Solid particle erosion of environmental barrier coatings and ceramic matrix composites

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Solid Particle Erosion of Environmental Barrier Coatings and Ceramic Matrix Composites

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Santa Fe, NM

Work performed under NASA's Transformative Aeronautics Concepts Program, Transformational Tools and Technologies Project
Outline

• Solid Particle Erosion (SPE) in Aero-Engines
• SPE Testing / Facility
• SPE in a Melt-Infiltrated SiC/SiC Ceramic Matrix Composite (CMC)
• SPE in a Plasma Spray – Physical Vapor Deposition (PS-PVD) Environmental Barrier Coating (EBC)
• Combined Mechanisms (CMAS + SPE)
• Roadmap for Modeling Efforts
• Conclusions
Solid Particle Erosion in Aero-Engines

- Engine hardware in both commercial and military aircraft can be subjected to surface damage and subsequent material loss due to the repeated impact of small, hard particulates.

- This mode of damage, termed solid particle erosion, can lead to deleterious effects of engine hardware which can reduce overall engine performance and shorten service lifetimes.

- As a result, it is important to characterize and understand the erosion behavior of gas-turbine grade materials.

Erosion damage in hot-section hardware:
Material removal of thermal barrier coating (TBC) and superalloy substrate

Presby et. al. (2020) J. Eng. Gas Turbine Power
Erosion Factors for Gas-Turbine Materials

Operating conditions: combustion environment, temperature, pressure, etc.

Erodent: material (properties), size, shape, etc.

Impact condition: velocity, angle, particle flux, etc.

Coating: EBC, T/EBC, material (properties), microstructure, thickness, etc.

Target/component: geometry, architecture, material (properties), etc.
NASA Glenn Erosion Burner Rig Test Facility

- Modified NASA Glenn Mach 0.3 burner rig with particle injection.
- \( T_{\text{surface}} \sim 300^\circ \text{C} \) to 1400°C
- Particle size: 27-µm to 560-µm – typically Al\(_2\)O\(_3\).
- Impingement angle: 10° to 90°.
- Gas Velocity: Mach 0.3 to Mach 1.0.
  - Particle size/type determines maximum particle velocity.
- Pyrometers and IR cameras.
- Rig optimization through coupled experimental and computational fluid dynamics modeling*.

*Kuczmarski, et. al. (2011) CFD-Guided Development of Test Rigs for Studying Erosion and Large-Particle Damage of TBCs. Modelling and Simulation in Engineering.
Solid Particle Erosion in a Melt-Infiltrated SiC/SiC Ceramic Matrix Composite


Experimental Procedure

Target Material Systems

- Melt-Infiltrated SiC\textsubscript{i}/SiC\textsubscript{m} Ceramic Matrix Composite
  - Hi-Nicalon\textsuperscript{TM} Type S (HNS) fibers
  - Boron nitride (BN) interphase
  - 8 plies
  - 0/90\degree, 2D-woven fiber layup
  - 25.4-mm (1.0-in) diameter by 2.1-mm thick
  - Density = 2.58 ± 0.06 g/cm\textsuperscript{3}

- Monolithic SiC
  - α-SiC (Hexoloy\textsuperscript{®} SA)
  - 25.4-mm (1.0-in) diameter by 3.0-mm thick
  - Density = 3.10 ± 0.02 g/cm\textsuperscript{3}

Test Parameters

- 1200\degree C (2192\degree F) surface temperature
- 150-μm Al\textsubscript{2}O\textsubscript{3} erodent
- 2-g/min feed rate
- Particle velocities: 100, 150, and 200-m/s
- Impingement angle: 30, 45, 60, 75, and 90\degree

\[ v = \frac{\omega L}{\theta} \]

Double disk velocimeter
Results: Cumulative Exposure Curves

- For both materials, a well-defined linear region (steady-state) is observed after an initial, non-linear transient region. Note – linear regression analysis was performed on the last 6 data points of each curve.

- Initial transient region:
  - MI SiC/SiC – high slope
  - α-SiC – low slope (incubation period)

- Greater period required for the build-up of surface / sub-surface damage responsible for material removal in the α-SiC compared to the MI SiC/SiC CMC.
Results: Steady-State Erosion Rate

- The MI SiC/SiC CMC and α-SiC follow a power law functional dependence with respect to particle velocity:
  \[ E = \Phi v^n \]  
  (1)
  \[ \Phi = f(H, K_c, E_m, D_p, \rho_p, ...) \]

- Theoretical erosion models based on lateral crack dominated material removal predict:
  - \( n = 2.44 \) – Quasi-static model\(^1\)
  - \( n = 2.33 \) – Modified quasi-static model\(^2\)
  - \( n = 3.17 \) – Dynamic model\(^3\)

\(^1\)Wiederhorn et. al. (1979) J. Am. Ceram. Soc.

- The MI SiC/SiC CMC and α-SiC exhibit velocity dependence close to that predicted by the quasi-static erosion models.
- Additional work is warranted to understand the effect of other properties (i.e., the constant \( \Phi \)).
- CMC will exhibit local variations in properties due to complex microstructure / architecture (i.e., ‘fiber-rich’, ‘matrix-rich’, interfacial regions).

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Results: Effect of impingement angle

- Assuming that material removal at all impingement angles is through brittle fracture, then the normal (indenting) component of the particle velocity will control the erosion response:
  \[ E \propto (v \sin \alpha)^n \]

- As \( \alpha \) decreases below 60°, the erosion rate becomes increasingly underpredicted suggesting a contribution from the tangential, \( v \cos(\alpha) \), component of velocity.
Results: ‘Isolated’ impact events – MI SiC/SiC CMC

- Some CMC samples were subjected to low levels of erodent (~0.1-g) to better elucidate the material removal mechanisms in the composite material.
- Material removal occurs via lateral cracking in ‘matrix-rich’ regions.
- Both brittle and ductile modes are operative at lower impingement angles, and act jointly to remove material.

\[ \alpha = 90^\circ \] \[ \alpha = 30^\circ \]

- For impact events near fiber tows, regions of exposed, intact fibers are observed.
- Cracking occurs along the ‘weak’ fiber-matrix interface and de-bonded matrix material is removed.
- Observations suggest interfacial strength may be an important parameter for understanding the erosion behavior.
Solid Particle Erosion in a Plasma Spray – Physical Vapor Deposition Environmental Barrier Coating

Journal Publication: Presby, M.J., Harder, B.J. (2021) “Solid particle erosion of a plasma spray – physical vapor deposition environmental barrier coating in a combustion environment,” Ceramics International. Accepted manuscript available on ntrs.nasa.gov
Experimental Procedure

Target Material System

- Ytterbium disilicate (Yb$_2$Si$_2$O$_7$/YbDS) EBC
  - Deposited via plasma spray – physical vapor deposition (PS-PVD)
  - No bond coat
  - SiC Hexoloy SA (α-SiC) substrate
  - Coating thickness: 250µm (average)
  - 25.4 x 25.4 x ~3.25-mm (L x W x t)

<table>
<thead>
<tr>
<th>Mean particle size Al$_2$O$_3$ erodent, $d$ [µm]</th>
<th>Impingement angle, $\alpha$ [deg]</th>
<th>Particle velocity, $v$ [m/s]</th>
<th>Particle kinetic energy, $U_k$ [µJ]</th>
<th>Test Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>90</td>
<td>150</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>135</td>
<td>4.07</td>
<td>1,200</td>
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<tr>
<td>150</td>
<td>90</td>
<td>100</td>
<td>34.90</td>
<td></td>
</tr>
</tbody>
</table>
Results: Normal Impingement

• A well-defined linear region (steady-state) is observed after an initial, non-linear transient region.

• The slope of the transient region is generally higher than in steady-state.
  • Initial erosion rate > steady-state erosion rate.
  • Correlates with initial surface roughness.

• PS-PVD EBC exhibits a power law dependence with respect to $U_K$.
  Dependence is comparable to prediction from quasi-static erosion models for monolithic, brittle solids.
  • $b \approx 1.22$ [Wiederhorn et. al. (1979) J. Am. Ceram. Soc.]
Results: Effect of Surface Roughness

- The initial erosion rate, $E'$, of the PS-PVD EBC exhibits a dependence on initial surface roughness:
  - Initial erosion rate, $E'$, defined as mass loss [mg] after 1-g of exposure.
  - Higher surface roughness results in higher initial erosion rate, $E'$.
  - This behavior is consistent with that reported for TBCs.
Results: Effect of Impingement Angle

- Maximum erosion rate is observed at 90 degrees.
- The erosion rate decreases as the impingement angle decreases from 90 degrees:
  - \( E_{90} < E_{60} < E_{30} \)
- This behavior is characteristic of brittle-dominated erosion behavior.
Results: Erosion Damage Morphology

- **$\alpha = 90^\circ$**
  - Micro-cracking
  - Impact site
  - Scale: 10 μm

- **$\alpha = 30^\circ$**
  - Micro-cracking
  - Impact site
  - Scale: 5 μm
  - Grooves
  - Al₂O₃ particle fragment
  - Scale: 20 μm
  - Groove
  - Scale: 20 μm


Results: Erosion Damage Morphology

- Near-surface cracking generally encompasses single or multiple splats resulting in delamination and subsequent material removal.

\[ d = 27 \mu m \]  \[ d = 60 \mu m \]  \[ d = 150 \mu m \]
### Results: Comparison to Plasma Sprayed EBCs

<table>
<thead>
<tr>
<th>Reference</th>
<th>Temperature [°C]</th>
<th>Particle Type</th>
<th>Particle Size, $d$ [µm]</th>
<th>Impingement Angle, $\alpha$ [°]</th>
<th>Velocity, $v$ [m/s]</th>
<th>Erosion Rate, $E$ [mg/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singh et. al.</td>
<td>90 (vacuum)</td>
<td>$\text{Al}_2\text{O}_3$</td>
<td>63</td>
<td>90</td>
<td>50</td>
<td>1.57</td>
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<tr>
<td></td>
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<td>90</td>
<td>100</td>
<td>9.88</td>
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<td>20</td>
<td>50</td>
<td>0.97</td>
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<td></td>
<td></td>
<td>20</td>
<td>100</td>
<td>4.19</td>
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<tr>
<td>Okita et. al.</td>
<td>1037</td>
<td>Quartz (Silica)</td>
<td>50</td>
<td>80</td>
<td>225</td>
<td>29.57 ($^{1}$39.97$^{2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>225</td>
<td>23.45 ($^{1}$31.61$^{2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>225</td>
<td>9.32 ($^{1}$19.05$^{2}$)</td>
</tr>
<tr>
<td>This study</td>
<td>1200</td>
<td>$\text{Al}_2\text{O}_3$</td>
<td>60</td>
<td>90</td>
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<td>135</td>
<td>10.51</td>
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<td></td>
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<td></td>
<td></td>
<td>150</td>
<td>100</td>
<td>14.95</td>
</tr>
</tbody>
</table>

1Polished - Ra = 0.25
2Unpolished - Ra = 6.1

Combined Mechanisms: CMAS + SPE

Current Research
**Combined Mechanisms: CMAS + SPE**

- In service, a combination of molten deposits (CMAS) adhering and reacting with EBCs, and damage due to solid particle erosion will be observed (e.g., particles may not all be fully molten upon impact).
- A more ‘realistic’ test for CMAS is to inject CMAS in a combustion environment (dynamic loading).
- There is a need to understand the difference between static and dynamic CMAS loading.
- A first step is to separate the mechanisms, and then systematically combine.

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**CMAS (static loading)**

- **CMAS (static) + SPE**
  - ~6 mg/cm²
  - ~18 mg/cm²
  - ~36 mg/cm²

- **CMAS (Dynamic Loading)**
  - 25.4mm Nozzle Diameter
  - Erodent Feed Line
  - CMAS
  - Flame
  - Cooling Air Ring
  - Aperture
  - Burner Nozzle
  - Duct, 300 mm x 26.5 mm ID
  - Burner Bar Test Article

*ASME Turbo Expo 2023 Proceedings (Accepted)*
Future work will begin exploration into the erosion behavior of next-generation HTEBCs.
Conclusions

• The solid particle erosion (SPE) resistance of current generation ceramic matrix composite (CMC) and environmental barrier coating (EBC) materials have been investigated at elevated temperature with respect to particle velocity / kinetic energy, and impingement angle.

• In service, EBC/CMC systems will be subject to a combination of solid and molten particles.
  • Thermomechanical mode – SPE
  • Thermochemical mode – CMAS

• Investigations into combined mechanisms (SPE + CMAS) is on-going.
  • Static vs. dynamic CMAS loading.

• Future, exploratory work on the erosion resistance of high temperature environmental barrier coatings (HTEBCs) is planned.
  • HTEBC target temperature capability is ~ 3000°F.