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

B. J. Harder
NASA Glenn Research Center, Cleveland OH 44135
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

GE90-115B 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

Cold Section Materials (Compressor)

- Intakes air and compresses it for the combustion chamber
- Desire low density (weight), but high stiffness and strength
  - Lightweight alloys (e.g., 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
Ni-based Superalloys vs CMCs

**Ni-based Superalloys**
- Ni alloy with Cr, Co, Mo, etc. additives
- Density \( \sim 9 \text{ g/cc} \)
- \( T_m \sim 1400^\circ\text{C} \)
  - Can be used up to \( \sim 0.8T_m \)
- 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

Ceramic Matrix Composites
- Si-based ceramics
  - SiC or Si₃N₄
- Density ~ 3.2-3.4 g/cc
- Tₘ > 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

<table>
<thead>
<tr>
<th>Ni-based Superalloys</th>
<th>Ceramic Matrix Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ni alloy with Cr, Co, Mo, etc. additives</strong></td>
<td><strong>Si-based ceramics</strong></td>
</tr>
<tr>
<td><strong>Density ~ 9 g/cc</strong></td>
<td>– SiC or Si₃N₄</td>
</tr>
<tr>
<td><strong>Tₘ ~ 1400°C</strong></td>
<td><strong>Density ~ 3.2-3.4 g/cc</strong></td>
</tr>
<tr>
<td>– Can be used up to ~0.8Tₘ</td>
<td><strong>Tₘ &gt; 2700°C</strong></td>
</tr>
<tr>
<td><strong>High strength</strong></td>
<td><strong>High stiffness</strong></td>
</tr>
<tr>
<td><strong>High stiffness</strong></td>
<td><strong>Low fracture toughness, ductility</strong></td>
</tr>
<tr>
<td><strong>Enhanced capability with coatings</strong></td>
<td><strong>Composite of fibers and matrix</strong></td>
</tr>
<tr>
<td>– Thermal Barrier Coatings (TBCs)</td>
<td><strong>Require coatings for turbine use</strong></td>
</tr>
<tr>
<td><strong>Currently make up the majority of engine weight</strong></td>
<td>– Environmental Barrier Coatings (EBCs)</td>
</tr>
<tr>
<td></td>
<td><strong>Currently being incorporated into engines</strong></td>
</tr>
</tbody>
</table>
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

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

Candidate Coating System Requirements

- Environmental Barrier Coating (EBC)
  - CTE match, isotropic CTE
  - Phase stability
  - No reactivity with underlying layers
  - Low reactivity with H$_2$O
  - 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: $1-x\text{BaO}\cdot x\text{SrO}\cdot \text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$, $0<x<1$
  - Mullite: $3\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$

- Proven up to 15,000h

- Limited use above 1300°C due to BSAS-silica eutectic reaction

Generation 2 EBCs (Early 2000s)

- 1480°C EBC surface temperature
- 1315°C CMC interface temperature
- Rare earth silicates ($\text{RE}_2\text{SiO}_5$, $\text{RE}_2\text{Si}_2\text{O}_7$)
  - 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 (1370°C)
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.

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
  - 0.5 m² 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.

---

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
Improved performance over EB-PVD

Room Temperature Erosion Testing

ASTM Standard G 76-02*

- 50 µm Al₂O₃ particles
- Fed at 2g/min
- 60 m/s velocity

Two spots tested on each sample

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
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

TBC

TBC + EBC

EBC

100 µm
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

  1” diameter substrates

  Plate Orientation from Normal
  0°, 45°, 60°, 75°
Microstructural Variation

19.05mm Diameter
90° Column Angle
255 microns thick

19.05mm Diameter
73° Column Angle
157 microns thick

19.05mm Diameter
74° Column Angle
48 microns thick

19.05mm Diameter
90° Column Angle
54 microns thick
NLOS Experiments

- Static Cylinder
  - Cylinder Diameters: 6.35, 9.53, 12.70, 19.05 mm
  - 1” diameter substrates

- Off-axis deposition
  - Plate Orientation from Normal: 0°, 45°, 60°, 75°
Deposition as a Function of Orientation

Plate Orientation from Normal

$0^\circ$, $45^\circ$, $60^\circ$, $75^\circ$
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.
Acknowledgements

- Mike Cuy (Vantage)
- Scott Panko (Vantage)
- Ed Sechkar (ZIN)
- Joy Buehler (Vantage)
- Don Humphrey (ZIN)
- Dongming Zhu (NASA)

- Mike Schmitt (NASA)
- Kayleigh Reamy (USRP)
- Rick Rogers (NASA)
- Terry McCue (SAIC)
- Bob Pastel (HX5 Sierra)
- Doug Kiser (NASA)

Funding Provided by Fundamental Aeronautics Program and the Transformative Tools and Technologies (TTT) Program