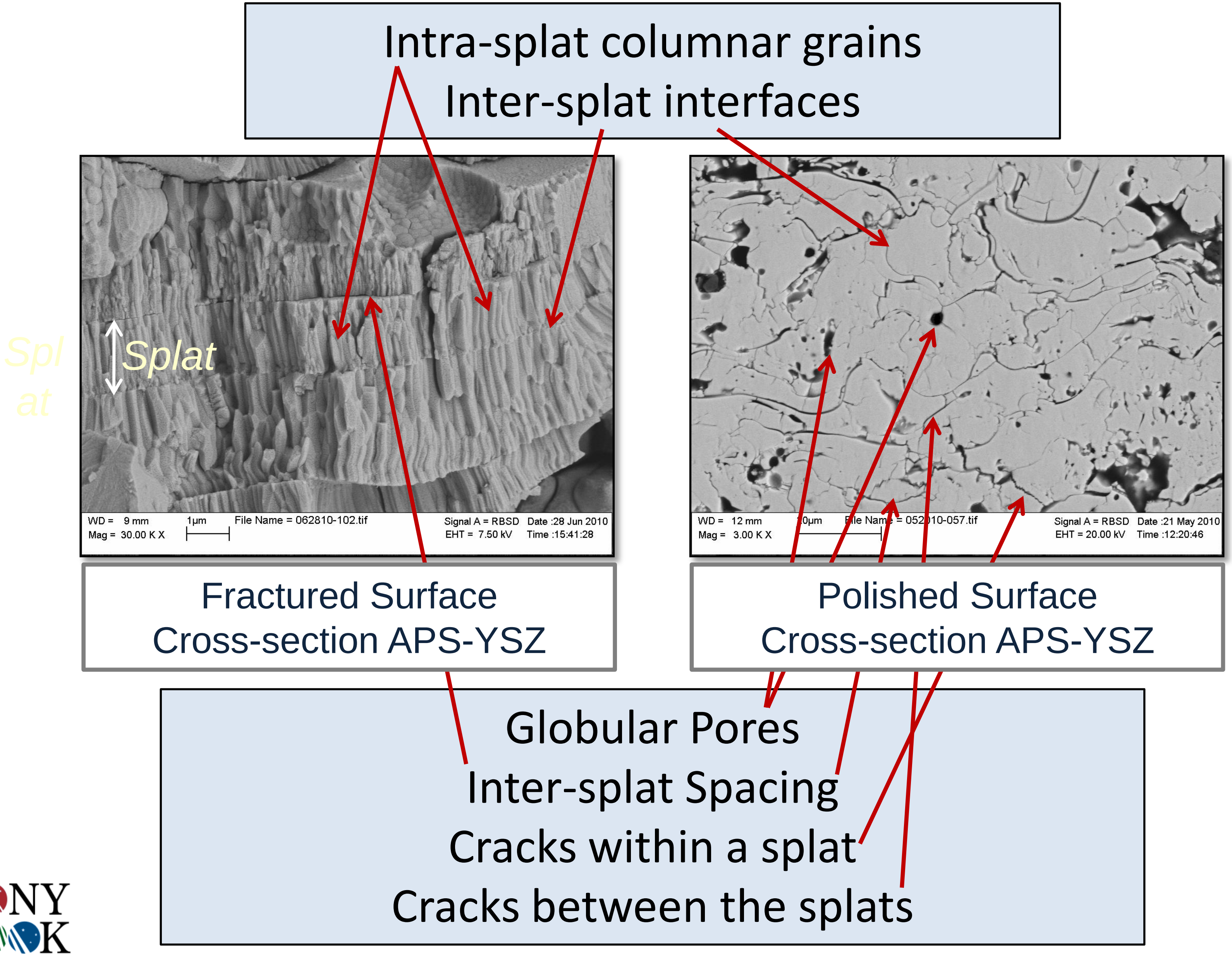
Elastic Modulus Map



Thermal Conductivity Map



Microstructural Effects on Mechanical Behavior



Intra-splat columnar grains
Inter-splat interfaces

Fractured Surface
Cross-section APS-YSZ

Polished Surface
Cross-section APS-YSZ

Globular Pores
Inter-splat Spacing
Cracks within a splat
Cracks between the splats

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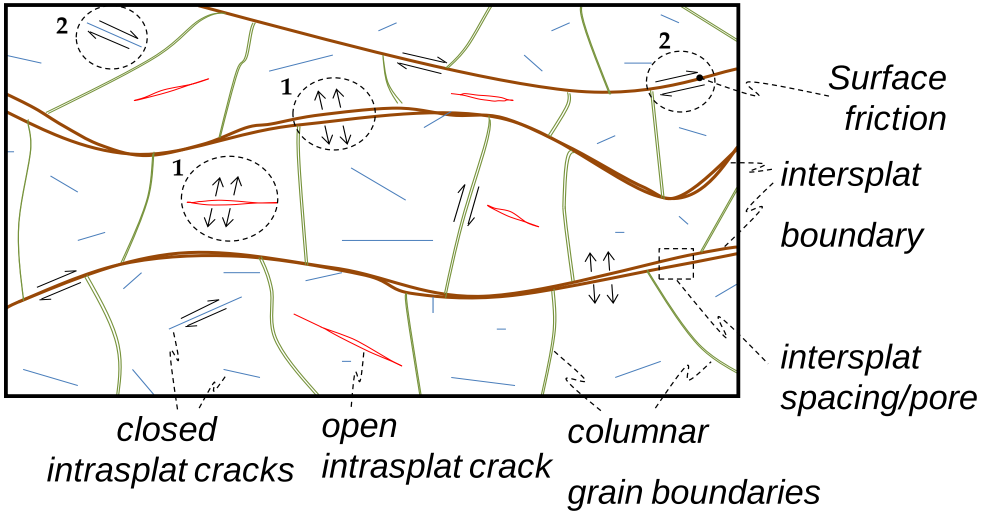
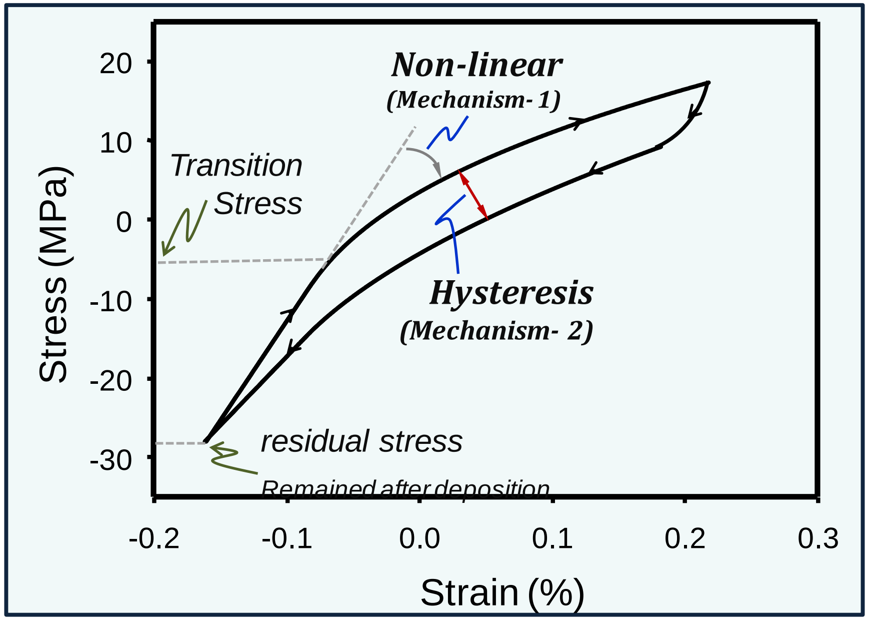
Microstructural Effects on Mechanical Behavior

Upon Mechanical Loading



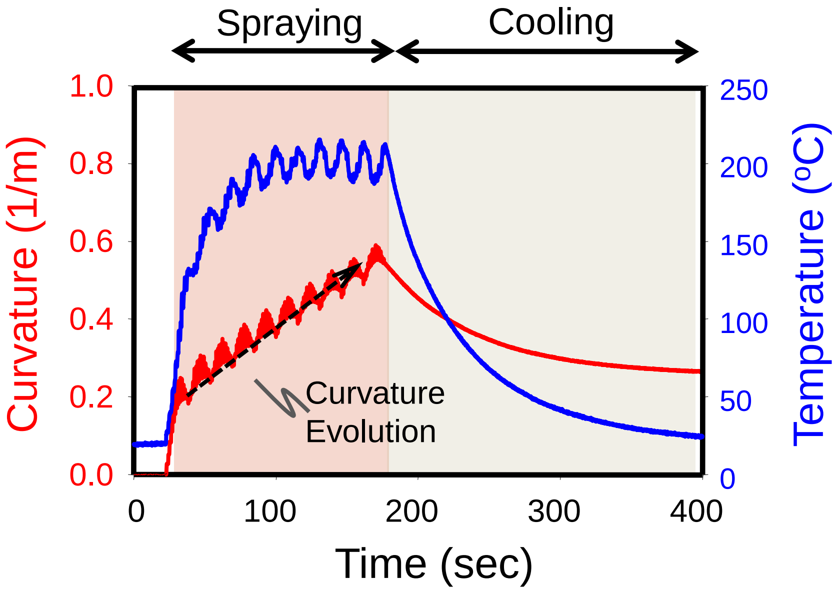


- ○ **Mechanism 1:** Opening/closure of pores or spacings, the source of <u>Non-linearity</u>
- ○ **Mechanism 2:** Sliding of defect surfaces causes frictional energy loss, Hysteresis behavior

Non-linearity of the coating represents the compliance present in it

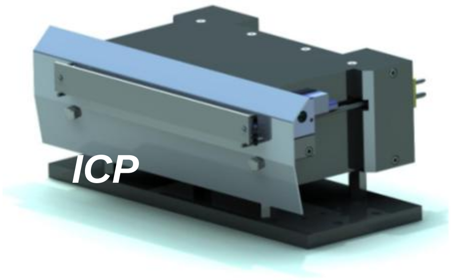
Microstructural Effects on Mechanical Behavior

In-situ: Curvature Monitoring

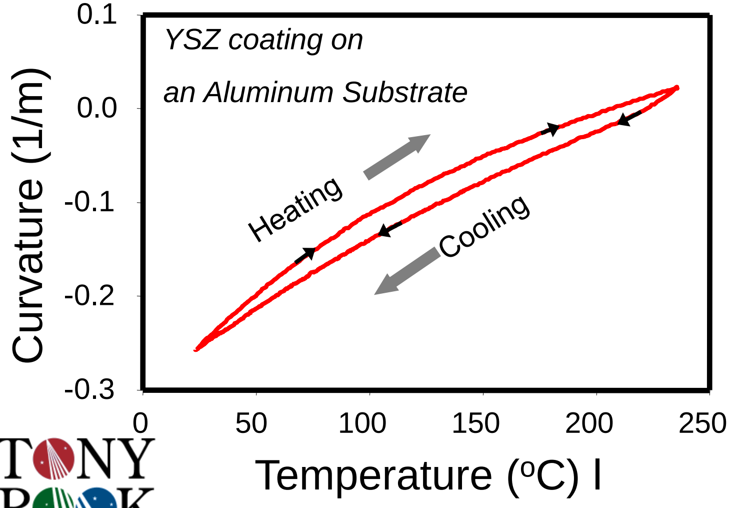


Measurement tells the evolution history of a deposited coating.

Each local peak corresponds to a pass (deposition of one layer). The slope of the curvature evolution is referred as "Evolving stress"



Ex-situ: Thermal Cycle of the Coated Specimen



After spraying, the coating (with substrate) is heated inside a furnace. The temperature change induces mismatch strain, and the curvature of coating changes. The continuous recording of one thermal cycle provides an ANELASTIC curv-temp plot, which is then converted to a stress strain curve to quantify the coating compliance.

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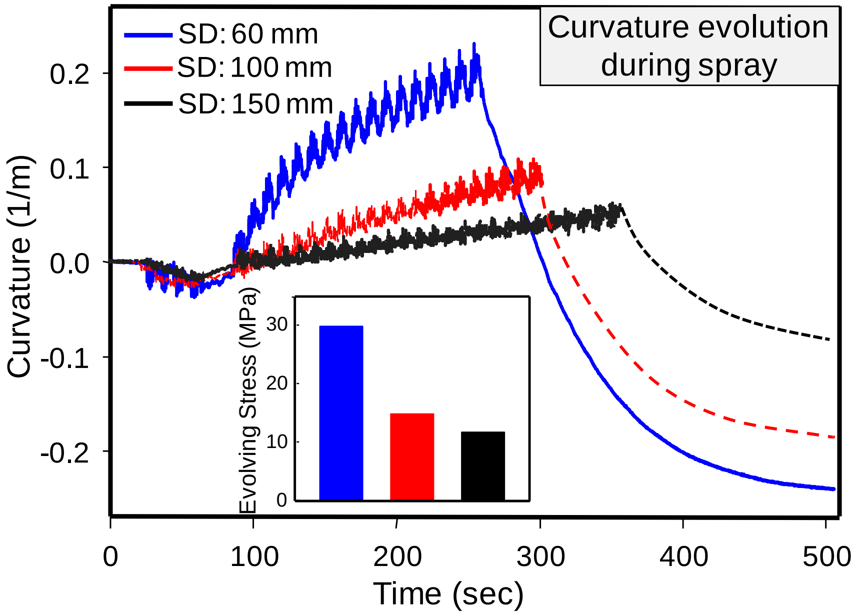
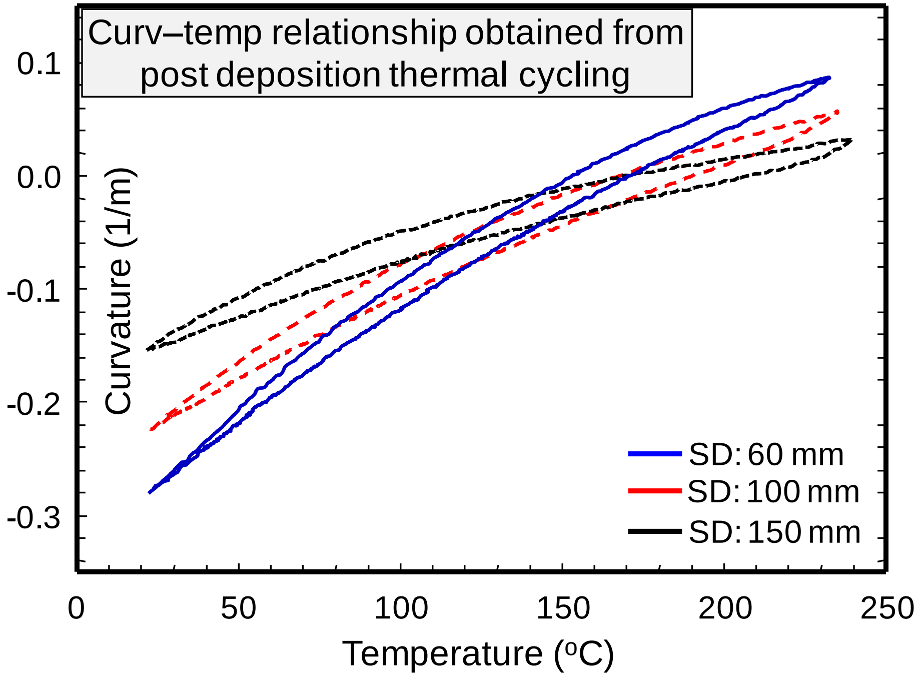
Microstructural Effects on Mechanical Behavior

Case study: three coatings deposited at three different spray distances

In-situ

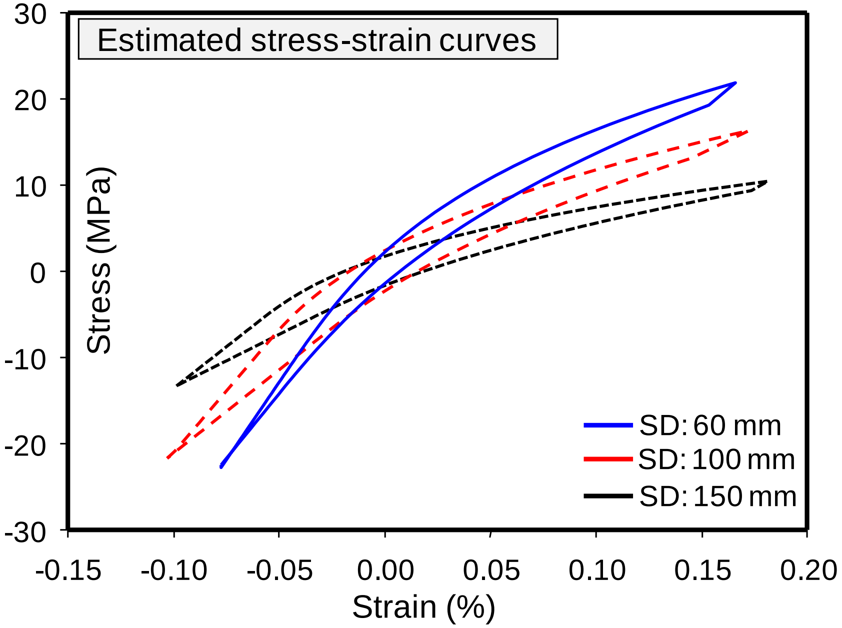


Ex-situ

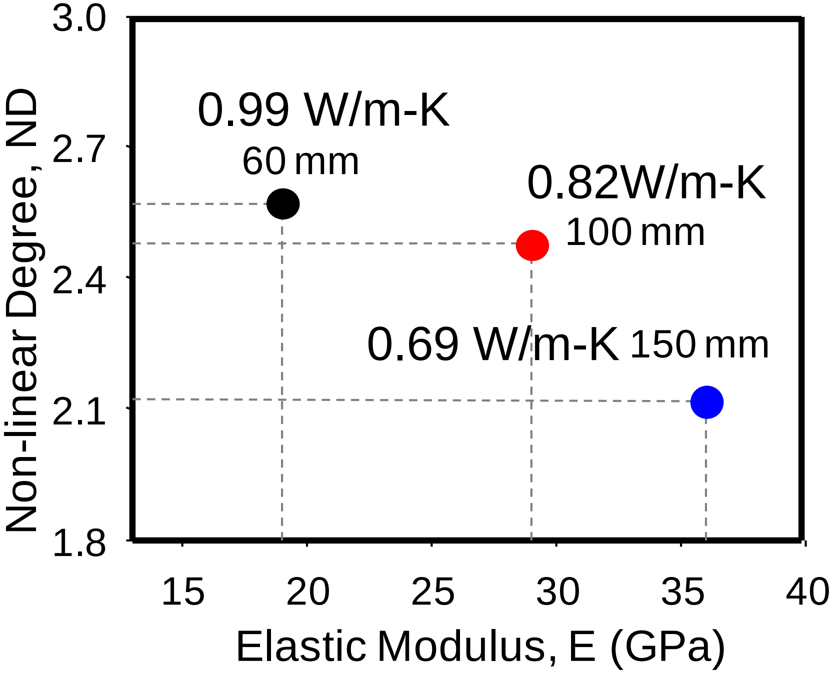


Microstructural Effects on Mechanical Behavior

Case study: three coatings deposited at three different spray distances

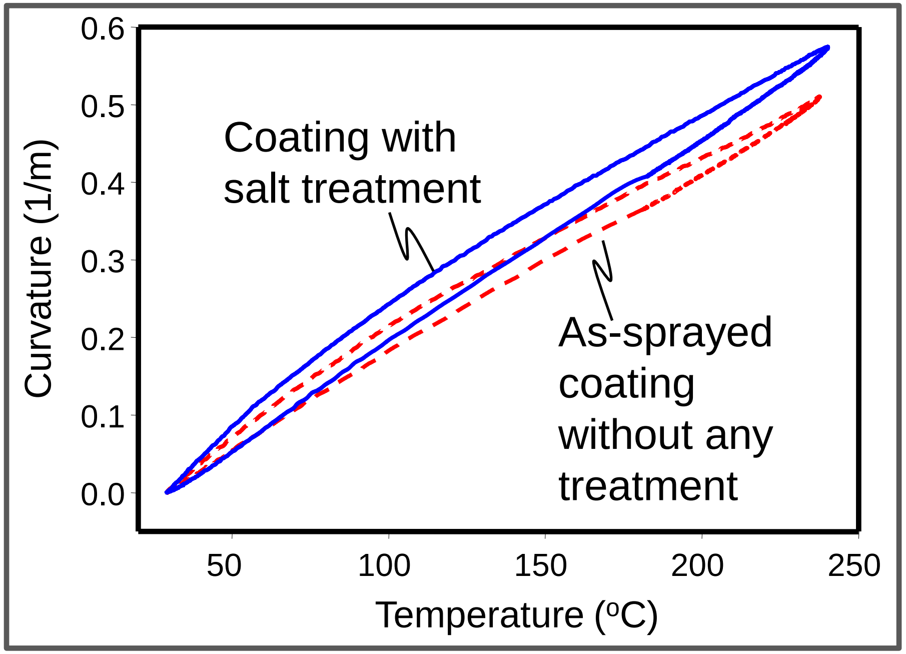


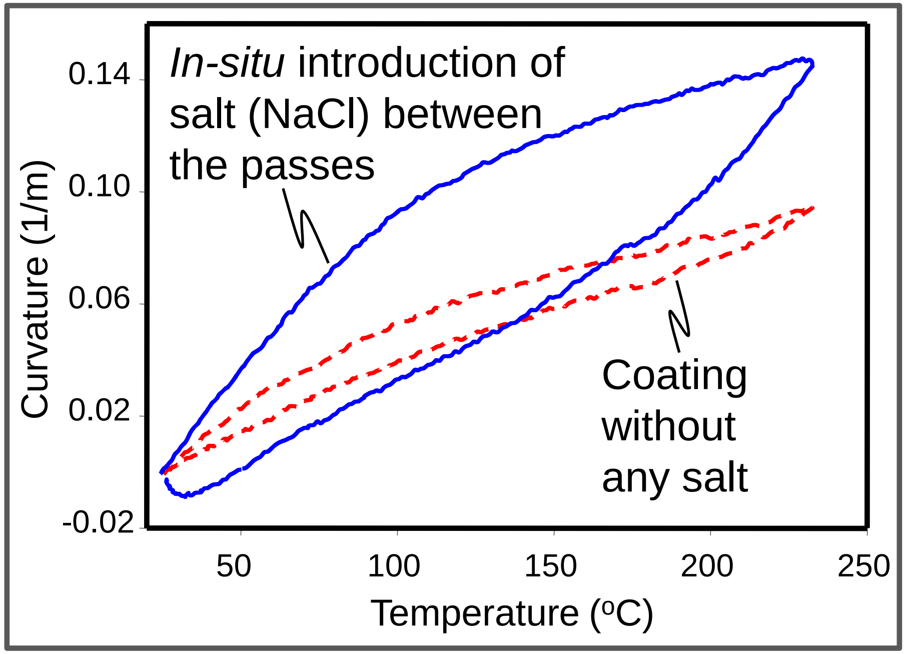
Non-linear parameters of the three coatings



Microstructural Effects on Mechanical Behavior

How could deposits impact mechanical behavior?





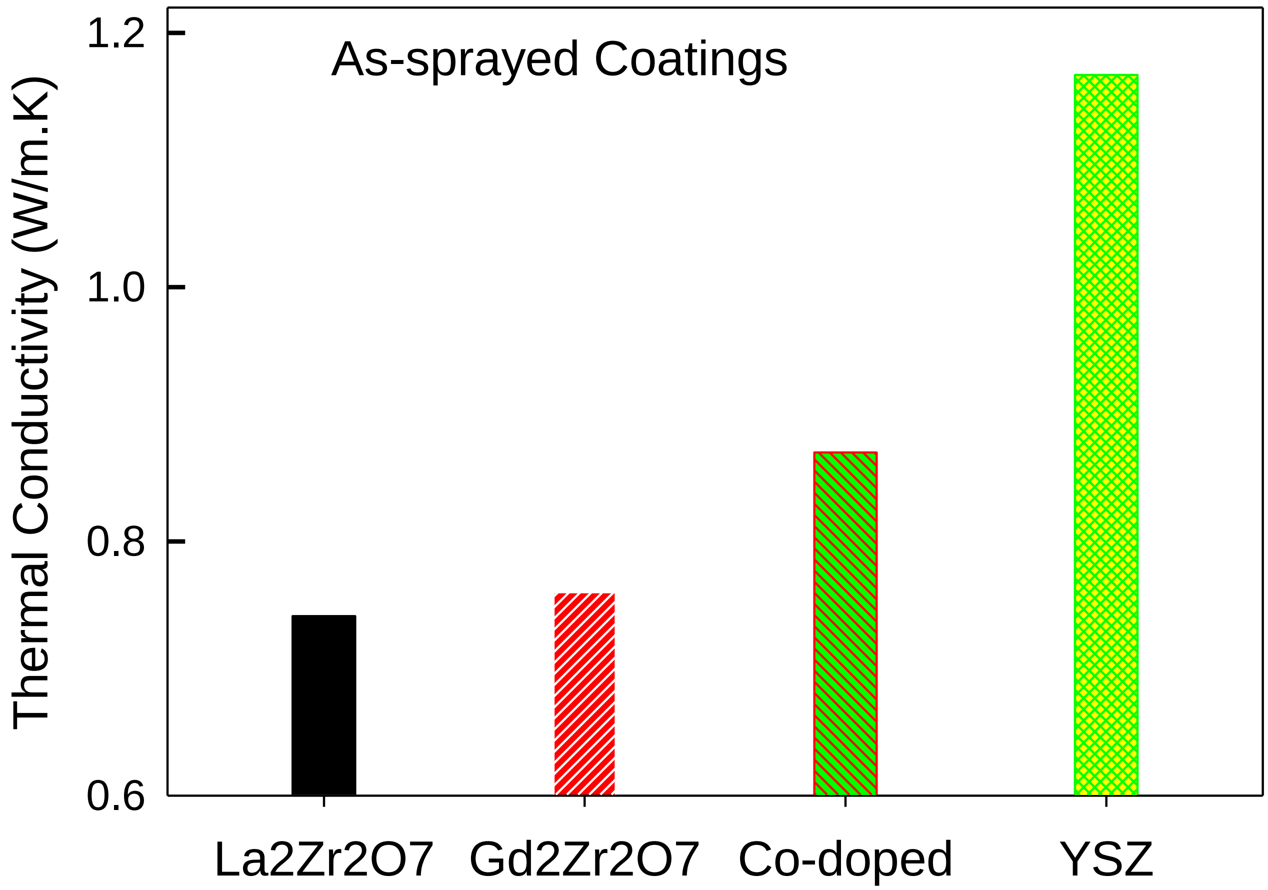
Coating with salt solution treatment was 30% stiffer than as sprayed one. It also showed more hysteresis in it.

Salt mist was introduced between some selective passes during coating deposition.

The presence of salt at defect surfaces made the coating stiffer, with increased non-linearity and hysteresis.

IGCC Turbine Coating Properties: Material Effects

Thermal Conductivity of As-Sprayed Coatings



Material choice influences thermal properties

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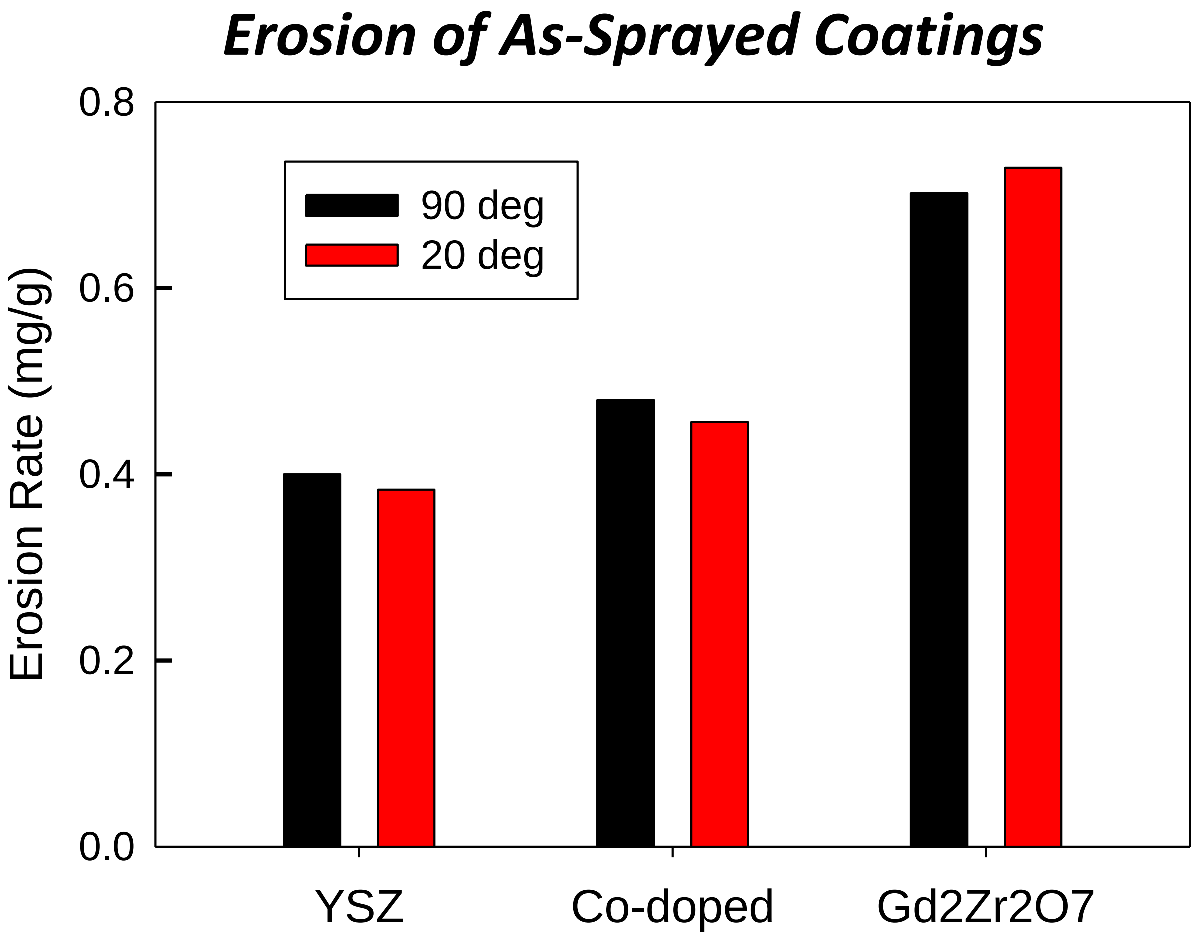
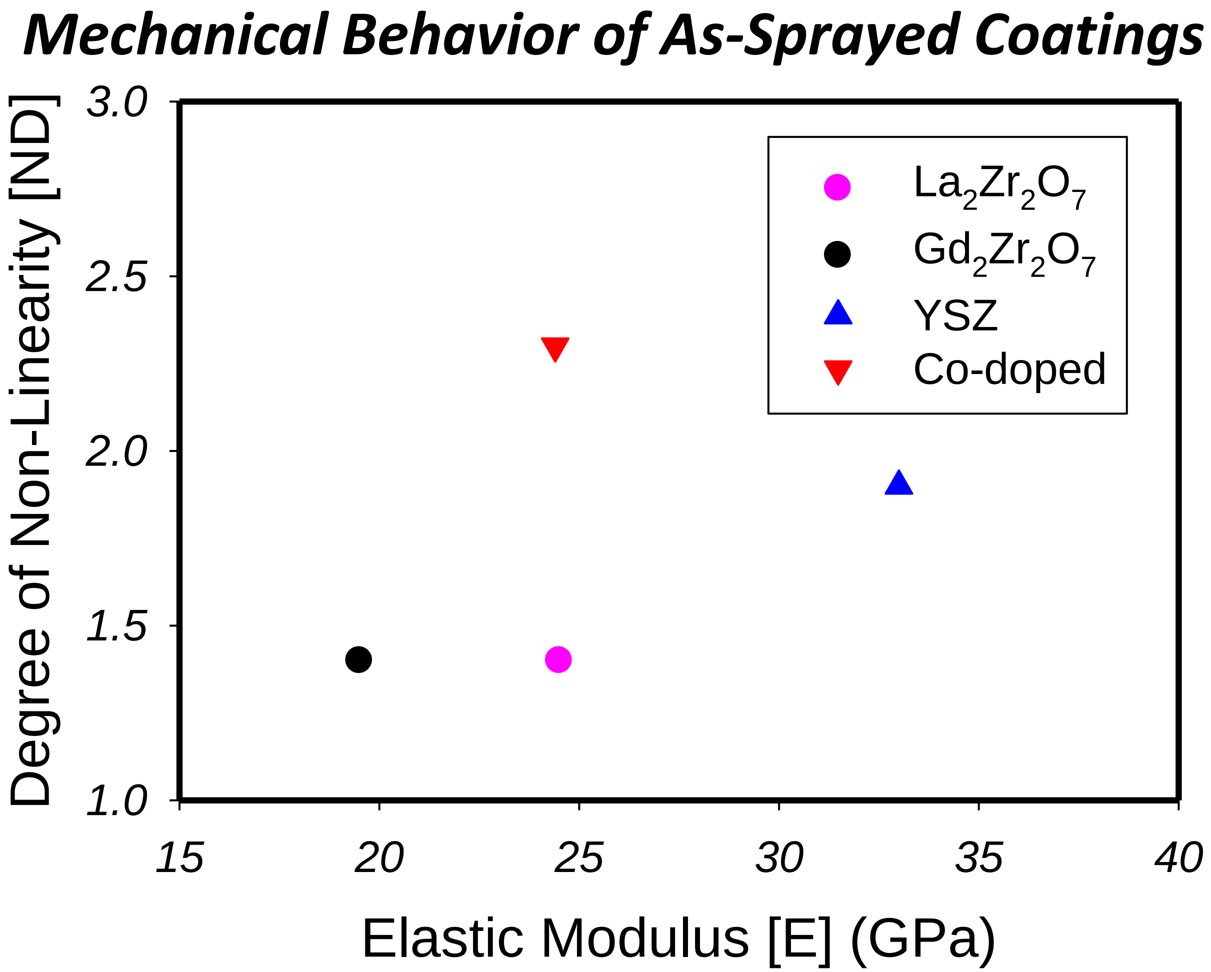
IGCC Turbine Coating Properties: Material Effects



Material choice influences erosion properties with $Gd_2Zr_2O_7$ having high erosion rates.

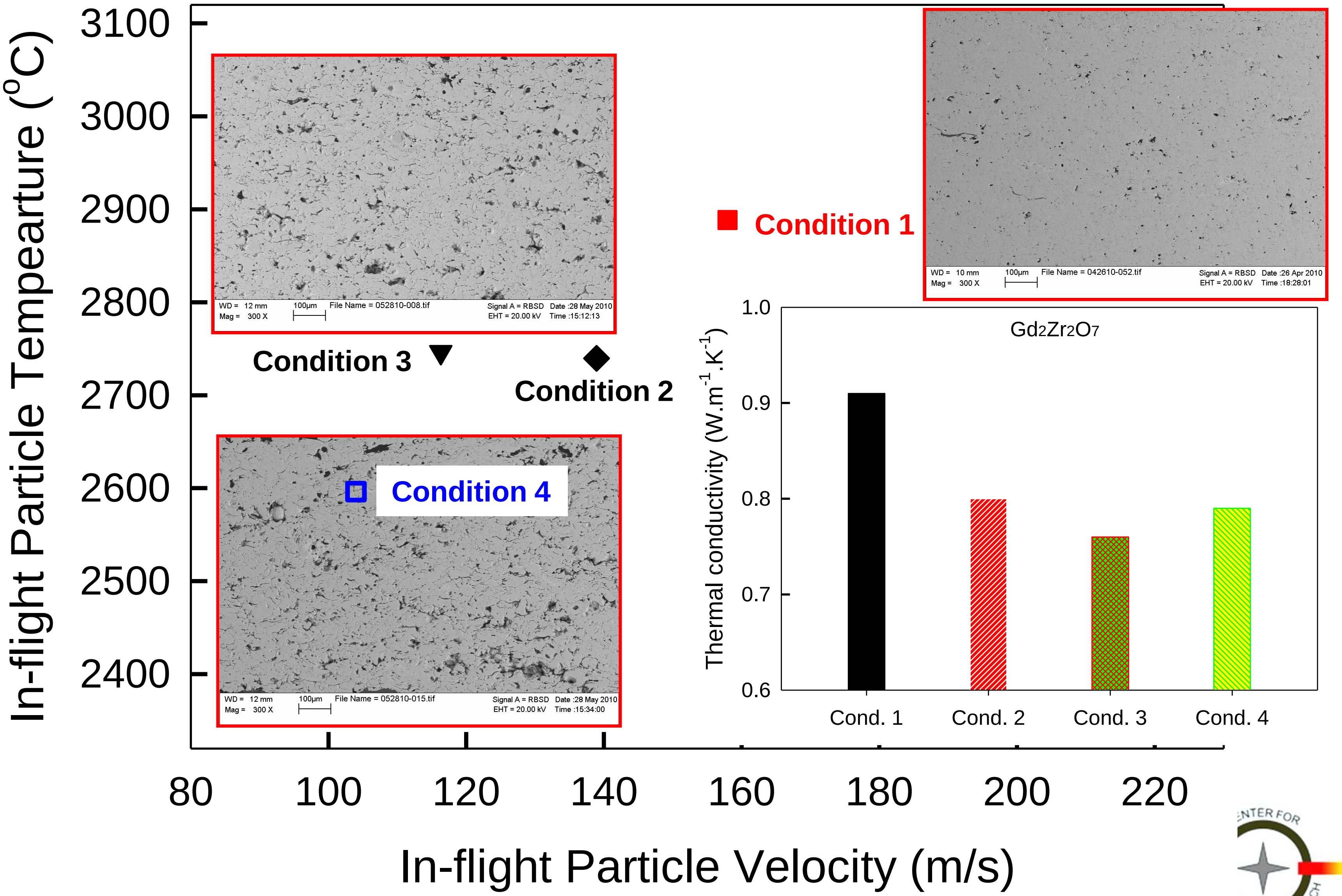
IGCC Turbine Coating Properties: Material Effects



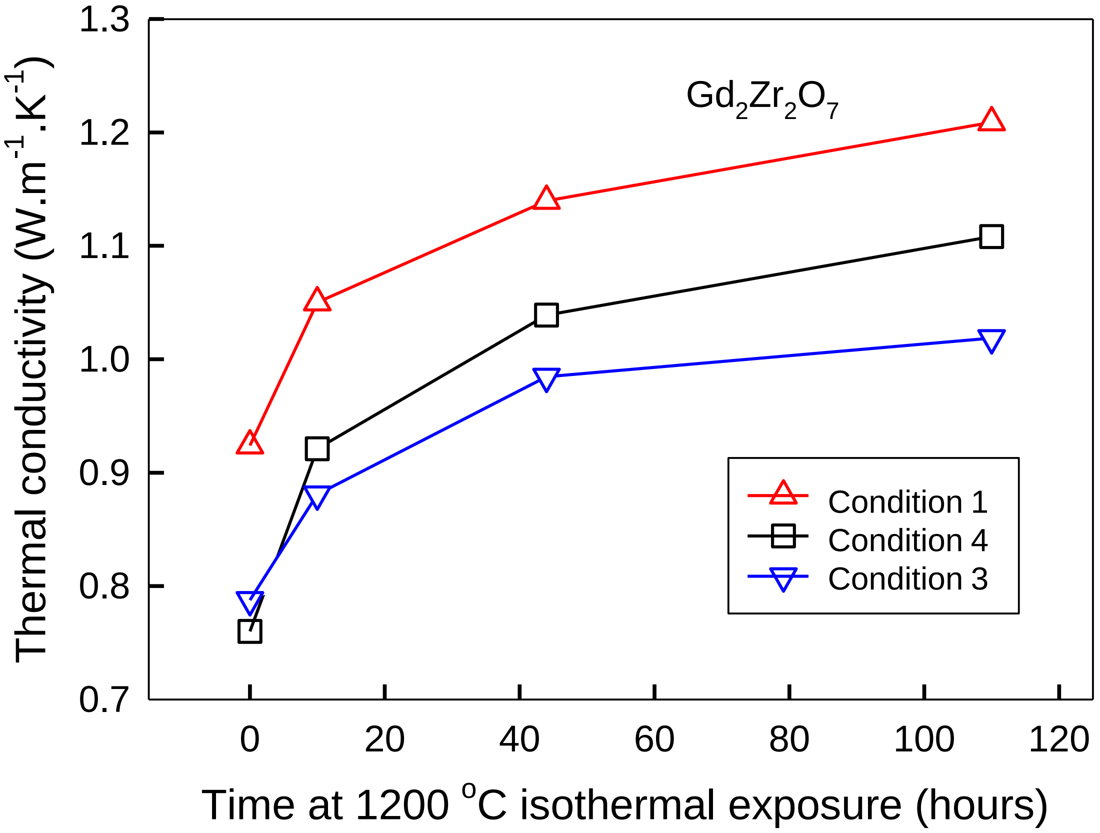
Material choice influences mechanical properties.

IGCC Turbine Coating Properties: Processing Effects

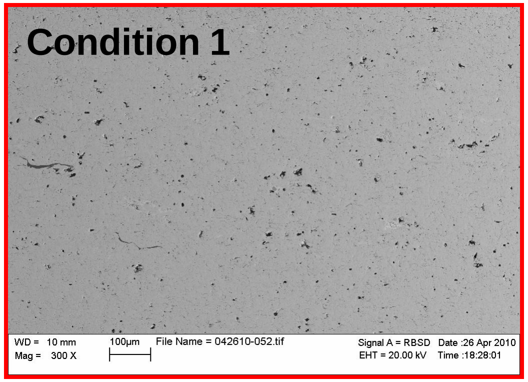
Gadolium Zirconate $Gd_2Zr_2O_7$

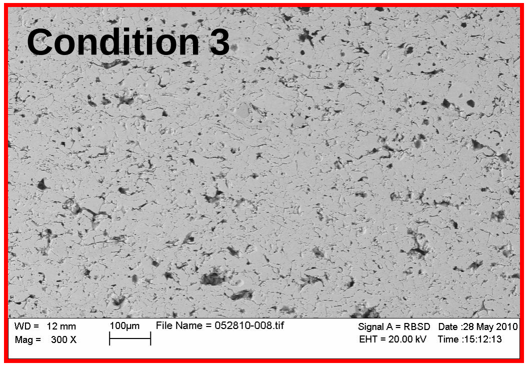


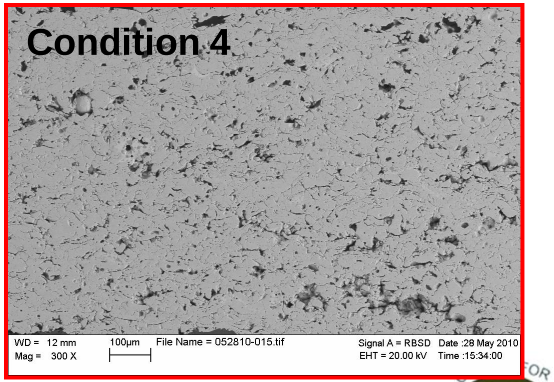
IGCC Turbine Coating Properties: Processing Effects



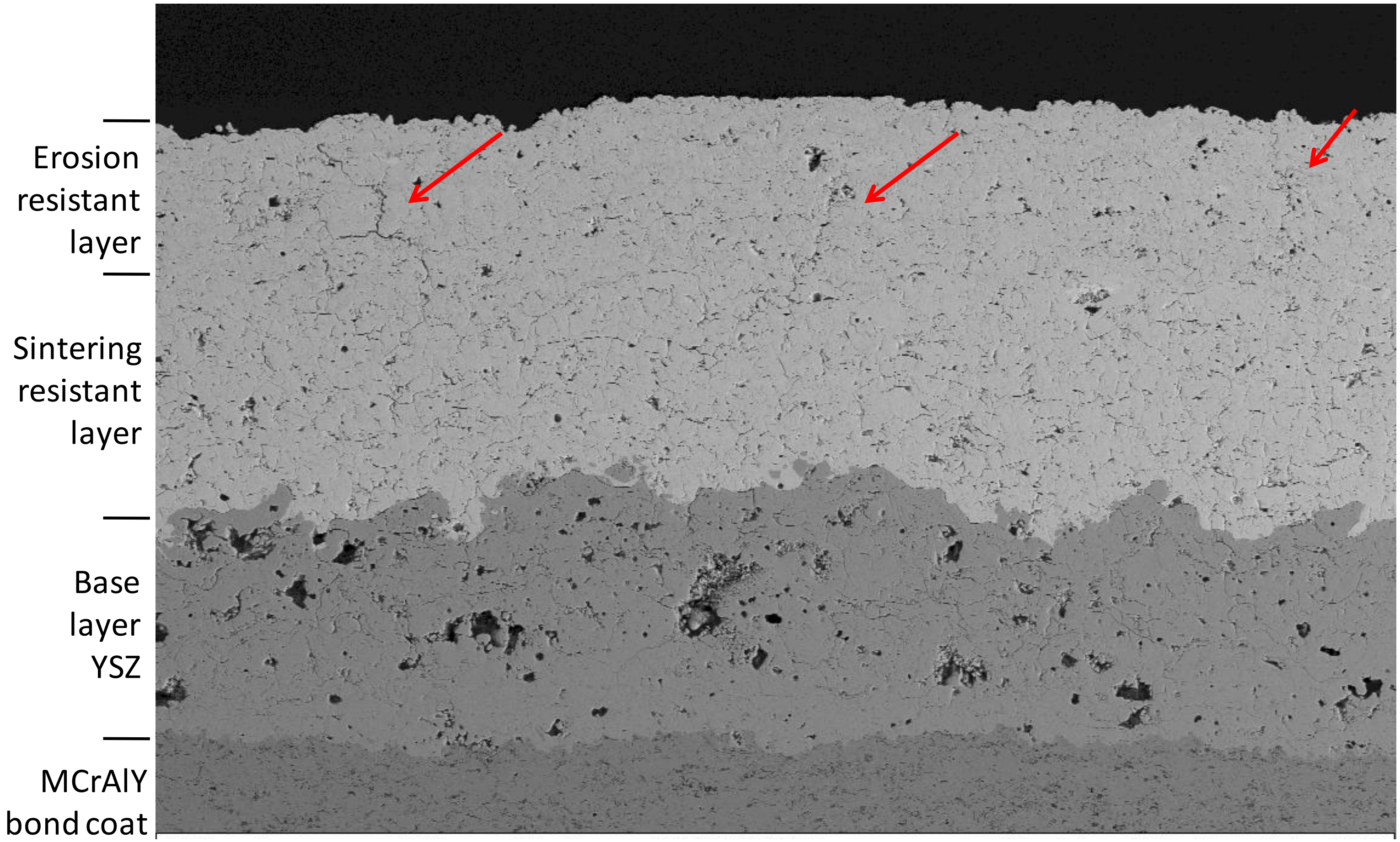
Microstructure influences thermal properties





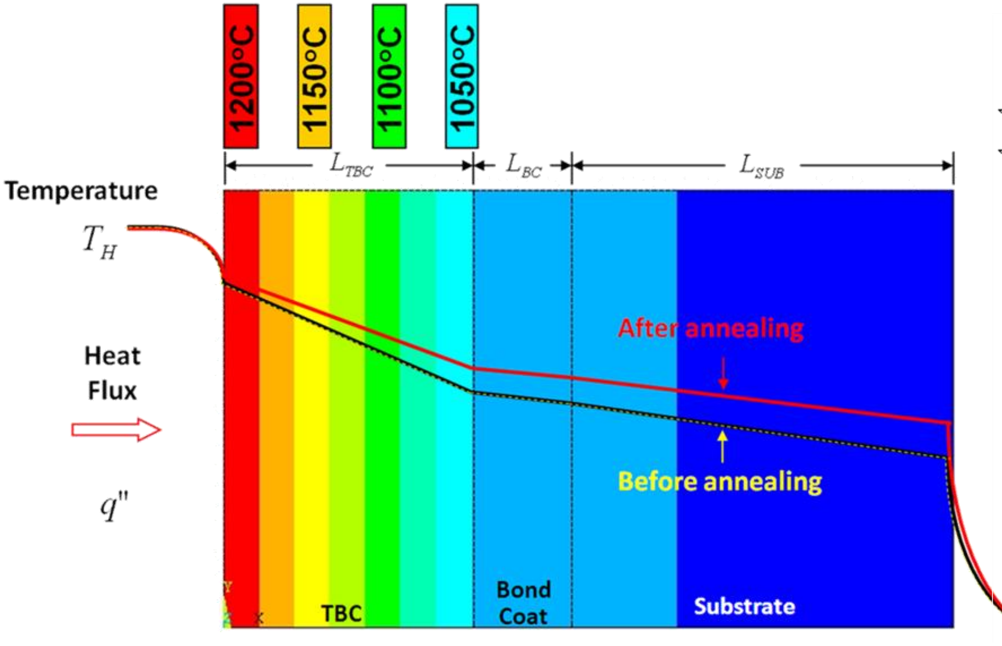


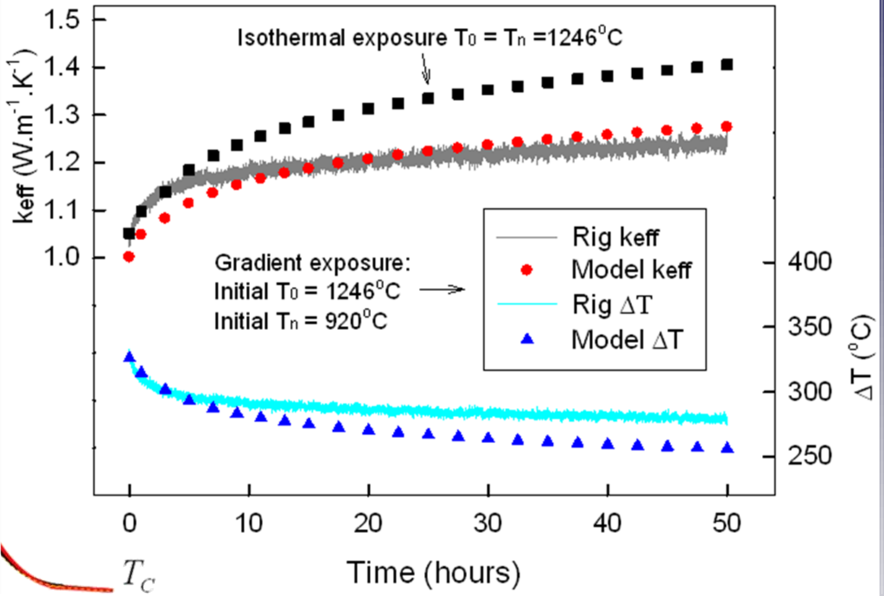
Thermally Sprayed Multilayer TBC



Multilayer coating demonstration

Modeling of Thermal Conductivity Evolution in a Gradient

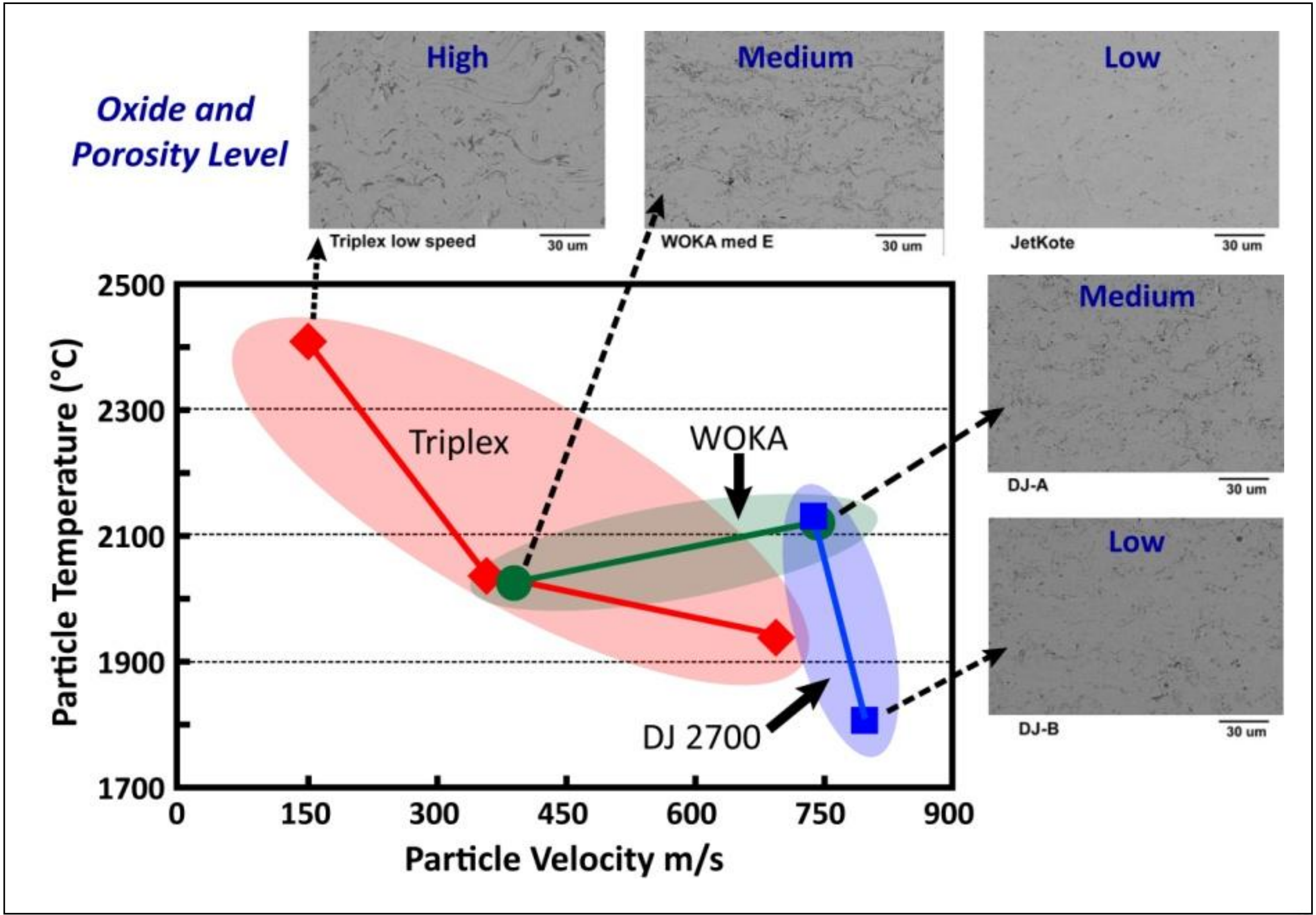




Schematic of the model used to predict temperature gradients in TBCs from thermal conductivity values determined isothermally.

Comparison of isothermal and thermal gradient models with rig test thermal conductivity and temperature change across the TBC data showing good agreement

Processing Effects on HVOF Bond Coats



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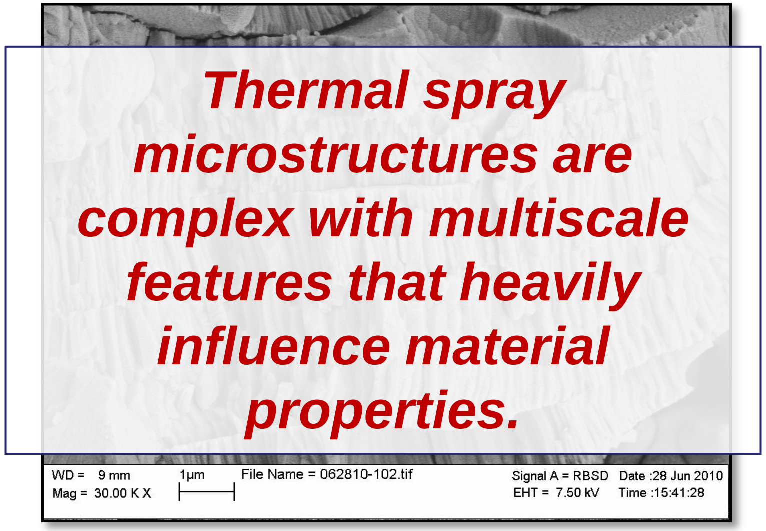
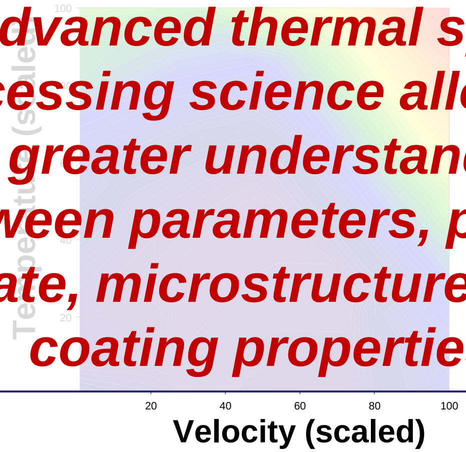
Summary

Advanced Thermal Barrier Coatings for Operation in High Hydrogen Content Gas Turbines



Thermal spray microstructures are complex with multiscale features that heavily influence material properties.

Thermal Conductivity



Advanced thermal spray processing science allows for a greater understanding between parameters, particle state, microstructure, and coating properties.

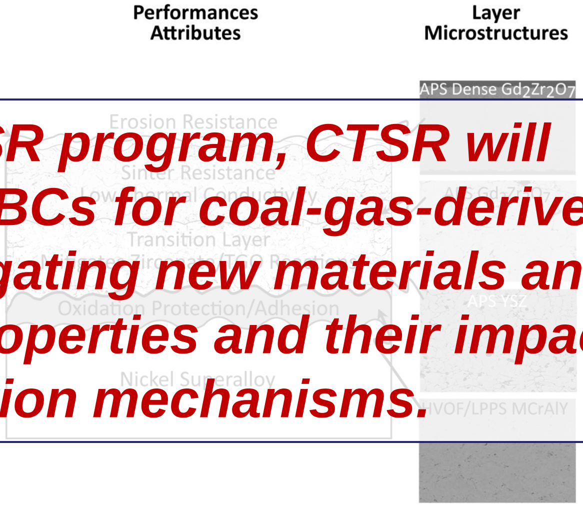
Development/ Evaluation Plan

Erosion Resistant Top Coat
- Produce dense YSZ and $Gd_2Zr_2O_7$ top coat layers
- Evaluate erosion resistance of dense materials
- Develop density-graded structure for top coat

Thermal Barrier Layers
- Determine $Gd_2Zr_2O_7$ properties (thermal/ mechanical) under thermal gradient
- Assess IGCC enviromental effects on degradation of zirconates

Bond Coat
- Evaluate processing (HVOF/LPPS + anneal) effects on microstructure and phase composition of MCrAlY (where M = Ni, Co, Si, Hf, and/or La)
- Determine IGCC environmental effects on long-term oxidation of bond coat materials

System Level
- Determine thermal gradient effects on overall multilayer TBC system
- Evaluate the impact of water vapor on degradation of multilayer TBC



Through the UTSR program, CTSR will assess multilayer TBCs for coal-gas-derived systems by investigating new materials and process-induced properties and their impact on degradation mechanisms.

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