Composites, Ceramics and Coatings: Game-Changing Materials for the Next Generation of Turbine Engines

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A Brief History of Flight and Propulsion

- 1903: Wright Brothers first successfully achieve heavier-than-air flight
  - 30 mph top speed, power/weight ~ 0.05 hp/lb
- WWI – WWII: Reciprocating engines allow faster and higher flight
  - P-51D top speed of 437 mph, power/weight ~ 0.8hp/lb

www.wright-brothers.org

https://en.wikipedia.org/wiki/North_American_P-51_Mustang

A Brief History of Flight and Propulsion

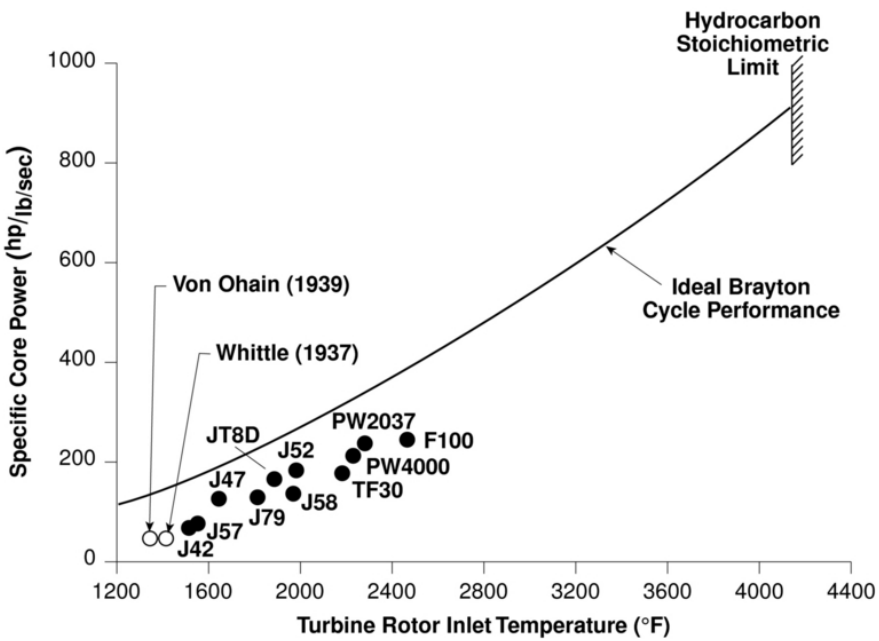
- 1930s: Sir Frank Whittle (GB) and Dr. Hans Von Ohain (DE) independently conceive of the concept of a jet engine
  - Flown 1939-1941, top speed ~350 mph, power/weight ratio of ~ 2.0 hp/lb
- 1960s: Turbofans become the norm for passenger travel for improved efficiency
- 1990s: High bypass (BPR ~ 5.5) turbofans provide even higher efficiencies
  - Reaching a limit on fan size for ground clearance

http://inventors.about.com/library/inventors/bljetengine.htm

http://howthingsfly.si.edu/media/turbofan-engine

Turbine Efficiencies

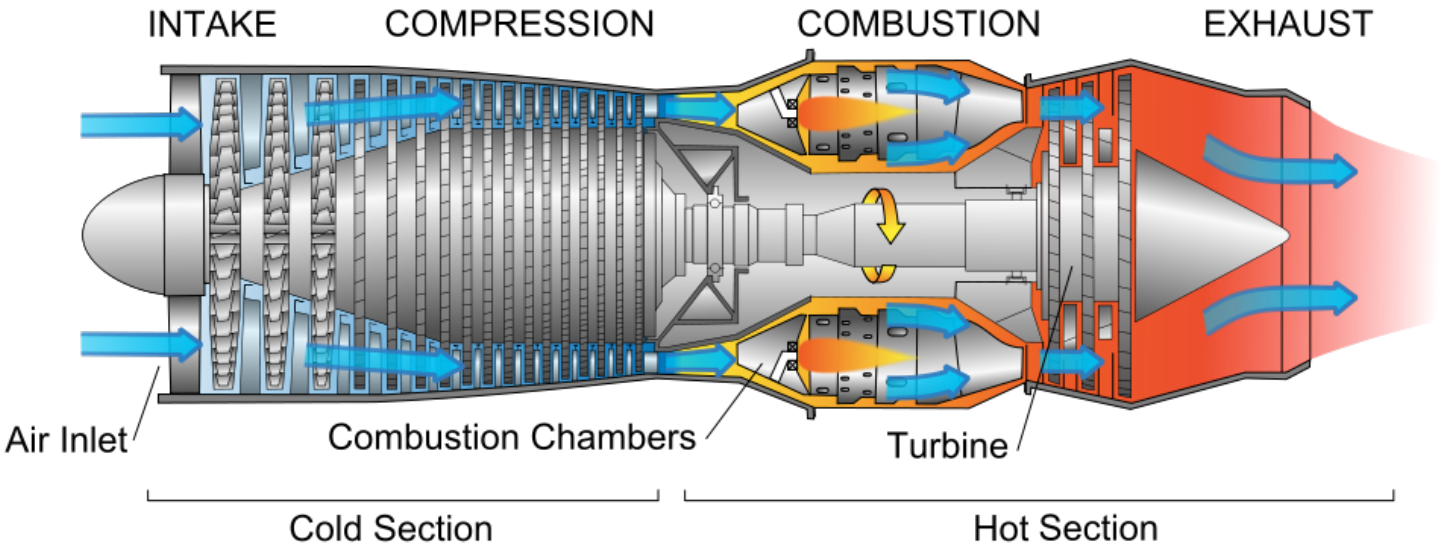
- Turbine efficiencies follow the Brayton cycle
  - Significantly impacted by temperature
- Increasing the inlet temperature results in a increase in engine power/weight ratio
- Engine efficiencies have been increased by 375% in the last 75 years
  - High bypass engines
  - Materials improvements
- Current engines are at or near the fundamental limit of Ni-based superalloys
- New materials are required for the next generation of turbine engines



Koff, “Spanning the World with Jet Propulsion”, AIAA, 1991

Cold Section Materials (Compressor)

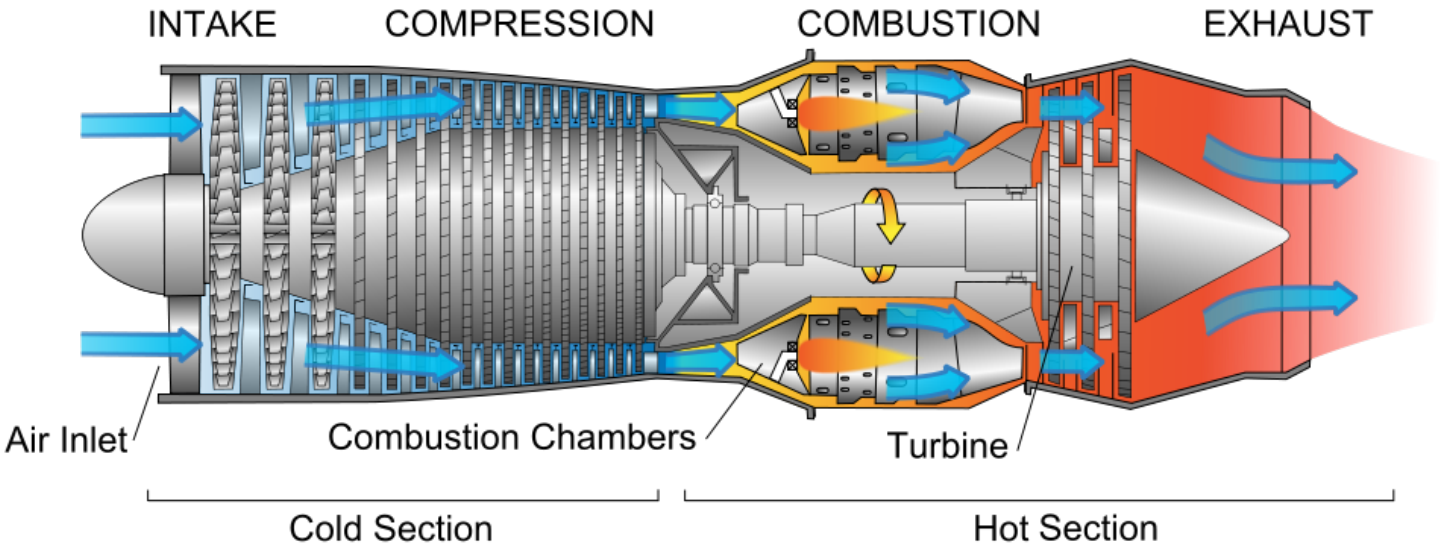
- Intakes air and compresses it for the combustion chamber
- Desire low density (weight), but high stiffness and strength
  - Lightweight alloys (eg. Titanium)
  - Polymer composites with carbon fibers



https://en.wikipedia.org/wiki/Turbine-electric_transmission

Hot Section Materials (Combustor and Turbine)

- Injects fuel and combusts, expanding gas rotates turbine
- Desire low density (weight), high strength, fatigue, oxidation and corrosion resistance
  - Ni-based superalloys
  - Ceramic matrix composites



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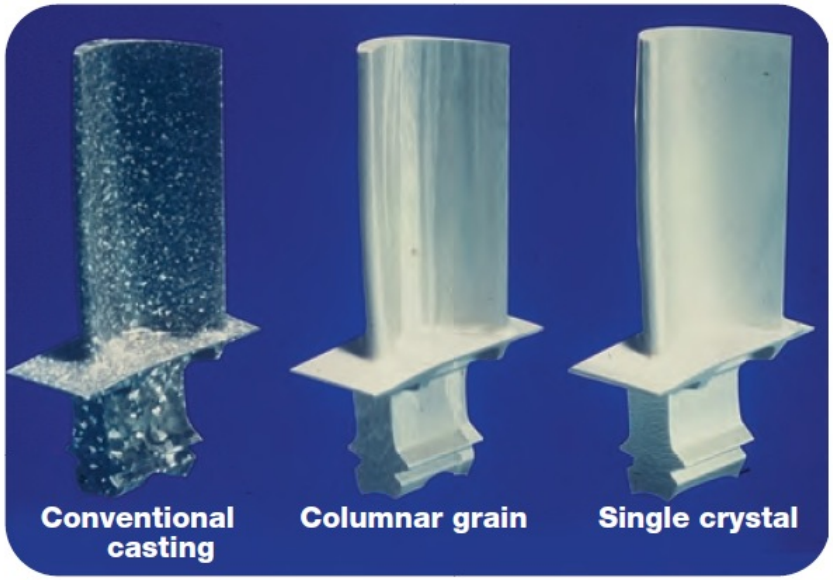
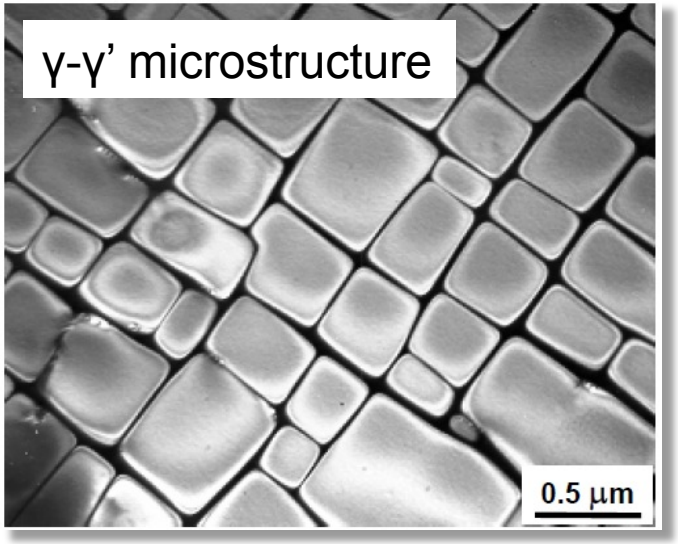
Ni-based Superalloys vs CMCs

Ni-based Superalloys

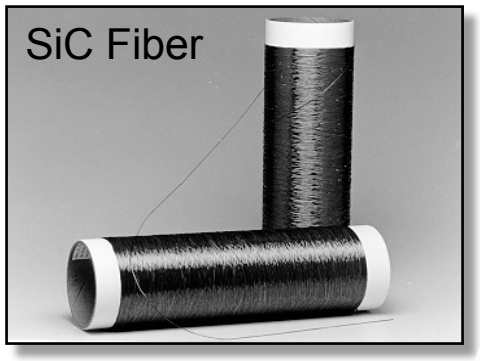
- Ni alloy with Cr, Co, Mo, etc. additives
- Density ~ 9 g/cc
- T_m ~ 1400°C
  - Can be used up to ~0.8T_m
- High strength
- High stiffness
- Enhanced capability with coatings
  - Thermal Barrier Coatings (TBCs)
- Currently make up the majority of engine weight



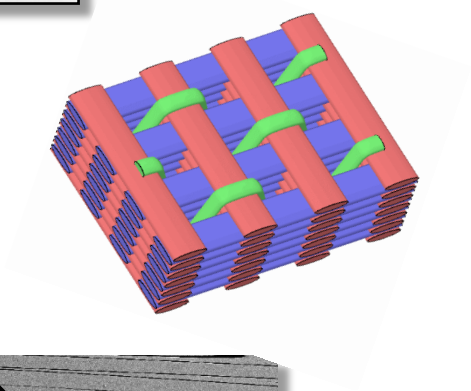


Caron, P. And T. K. Khan, Aerospace Science and Technology, Dec. 1999

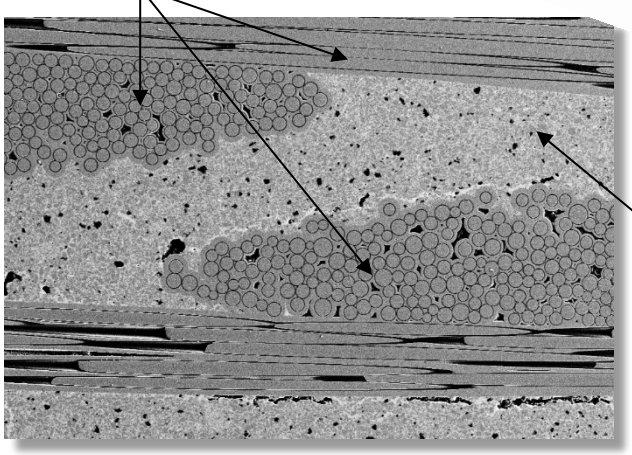
Ni-based Superalloys vs CMCs



2D or 3D weave



SiC Fiber Tows



SiC Matrix

Ceramic Matrix Composites

- Si-based ceramics
  - SiC or Si_3N_4
- Density ~ 3.2-3.4 g/cc
- T_m > 2700°C
- High stiffness
- Low fracture toughness, ductility
- Composite of fibers and matrix
- Require coatings for turbine use
  - Environmental Barrier Coatings (EBCs)
- Currently being incorporated into engines

Ni-based Superalloys vs CMCs

Ni-based Superalloys	Ceramic Matrix Composites
• Ni alloy with Cr, Co, Mo, etc. additives	• Si-based ceramics – SiC or Si_3N_4
• Density ~ 9 g/cc	• Density ~ 3.2-3.4 g/cc
• T_m ~ 1400°C – Can be used up to ~0.8T_m	• T_m > 2700°C
• High strength	• High stiffness
• High stiffness	• Low fracture toughness, ductility
• Enhanced capability with coatings – Thermal Barrier Coatings (TBCs)	• Composite of fibers and matrix • Require coatings for turbine use – Environmental Barrier Coatings (EBCs)
• Currently make up the majority of engine weight	• Currently being incorporated into engines

CMCs: Game Changing Materials

- CMCs offer substantially higher temperature capabilities, reducing cooling requirements and turbine weight, which results in

Reduced Fuel Consumption
Higher thrust/weight ratio
Reduced NOx and CO emissions

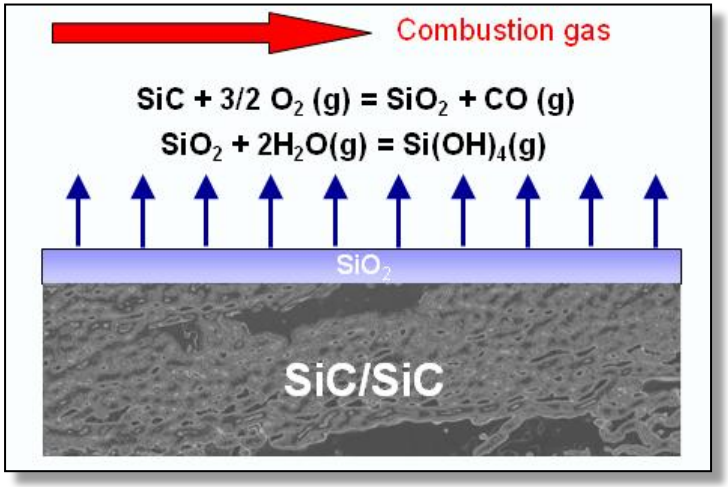
- CMCs are a completely different materials system for turbines and a substantial amount of research is being done to help with scalability and life prediction.

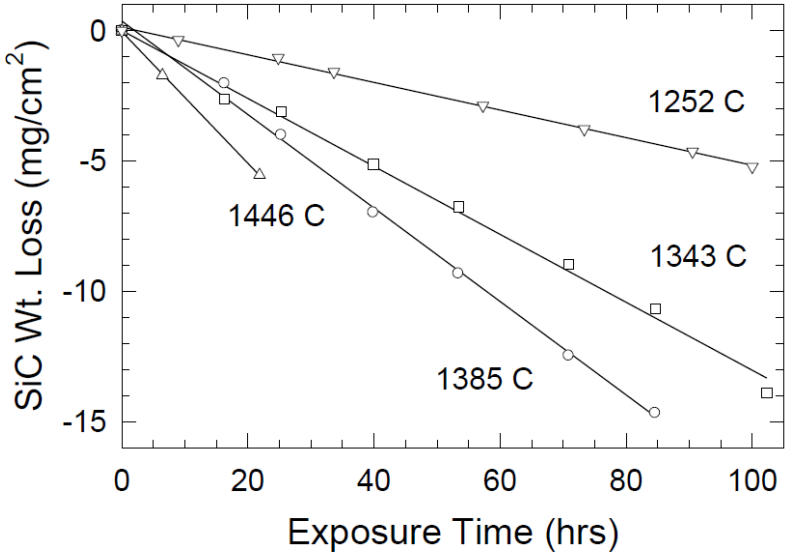
- Despite these requirements, the financial and environmental benefits of these materials are driving the incorporation of these materials into new engines.

- A NASA 2011 study indicated that a 37°C (100°F) increase in material capability could provide ***758 million gallons of fuel savings for the US market*** if the entire fleet (737 class aircraft) was replaced.

Degradation of Si-based Ceramics

- Incorporation of Si-based ceramics into turbine hot section has substantial benefits
- 1990: Observation that SiC undergoes rapid recession in water vapor (Opila/ NASA)
- 1990s: Develop dense oxide coatings to protect against water vapor attack (Lee/ NASA)
- 2000-Present: Development of refractory oxide coatings to minimize water vapor effects: Gov't labs (US, Japan, Germany); turbine companies





Robinson and Smialek, J. Amer. Ceram. Soc 82, 1817 (1999)

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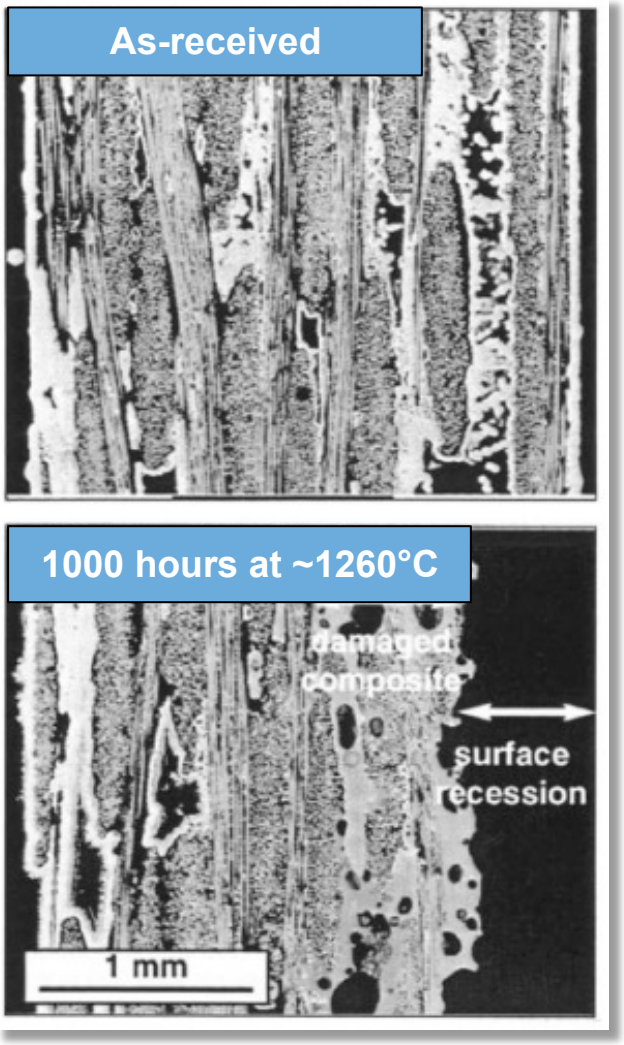
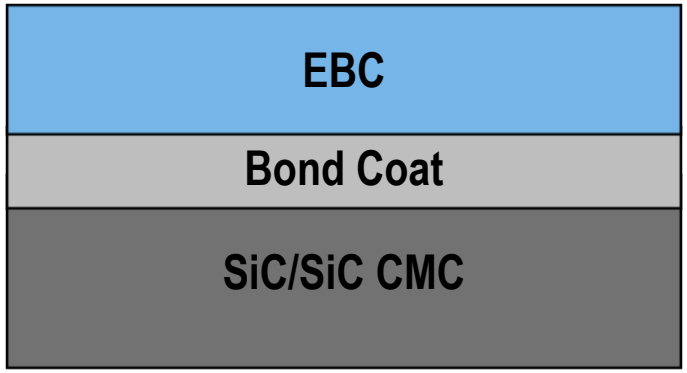


More, K. L. et al., J. Am. Ceram. Soc. 83 [1] 211-213 (2000).

Candidate Coating System Requirements

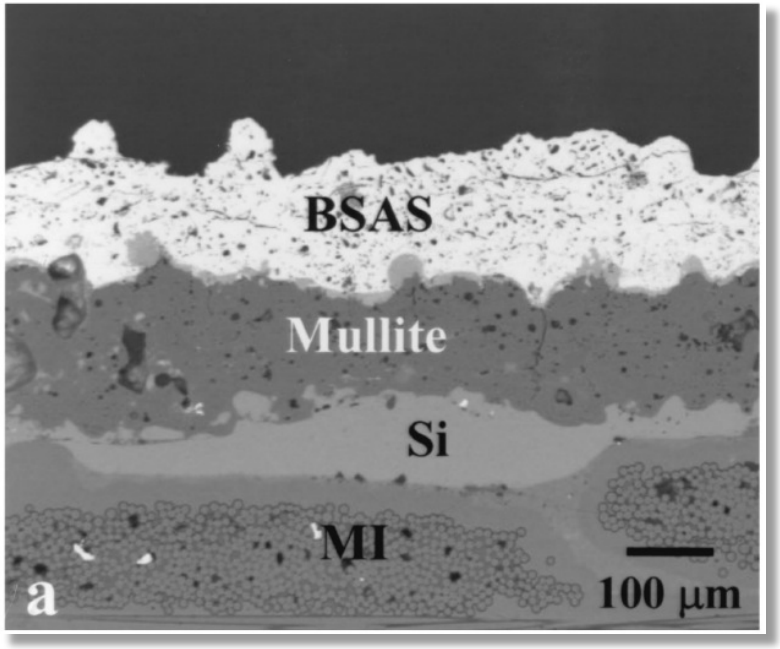
- Environmental Barrier Coating (EBC)
  - CTE match, isotropic CTE
  - Phase stability
  - No reactivity with underlying layers
  - Low reactivity with H_2O
  - Limited cracking/pathways for oxidants



- Bond Coat
  - CTE match
  - Phase stability
  - No reactivity with substrate
  - Adhesion to EBC/substrate

Generation 1 EBCs (1990s)

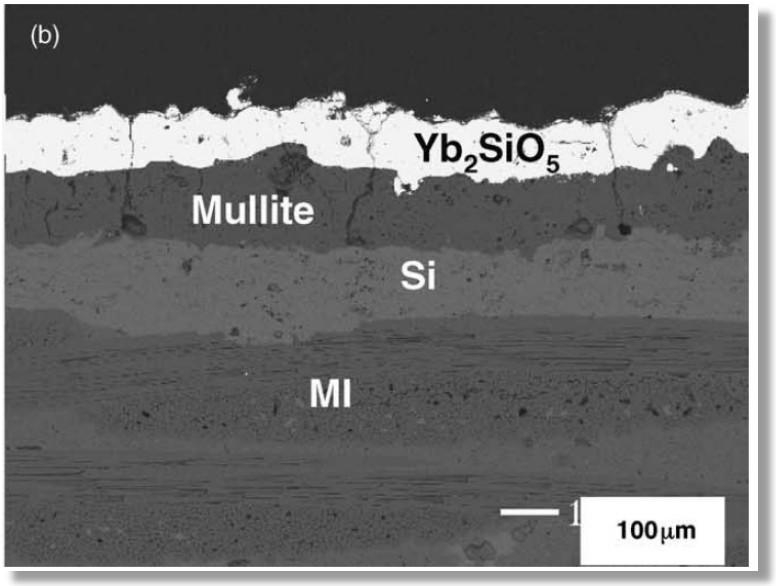
- Developed at NASA GRC in collaboration with GE and P&W
- BSAS/Mullite+BSAS/Silicon multilayer
  - BSAS: $1\text{-}xBaO{\bullet}xSrO{\bullet}Al_2O_3{\bullet}2SiO_2$, $0<x<1$
  - Mullite: $3Al_2O_3{\bullet}2SiO_2$
- Proven up to 15,000h
- Limited use above 1300°C due to BSAS-silica eutectic reaction

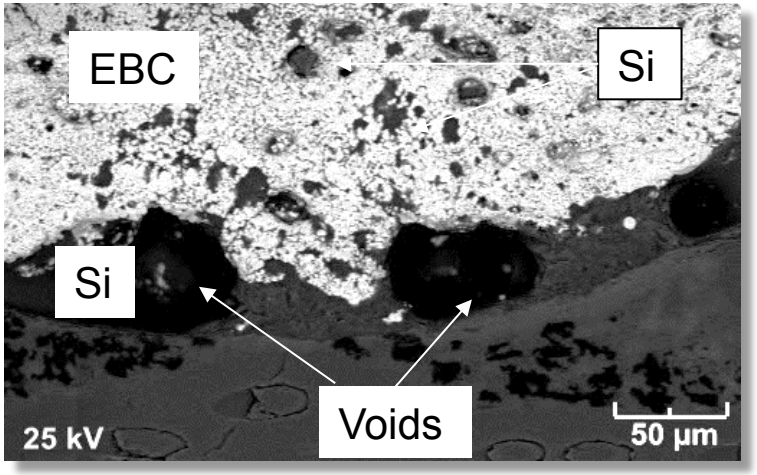


K. N. Lee et al., J. Am. Ceram. Soc. 86 [8] 1299-1306 (2003).

Generation 2 EBCs (Early 2000s)

- 1480°C EBC surface temperature
- 1315°C CMC interface temperature
- Rare earth silicates (RE_2SiO_5, $RE_2Si_2O_7$)
  - RE = Y, Yb, Sc, Lu, etc.
- Higher thermodynamic stability over Gen 1 EBC systems
- Limited by Si bond coat



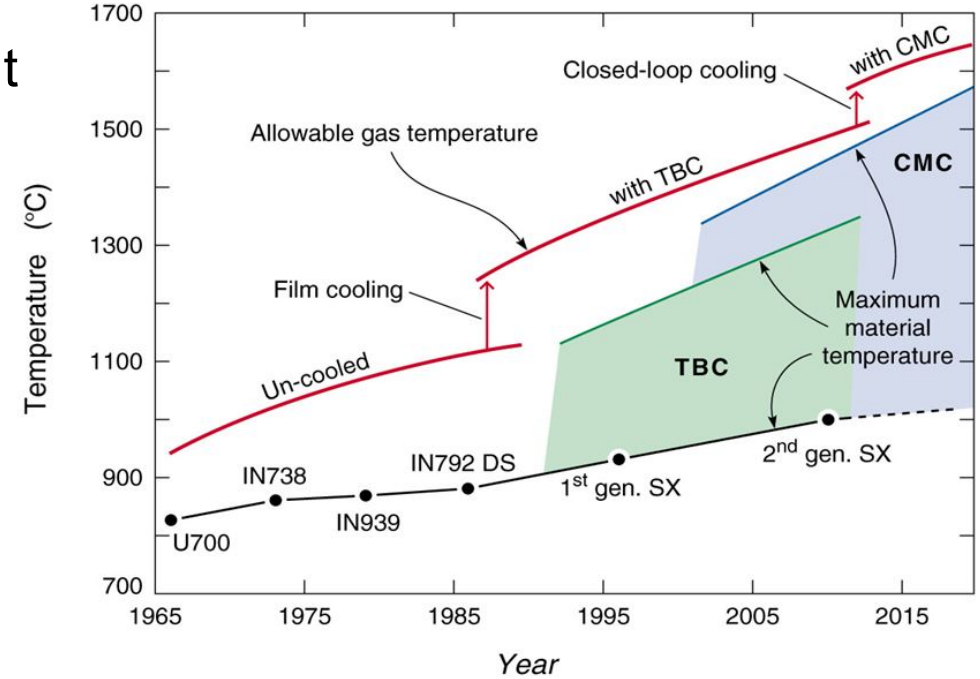


Example of Si bond coat failure (1370C)

K. N. Lee et al., J. Eur. Ceram. Soc. 25 1705-1715 (2005).

Development Beyond Generation 2 EBCs

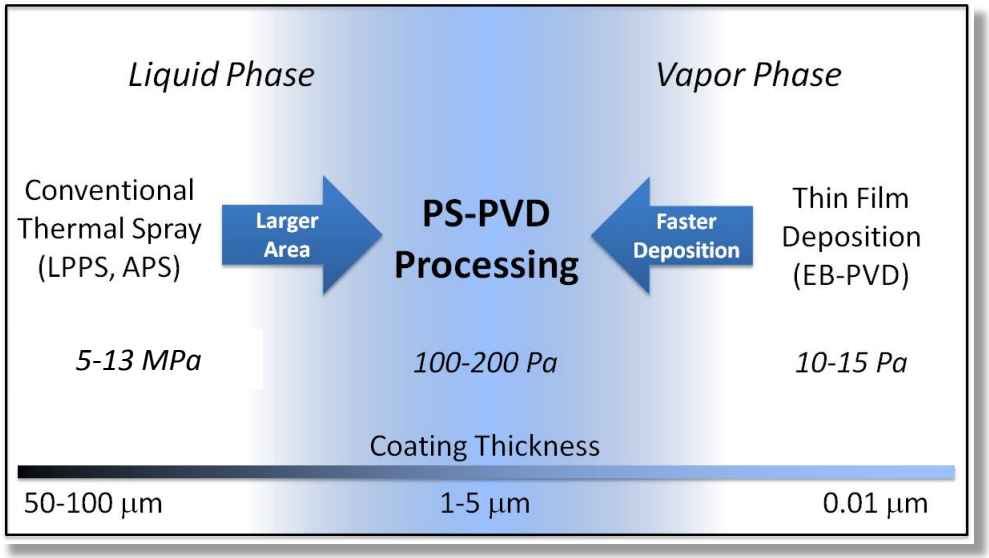
- Target surface temperature of 1480°C and beyond
- Increase interface temperature and target uncooled components
- Must be durable and prime-reliant
  - Impact, erosion, CMAS
  - Life prediction is critical
- Coatings must be smoother and thinner for rotating components
  - New coating methods required



http://www.virginia.edu/ms/research/wadley/high-temp.html

Plasma Spray- Physical Vapor Deposition (PS-PVD)

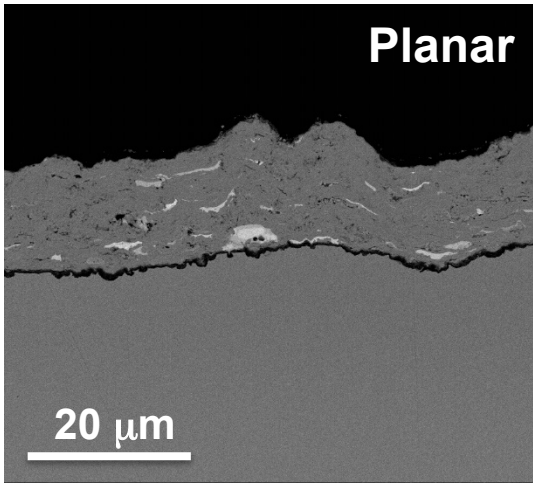
- Developed by Sulzer Metco (now Oerlikon Metco) in the early 2000s

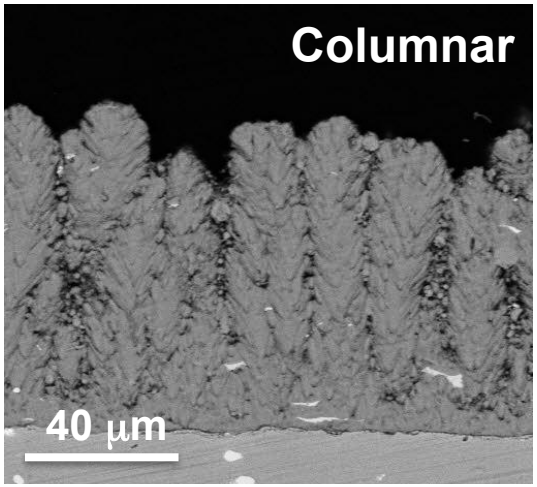


- Several facilities worldwide
  - NASA Glenn, Sandia National Lab, Jülich, Rzeszow University, Wohlen (Oerlikon Metco)

Plasma Spray- Physical Vapor Deposition (PS-PVD)

- Bridges the gap between plasma spray and vapor phase methods
  - Variable microstructure
  - Multilayer coatings with a single deposition
- Low pressure (70-1400 Pa)
  High power (>100 kW)
  - Temperatures 6,000-10,000K
- High throughput[1]
  - 0.5 m^2 area, 10 μm layer in < 60s
- Material incorporated into gas stream
  - Non line-of-sight deposition
- Attractive for a range of applications
  - Solid oxide fuel cells, gas sensors, etc.





[1]A. Refke, et al. *Proc. of the ITSC, May 14-18,* (Beijing, China), 705-10 (2007).

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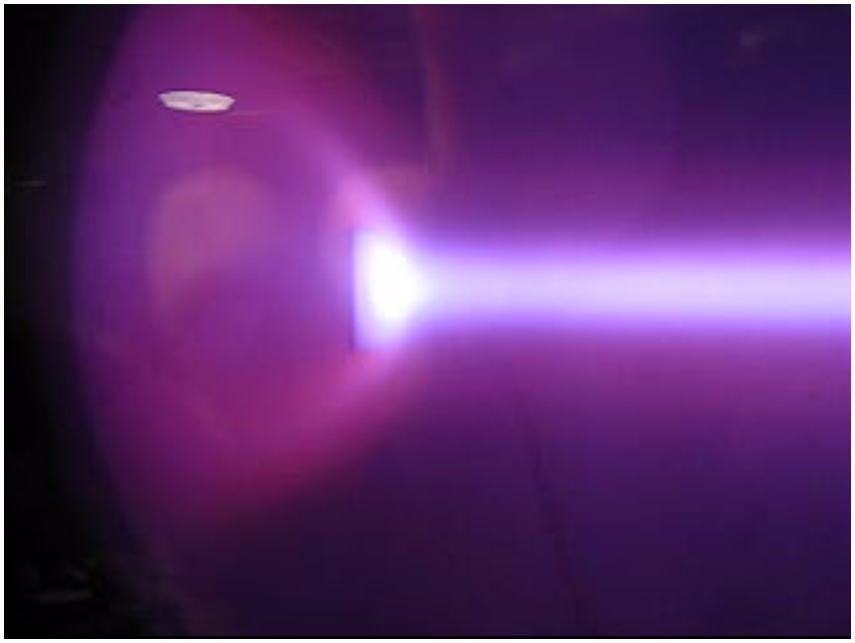
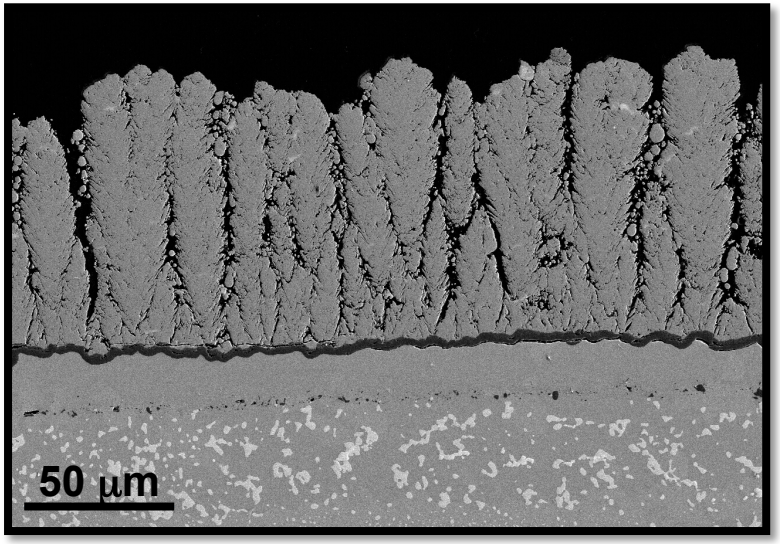


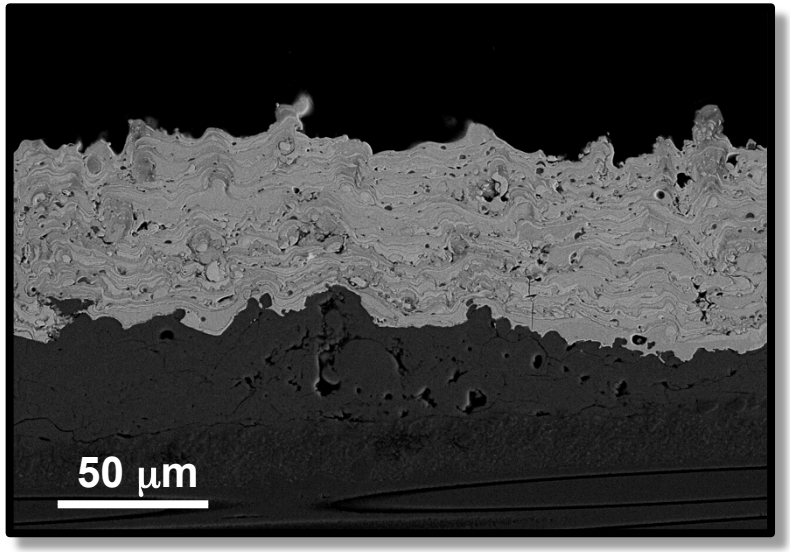
[1]A. Refke, et al. *Proceedings of the International Thermal Spray Conference, May 14-18,* (Beijing, China), 705-10 (2007).

PS-PVD Coatings

- Thermal Barrier Coatings
  - Columnar microstructure
  - High throughput
  - Deposition efficiency similar to EB-PVD
  - Structure-process relationships

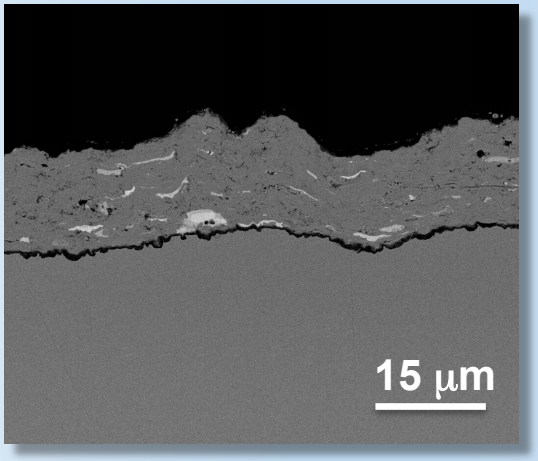


- Environmental Barrier Coatings
  - Planar microstructure
  - Thin, dense layers
  - Enabling technology for CMCs
  - Potential for NLOS

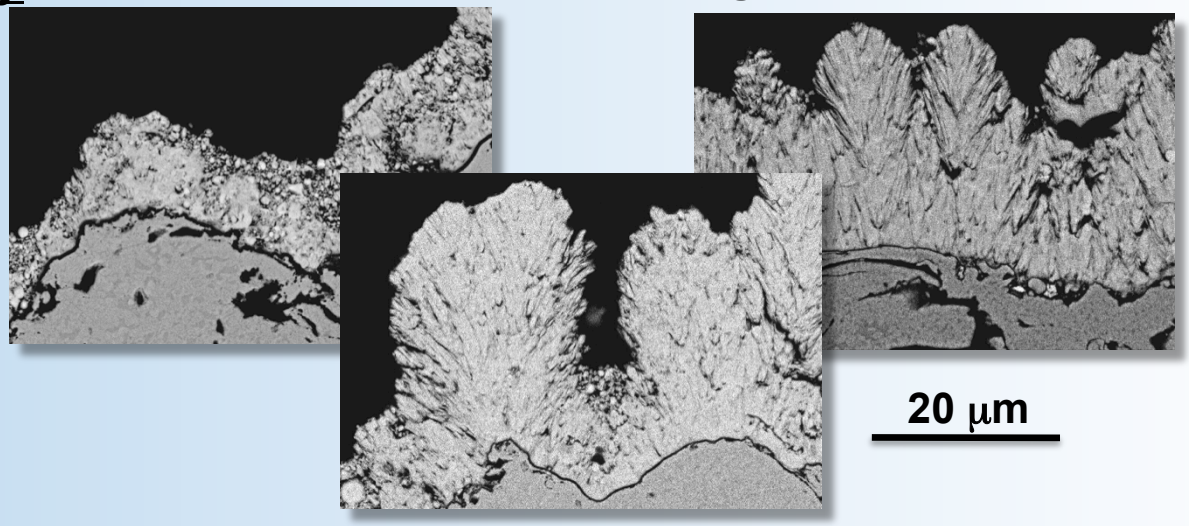


Process-Structure Development

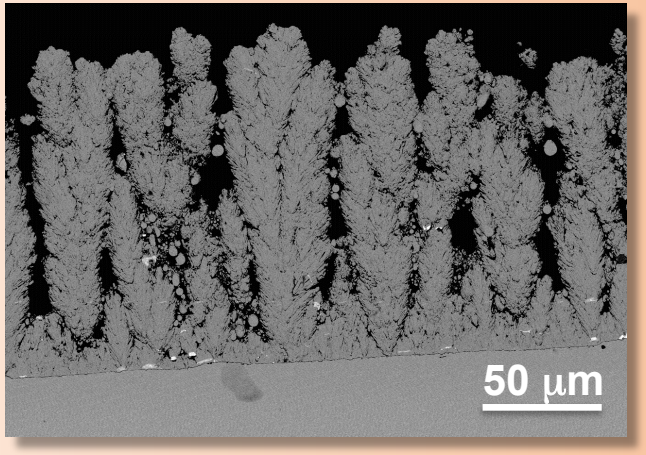
High Pressure, High Velocity

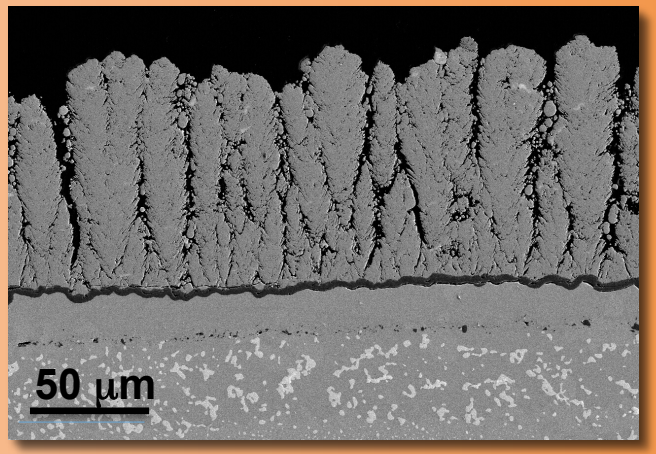


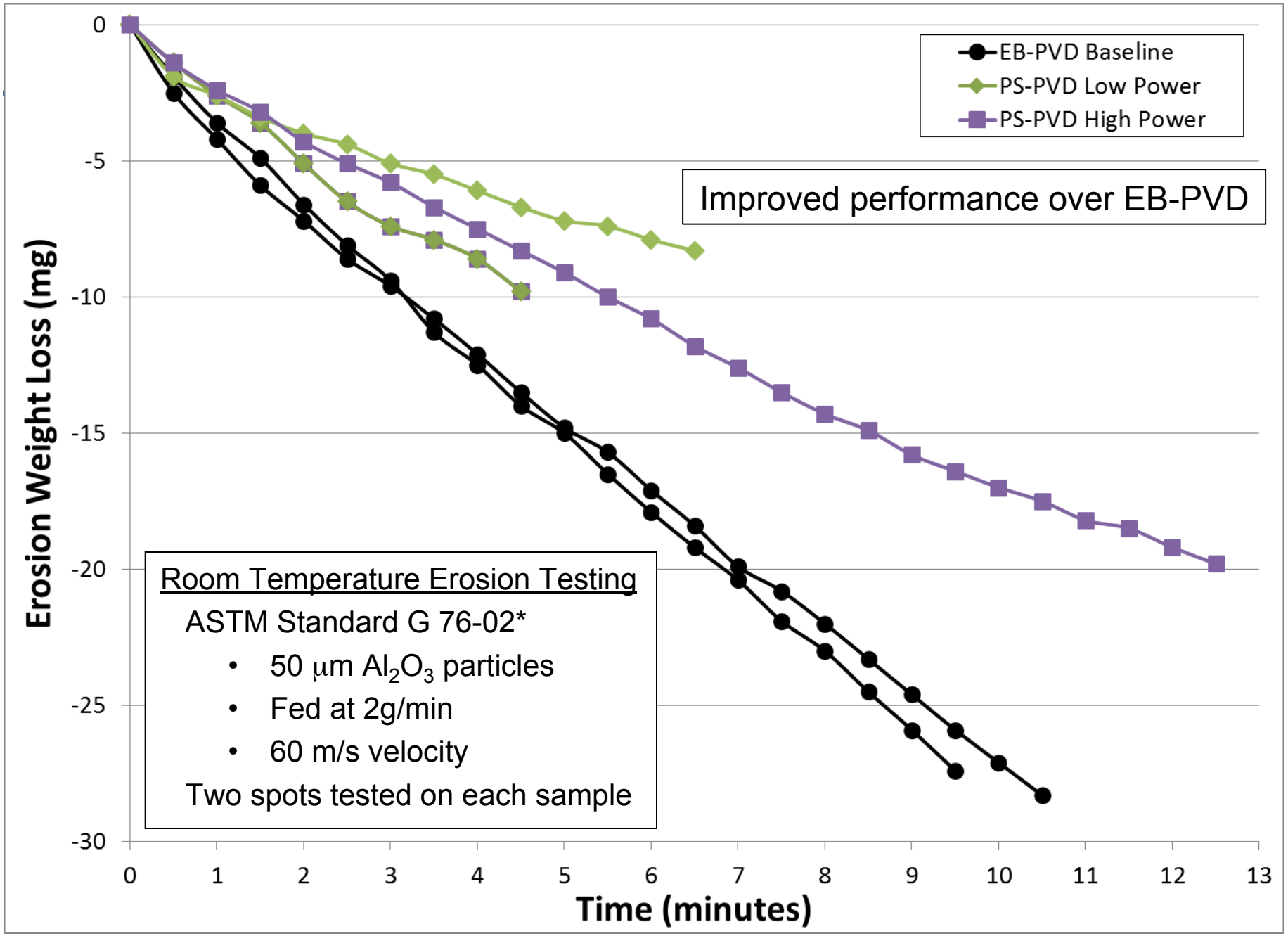
Lower Pressure, Higher Power



High Power, Low Pressure, Low Feed Rate





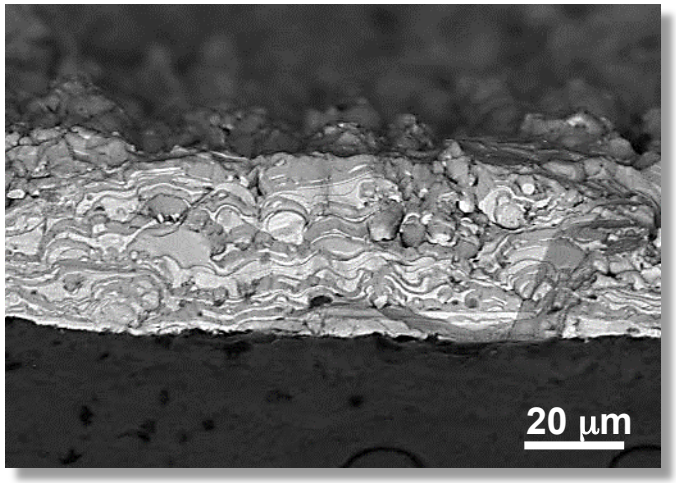


*ASTM Standard G 76-02, "Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets"

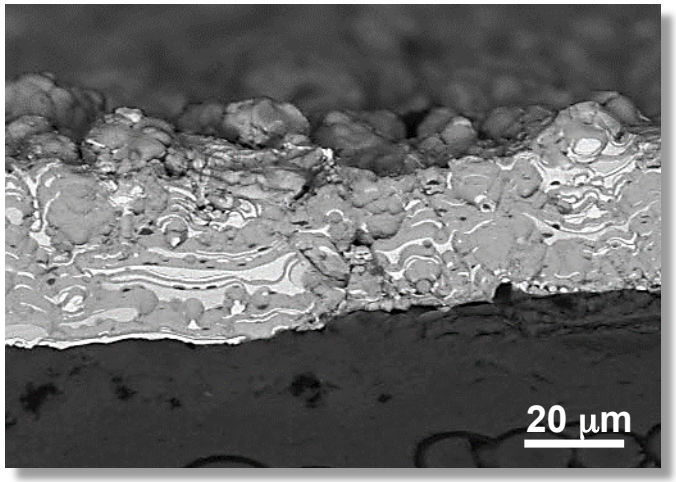
Environmental Barrier Coatings

- EBCs deposited on CMCs
- Processing condition variations can change composition
- Increasing power or standoff increased vapor phase content
- Vapor deposition is ideal for coating complex shapes
- Composition can be changed to idealize volatility, CTE

High liquid (splat), low vapor

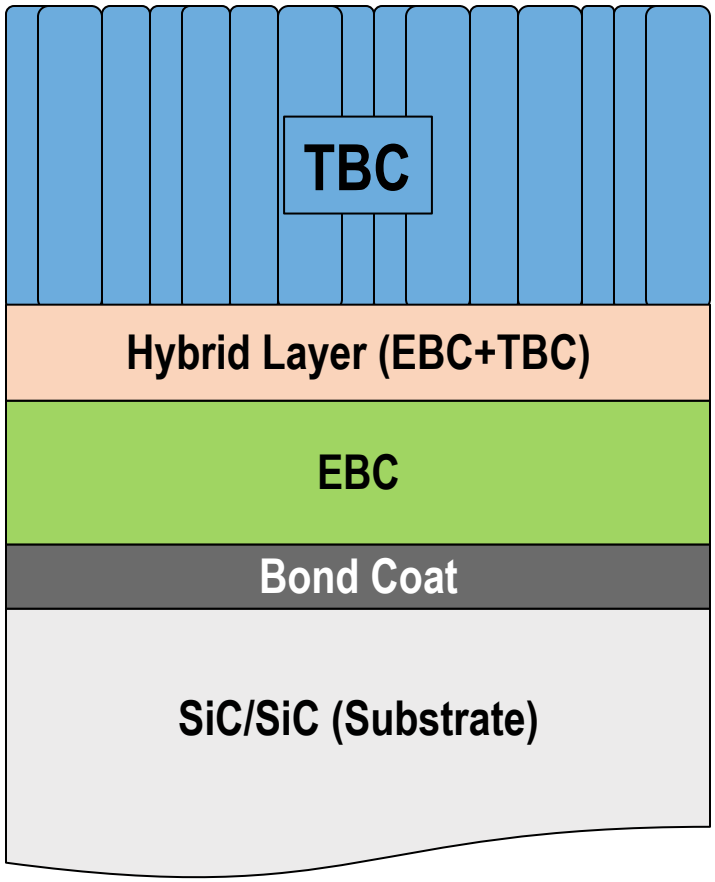


Low liquid (splat), high vapor

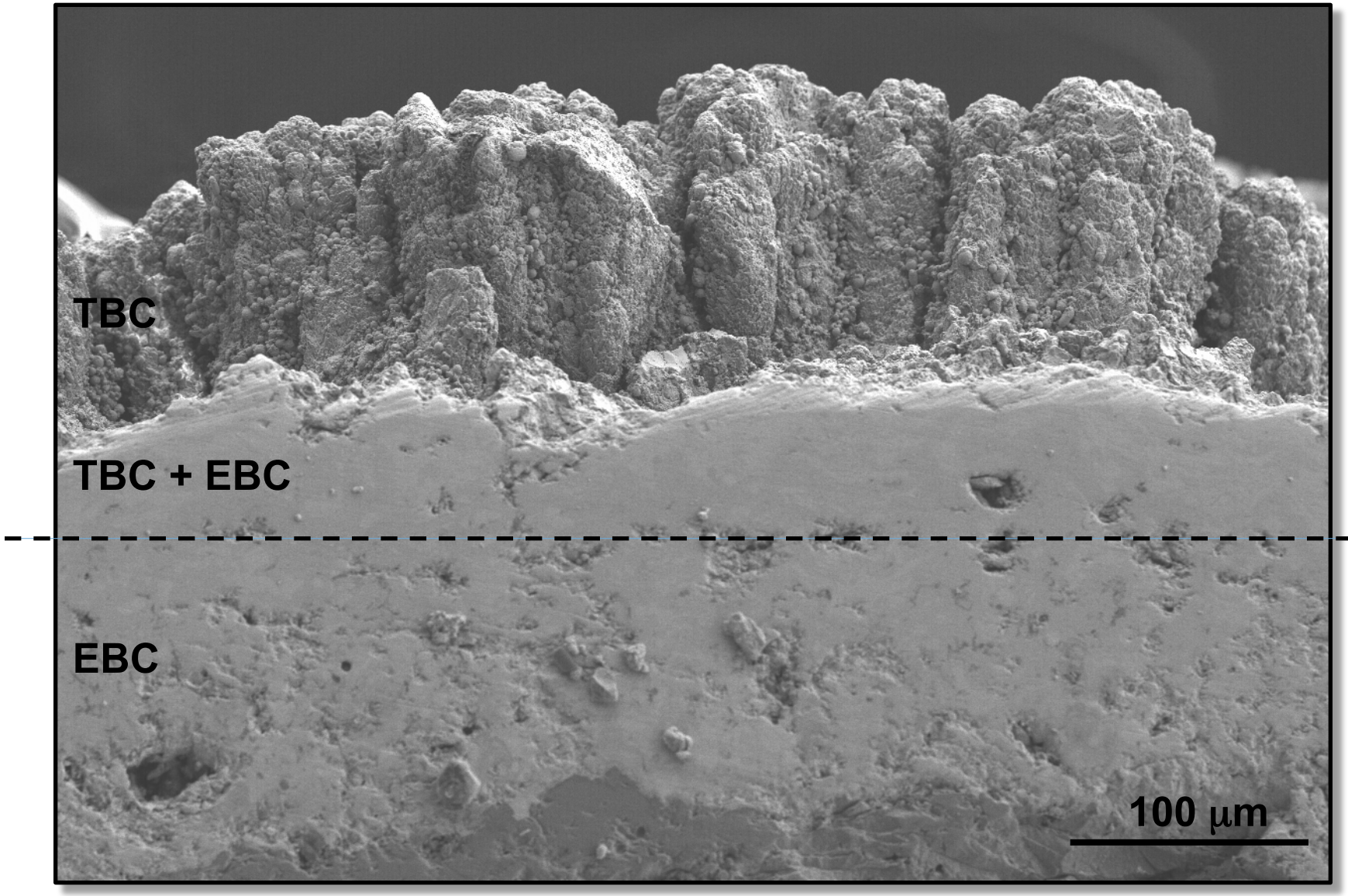


T/EBC Multilayer

- Multilayer “T/EBC” system deposited using PS-PVD system
- TBC topcoat expected to improve water vapor resistance and erosion
- PS-PVD system ideal for blending materials and architectures
- Coatings tested under gradient heating with high heat flux laser

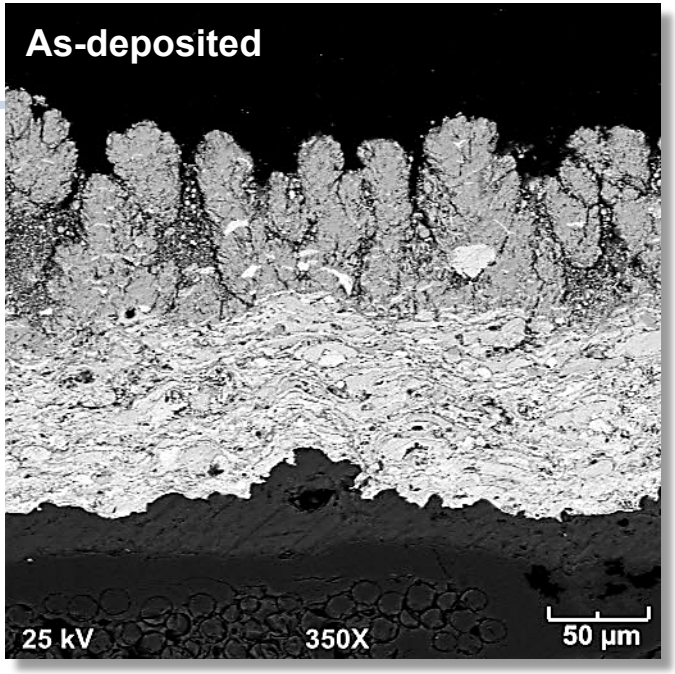


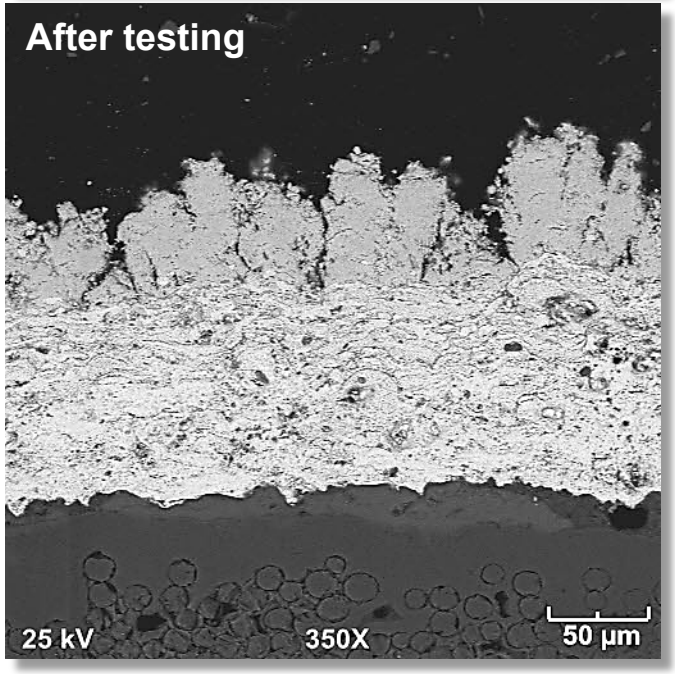
T/EBC Multilayer Microstructure



T/EBC Microstructure

- Surface temperature of 1450°C
  - Thermal conductivity of ~2 W/m•K
- Microstructure showed some changes due to gradient testing
  - TBC topcoat sintered
  - EBC layer did not change significantly
- T/EBC system remained well adhered during testing
- Performance of three-layer system was superior to single layer EBC system
  - Reduced bond coat temperature





Non-Line of Sight (NLOS) Processing

- Turbine engine components require thermal or environmental barriers for enhanced performance

- Components complex in shape or with high aspect ratios, can be difficult to coat with line of sight methods like APS or EB-PVD

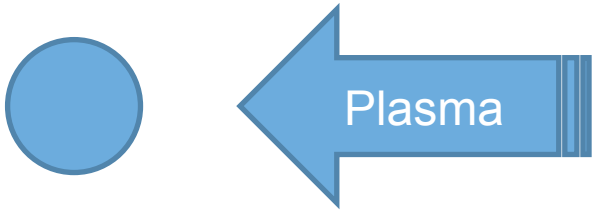
- Applying coatings using non-line of sight (NLOS) processing would provide significant benefits
  - Reduction of processing costs
  - New component designs
  - Improvement in performance

- Plasma Spray- Physical Vapor Deposition (PS-PVD) has been shown to have some NLOS capability for coating components

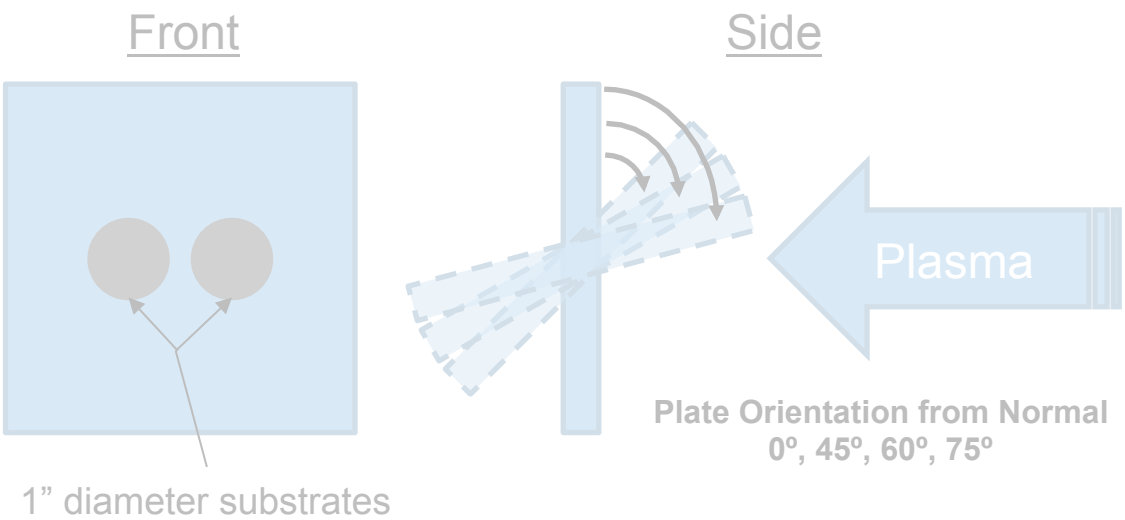
NLOS Experiments

- Static Cylinder

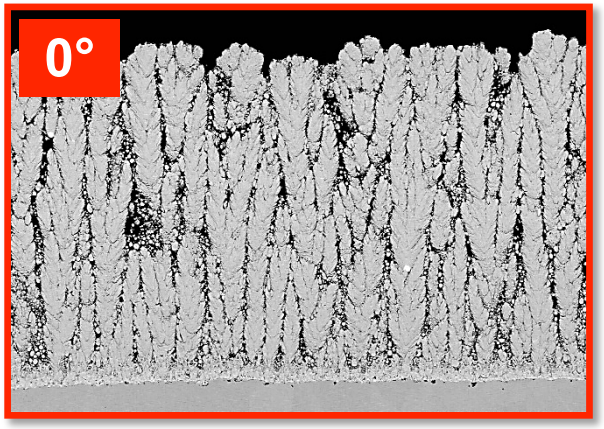
Cylinder Diameters
6.35, 9.53, 12.70, 19.05 mm



- Off-axis deposition



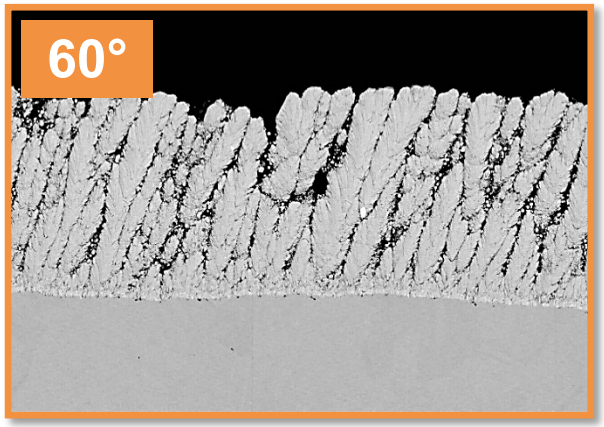
Microstructural Variation



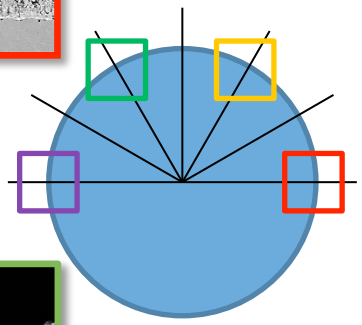
100 μm

19.05mm Diameter
90° Column Angle
255 microns thick

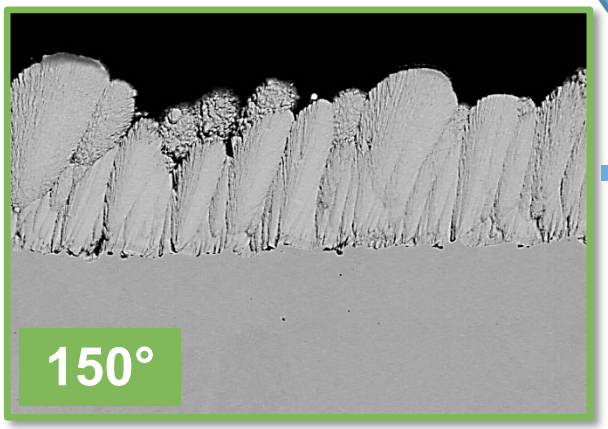
100 μm



19.05mm Diameter
73° Column Angle
157 microns thick



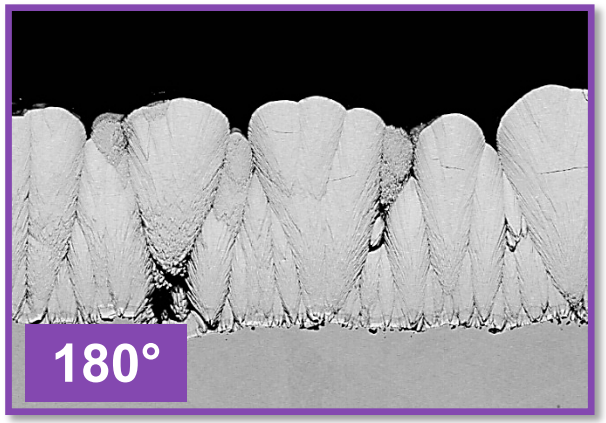
Plasma



50 μm

19.05mm Diameter
74° Column Angle
48 microns thick

50 μm



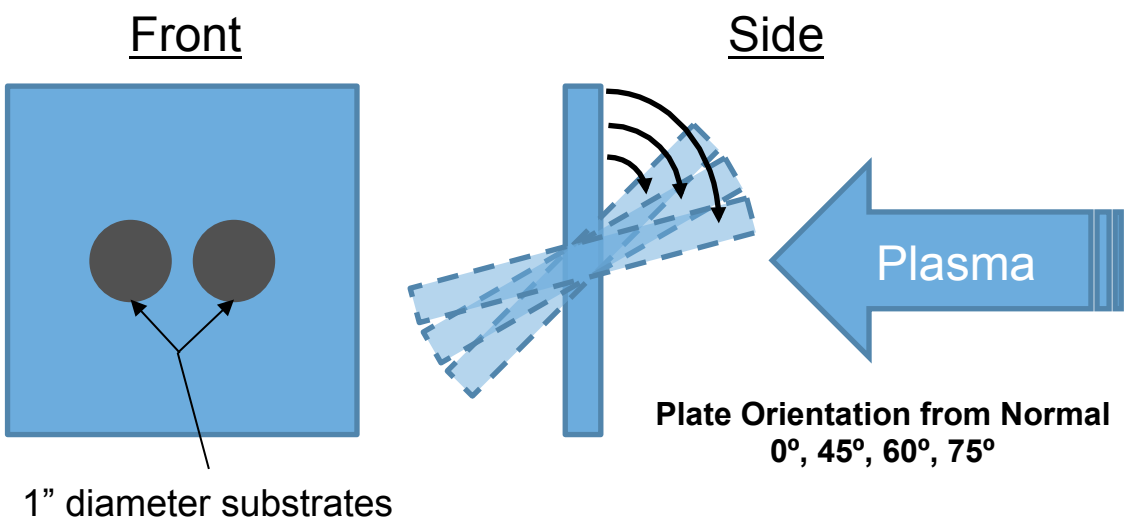
19.05mm Diameter
90° Column Angle
54 microns thick

NLOS Experiments

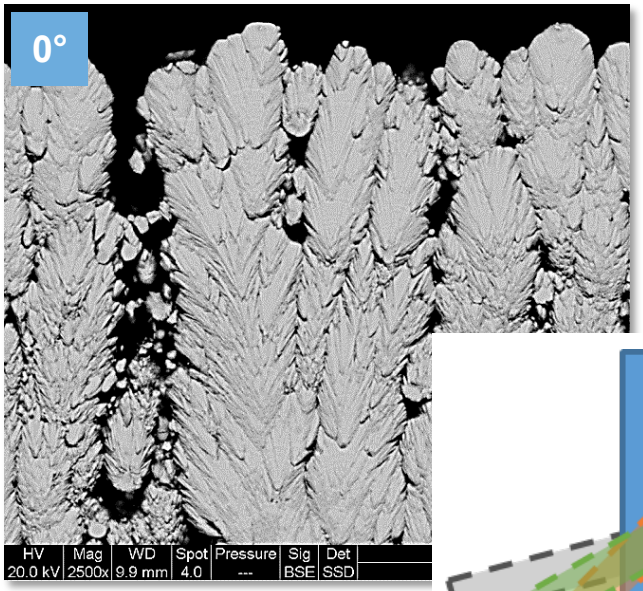
- Static Cylinder

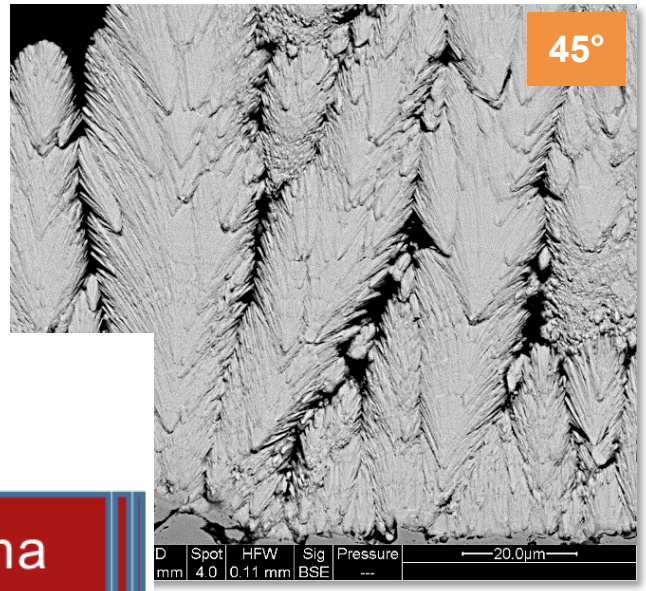
Cylinder Diameters
6.35, 9.53, 12.70, 19.05 mm

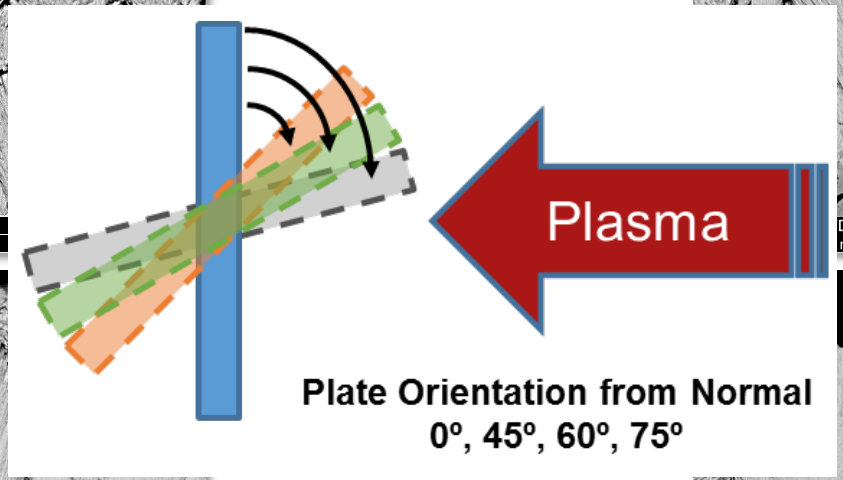
- Off-axis deposition

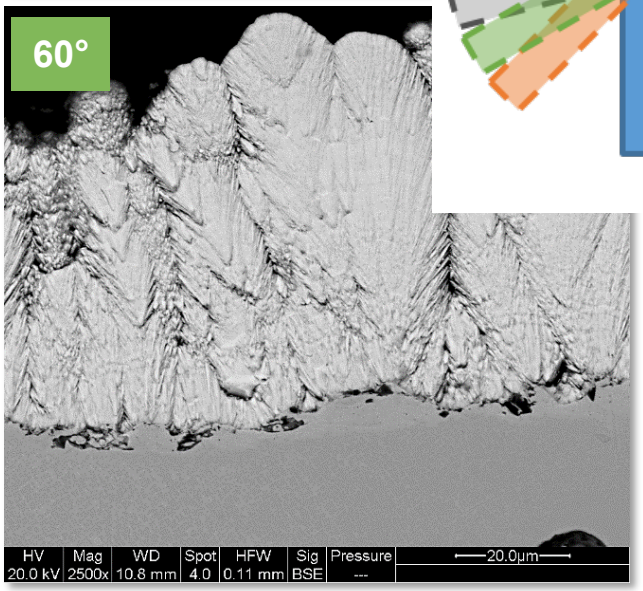


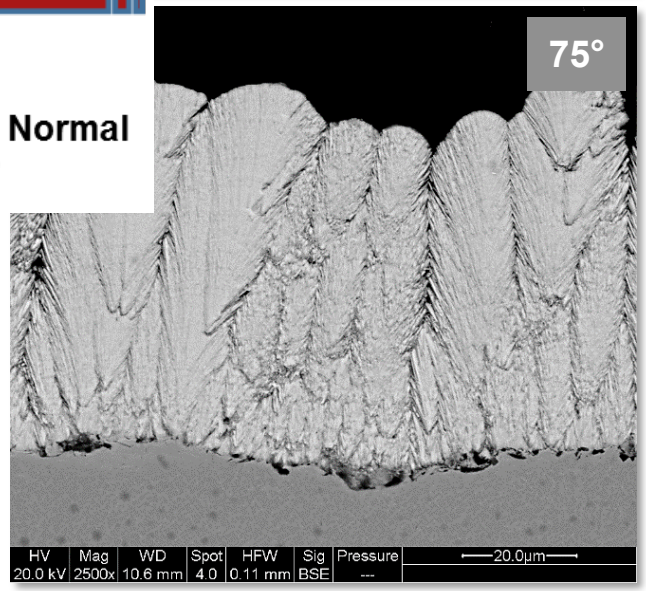
Deposition as a Function of Orientation











Conclusions

- Turbine technology has vastly improved efficiencies over the past 80 years, but there is a persistent demand for higher efficiencies and reduced emissions in next generation engines.

- Incorporation of new material systems such as ceramic matrix composites (CMCs) can provide a step change increase in turbine inlet temperature.

- Environmental Barrier Coatings (EBCs) were developed in the 1990s to allow for the incorporation of CMCs and have laid the foundation for today's protection systems.

- Although significant challenges exist with material fabrication, coating processing, scalability and life prediction, the fuel efficiency and performance benefits of ceramics will drive their eventual incorporation into future turbine engines.

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