Additive Manufacturing of Functionally-Graded Refractory Metal-Ceramic Structures using the Electron Beam Sintering (EBS) Process

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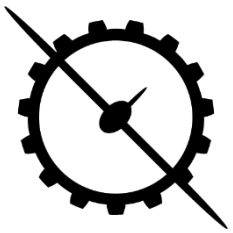


Motivation

- Enabling the efficiency of gas turbines, which introduces significant reductions in wasted energy and carbon emissions
  - power generation
  - aviation industries
- Developing novel ultrahigh-temperature materials in combination with compatible coatings
  - Be able to operate continuously in extreme environments, enabling gas turbine inlet temperatures of 1800 °C or higher
  - Complex geometries that can be seamlessly integrated into the system design

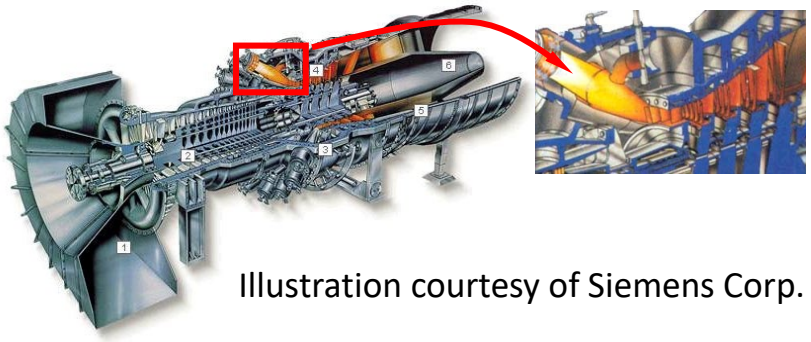
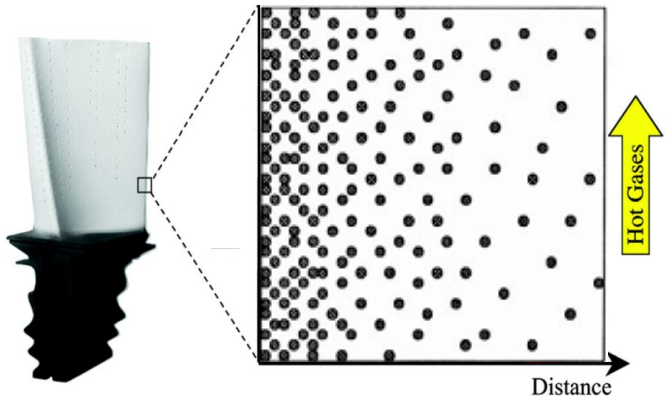


Illustration courtesy of Siemens Corp.

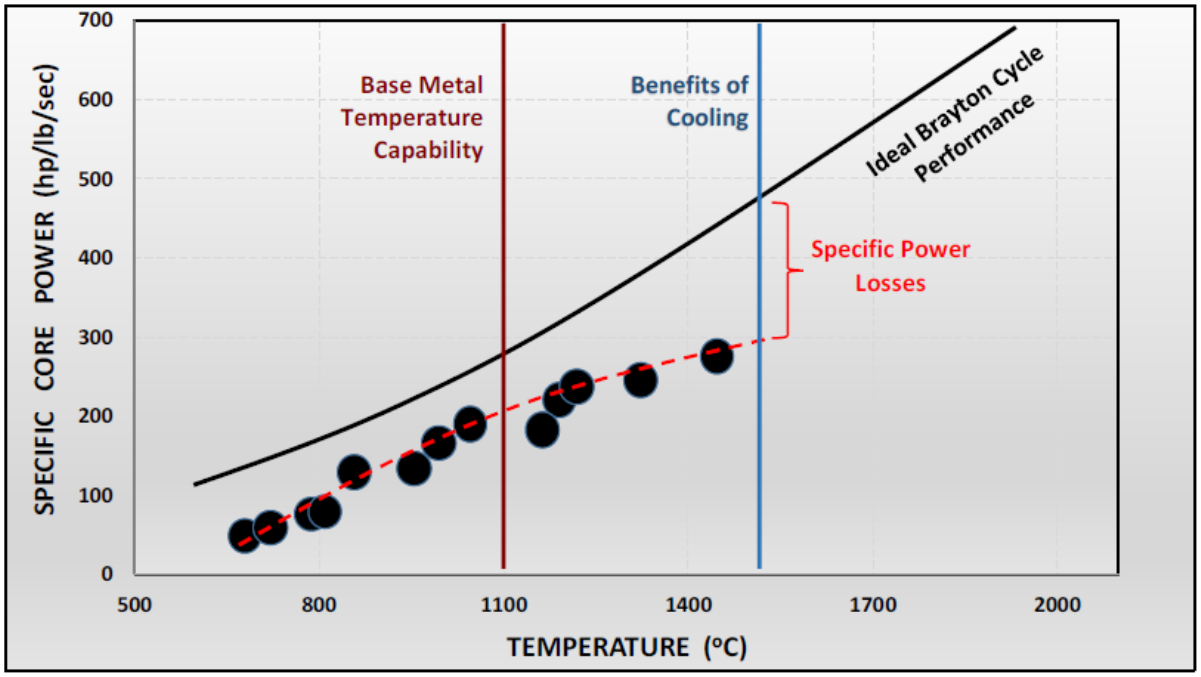


Functionally-gradient turbine blade structure

Example of BAA: ARPA-E DE-FOA-0002337

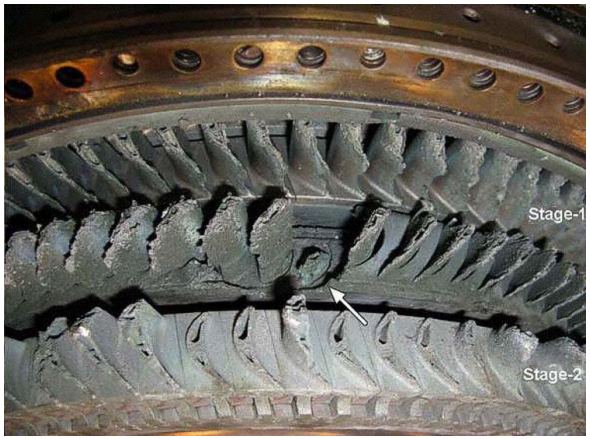
State-of-the-Art

- The efficiency of a gas turbine depends to a large degree on the peak temperature of the working fluid (e.g., air or combustion products). The higher the peak temperature, the higher the efficiency and specific core power.
  - Current state-of-the-art alloys used in turbines can not operate at temperatures higher than 1100 °C.
  - In practice, turbine blades are coated with thermal barrier coatings (TBC), which allow the surface temperature of a coated blade to be significantly higher - up to 1500 °C.



The specific core power of an aircraft engine as a function of temperature

Market Impacts



completely burn out of nozzle guide vane

corrosion and melting

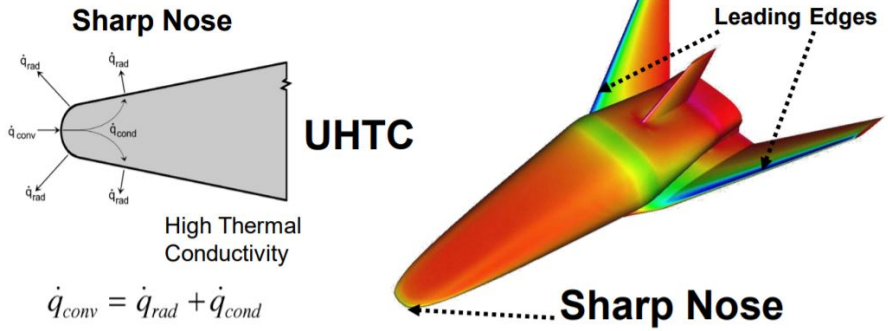
- A 7% improvement in efficiency in the natural gas turbines used for electricity generation in the U.S. represents a saving of up to 15-16 quads of energy by 2050.
- A similar improvement in the turbines used for civilian aircraft represents another 3-4 quads of potential savings for U.S. air travel over the same time span.

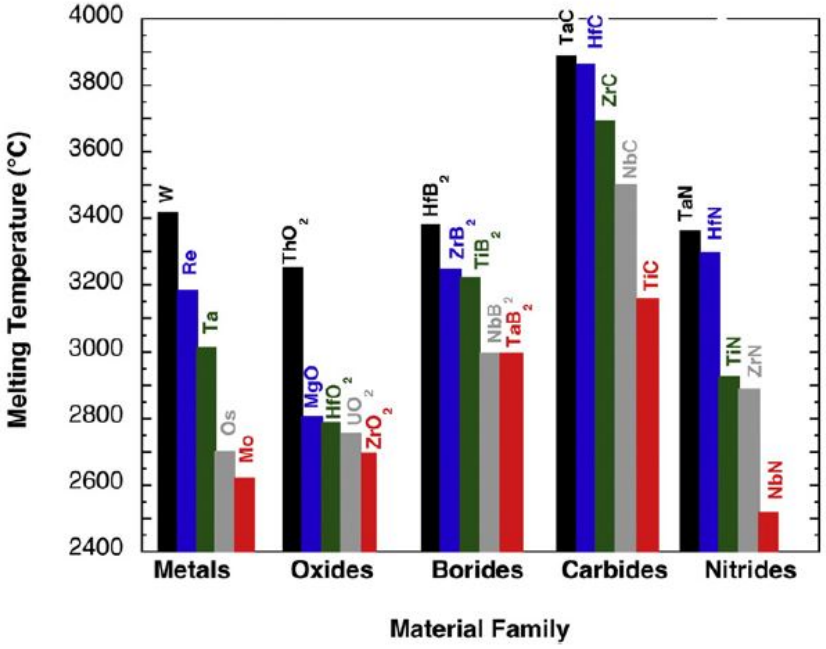
A quad is a unit of energy equal to 10^{15} (a quadrillion) BTU, or 1.055×10^{18} joules in SI units.

Ultra-High Temperature Ceramics (UHTCs)

- UHTCs are materials suitable for extreme environments that are generally used in next-generation aviation vehicles with sharp leading edges and nose cones, thermal protection systems of atmospheric re-entry vehicles, etc.

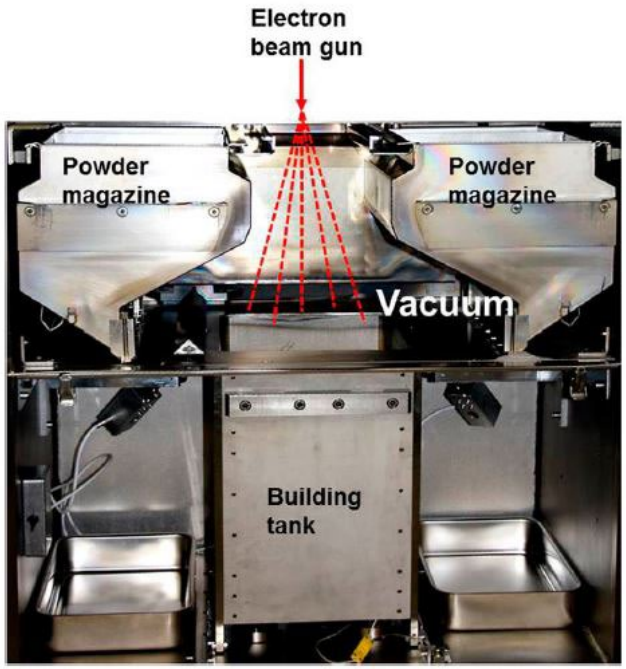
- Borides, Nitrides, Carbides of early transition metals such as Zr, Hf, Nb, Ta, etc.
- Properties of UHTCs:
  - High Melting Points (>3000 °C)
  - Oxidation resistance at high temperatures
  - High Strength
  - High thermal conductivity
  - Good thermal shock resistance



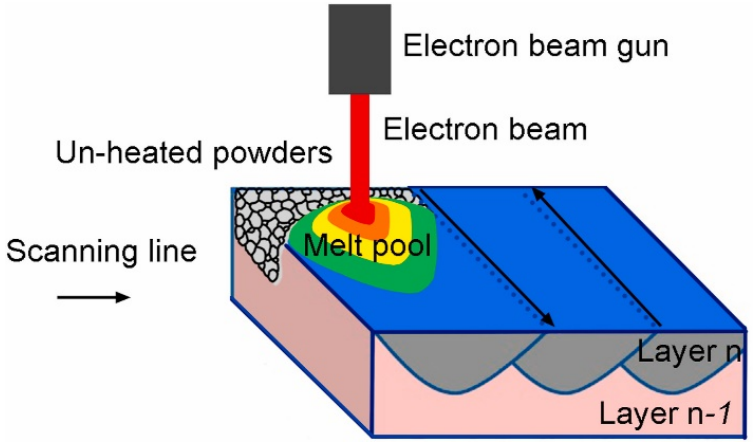


W.G. Fahrenholtz, E.J. Wuchina, W.E. Lee, Y. Zhou, Ultra-high Temperature Ceramics: Materials for Extreme Environment Applications, John Wiley & Sons, 2014.

Electron Beam Sintering (EBS)



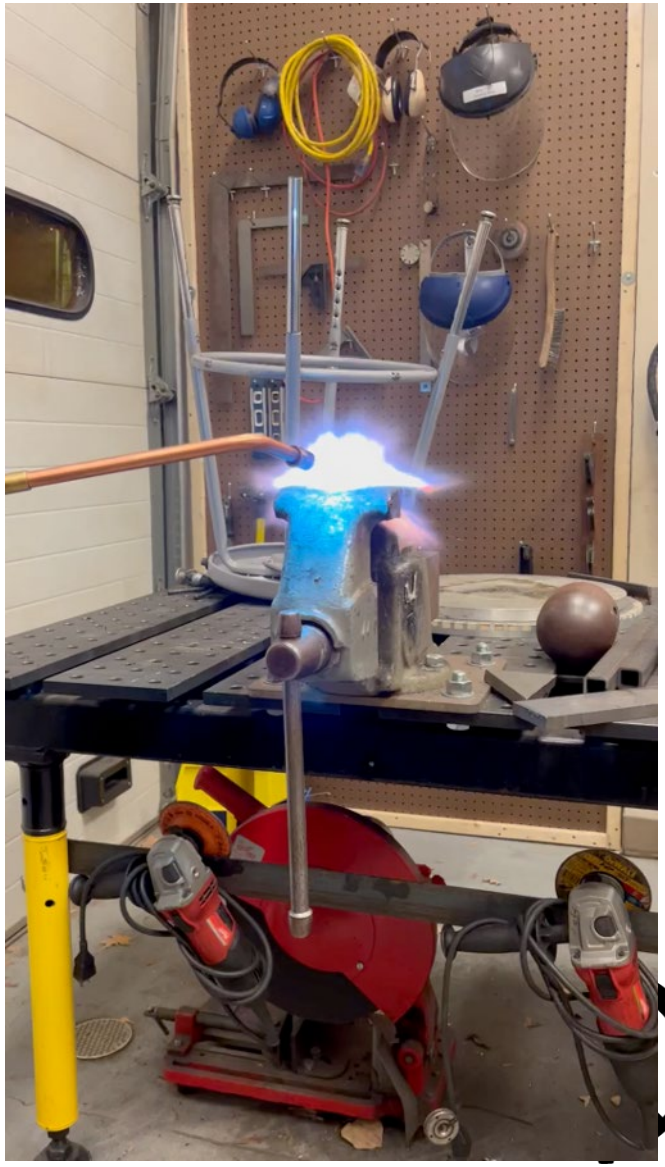
- EBS uses a concentrated electron beam as an energy source to rapidly heat, melt, and consolidate powder particles to produce shapes directly from 3D CAD model.
- Process Schematic:
  - Apply a powder layer
  - Preheat powder to enable a light necking
  - Melt powder bed according to 2D layer geometry
  - Lower the Bed to apply a new layer of powder
- The use of an electron beam has advantages:
  - High energy density
  - Vacuum enabling the processing of reactive materials
  - Low thermal stresses thanks to elevated temperatures achieved by preheating



C. Körner (2016) Additive manufacturing of metallic components by selective electron beam melting — a review, International Materials Reviews, 61:5, 361-377, DOI: 10.1080/09506608.2016.1176289.

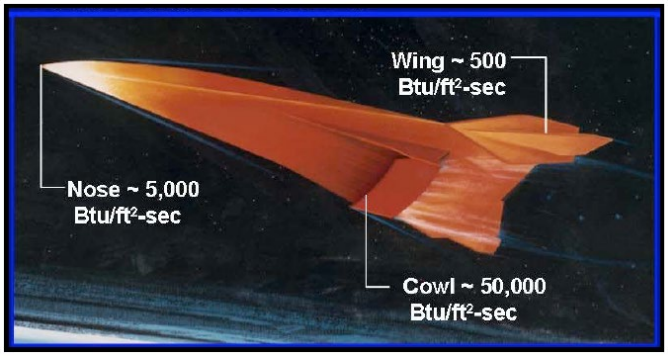
Torch Tests

- Samples that were able to survive 5-minute torch tests

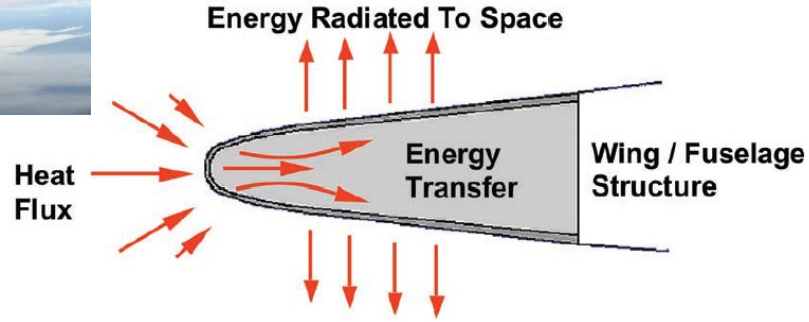


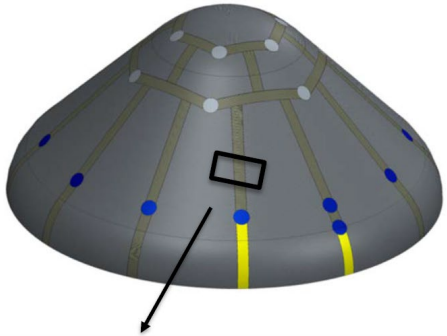
Broader Impacts

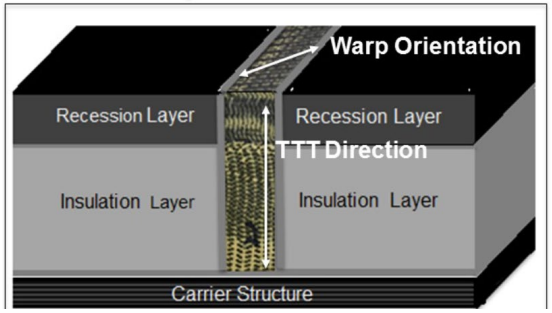
- Gas turbine applications in power generation and aviation industries
- Marine engines and components
- High-temperature industrial applications
- Nuclear applications



Typical ascent leading-edge heat flux for an SSTO vehicle (Glass, D., 2008, AIAA)







3D-woven heatshield (NASA HEEET Project).

Thank you for your attention!

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