Materials Opportunities for Aero-propulsion Efficiency

John Sharon
Adv. Materials Group, UTRC
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UTC Business Units.

World-wide leader in Aerospace Industry

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An innovation hub.

A research model that advances science

**Collaboration**
- Partner with UTC business units & external research organizations

**Innovation**
- Expand the boundaries of science & technology through research & innovation

**Customer-centricity**
- Delivers tech options that meet & anticipate customer needs
Fuel costs can widely fluctuate and drive aviation economics and affordability.

- Reduced fuel consumption provides better value for the customer and the environment.
Where Can Materials Help…

Opportunities to influence range (or reduce fuel burn) via

- Reductions in aircraft weight: airframe, wings, turbine, nacelle, etc.
- Improvements in overall turbine efficiency

**Breguet Range Equation**

\[
\text{Range} = \eta h \left( \frac{L}{D} \right) \ln \left( 1 + \frac{W_{\text{fuel}}}{W_{\text{cargo}} + W_{\text{structure}}} \right)
\]

- \( V \) = Velocity
- \( L/D \) = Lift to Drag ratio
- \( W \) = weight
- \( h \) = specific fuel energy
- \( \eta \) = turbine efficiency

Aerodynamics

Empty aircraft weight

Turbine Efficiency

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Turbine Efficiency Opportunities

- Higher temperature materials needed, efficiency gains via:
  - Increasing OPR → increases compressor exit temperature
  - Increasing turbine inlet temperature → material limited
  - Reducing compressor bleed air for turbine cooling

Brayton Cycle Efficiency,

\[
\eta_{\text{thermal}} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{(P_2/P_1)^{\frac{k-1}{k}}} = \frac{W_{\text{net}}}{Q_{\text{in}}}
\]

*adapted from F. Preli, Aero Engine Challenges, ASM Summit 2018

*adapted from Koff, 1991
Light-weighting Opportunities

- *1% reduction in empty aircraft weight reduces fuel burn by 0.725%*
- Ni superalloy accounts for over ~ 40% of the engine weight; noteworthy savings possible from a slight reduction in the density of Ni-alloys

### PW4168 Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Lbs</th>
<th>%</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan</td>
<td>2,658</td>
<td>25.1</td>
<td>Composite, Ti, Al</td>
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<tr>
<td>LPC</td>
<td>670</td>
<td>6.32</td>
<td>Ti, Ni</td>
</tr>
<tr>
<td>HPC</td>
<td>1,161</td>
<td>10.97</td>
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</tr>
<tr>
<td>Burner</td>
<td>521</td>
<td>4.92</td>
<td>Ni Superalloy</td>
</tr>
<tr>
<td>HPT</td>
<td>1,301</td>
<td>12.29</td>
<td>Ni disk + blades</td>
</tr>
<tr>
<td>LPT</td>
<td>2,438</td>
<td>23.02</td>
<td></td>
</tr>
<tr>
<td>Accessories</td>
<td>1,634</td>
<td>15.44</td>
<td>Various</td>
</tr>
<tr>
<td>Other</td>
<td>205</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td><strong>10,588</strong></td>
<td><strong>100</strong></td>
<td></td>
</tr>
</tbody>
</table>


**Data from N+3 Aircraft Concept Designs & Trade Studies Vol. 2, NASA cooperative research agreement NNX08AW63A**
Of Current Interest

- Ceramic Matrix Composites (CMCs)
- High Entropy Alloys (HEAs)
- Additive Manufacturing

<table>
<thead>
<tr>
<th>System</th>
<th>Processing Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Matrix Composites</td>
<td>Melt infiltration, chemical vapor infiltration, polymer infiltration pyrolysis</td>
</tr>
<tr>
<td>Metal Alloys</td>
<td>Wrought, cast, powder metallurgy, additive manufacturing</td>
</tr>
</tbody>
</table>
Ceramic Matrix Composites

Benefits
- Higher T capability than Ni-superalloy (+300°F)
- 1/3 the density of Ni-superalloy
- Several % improvement in specific fuel consumption

Challenges
- Oxidation resistance
- CMAS resistant coatings (EBCs)
- Low ductility
- Cost

EBC (Durability)
SiC Matrix (Strength)
SiC Fiber (Toughness)
IFC (Toughness)

SiC/SiC Turbine Blade & Vane

* slide from F. Preli, Aero Engine Challenges, ASM Summit 2018

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High Entropy Alloys (HEA): 3+ elements present from 5 to 35 at.%

**Benefits**: potential for lower density & higher strength at temperature compared to Ni-superalloy

**Challenge**: a palette of 72 elements results in billions of compositions to consider.

**Potential Solution**: employ machine learning to rapidly search for & identify ideal alloys

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**Figure**: Graph showing the specific strength of different HEA compositions as a function of temperature. The graph includes data points for various HEA compositions, such as AlNbTiV, AlCrMoTi, AlCr1.5NbTiV, AlMn0.5NbTa0.5TiZr, MoNbTaW, and IN718. The x-axis represents temperature in degrees Celsius, and the y-axis represents specific strength in MPa cm² g⁻¹.

**Data Source(s)**
- Senkov et al.; Entropy (2016)
- Senkov et al.; Intermetallics (2011)

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Sarkar et al., Machine Learning-aided Accelerated Discovery of HEA for Turbomachinery Applications. (Oral) In 1st World Congress on High Entropy Alloys, Nov. 2019
Additive Manufacturing

Possibilities to impact parts at the meso-, micro-, & nano-levels.

**Meso**
Potential for new architectures that cannot be cast or machined

- Laser powder bed fusion heat exchanger

*Conformal, lower weight, less bleed air*

**Micro**
Control grain structure for site specific property optimization

- Finer more equiaxed gains for fatigue resistance
- Coarser, columnar grains for creep resistance

**Nano**
New alloys / augment current ones

- Incorporate nano reinforcement particles → enhanced creep resistance


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Enabling Materials Achievements, What's Next?

Propulsion Innovation Enabled by Materials and Processing Technology

J58 Powered SR-71
- DS blades, Cast & Wrought disks, Thermal Spray TBC coatings

JT9D powered Boeing 747
- Single Crystal blades, Powder metal disk, EB-PVD TBC

F100 Powered F-15 / F-16
- Aluminide coatings, PM/fracture tolerant disk

F119 Powered F-22
- LFW Ti IBR, Dual Property Ni Disk, Burn resistant Ti

F135 Powered F-35
- High modulus blade

PW1133G Powered A320neo
- Hybrid metallic airfoils, γ-TiAl blades

*from F. Preli, Aero Engine Challenges, ASM Summit 2018

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New Engine Architectures: Electric & Hybrid Electric

- Storage in current batteries insufficient for long range (regional & commercial) flights. Turbines working in concert with electric motors may enable more efficient systems.

Turboprop optimized for cruise, electric motor assists takeoff & climb → ~30% reduction in fuel for a 1 hr flight

https://utap.utc.com/our-projects/project-804

*adapted from F. Preli, Turbomachines for Clean Power and Propulsion Systems, ASME Turbo Expo, 2019
Materials innovation needed to improve turbine efficiency and reduce fuel burn.

Increasing efficiency requires increasing compressor exit and turbine inlet temperatures while reducing structural weight.

Additive manufacturing offers opportunities for unprecedented design complexity and microstructure control.

“Near” term electric propulsion concepts likely to require gas turbines to work in concert with battery powered motors.
Thank you.