SAIW
Southern African Institute of Welding

Thermal Spray Association of Southern Africa - TSASA

Thermal barrier coatings (TBCs)
Abradable coatings

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TWI

Thermal Spray Association of Southern Africa - TSASA

Thermal Barrier Coatings (TBCs)

Outline

- Introduction to Thermal Barrier Coatings
- Required Material Properties
  - Requirements for the bond coat
  - Requirements for the top coat
  - Phase composition
  - Microstructural considerations
- Coating Deposition Methods
  - Physical Vapour Deposition (PVD)
  - Thermal Spray Methods
- TBC Degradation Mechanisms

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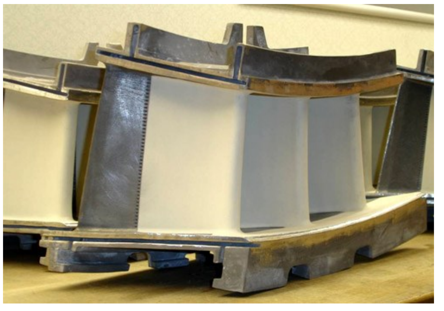
Introduction

Power generation

Aviation

TBCs in gas turbines

- Used in hottest zones of a gas turbine:
  - Combustor cans and transition ducts (from combustor to turbine)
  - 1st / 2nd stage HP turbine blades (rotating blades)
  - 1st / 2nd stage HP nozzle guide vanes (static NGVs)



TBCs in gas turbines

- Reduces metal surface temperature by 100-150°C
  - Used with forced cooling of the components
  - Allows a higher operating temperature and/or reduces cooling air requirements
    - Greater fuel efficiency
    - Higher thrust:weight ratio
    - Reduced NO_x/CO_2 emissions

TBCs in internal combustion engines

- Marine diesel engines
  - Cylinder head exhaust ports, valve faces, combustion chambers
  - Piston crowns
- High performance cars
  - Cylinder head exhaust ports, valve faces, combustion chambers
  - Piston crowns
  - Exhausts, turbochargers

Thermal Barrier Coatings - Concept

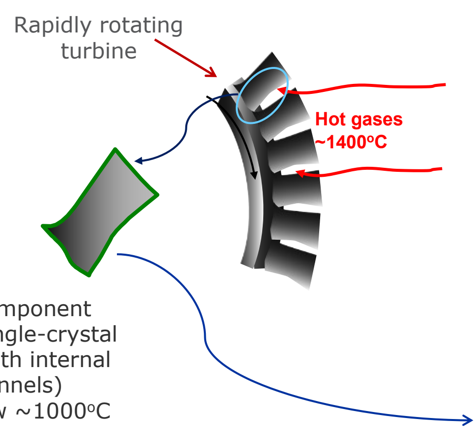


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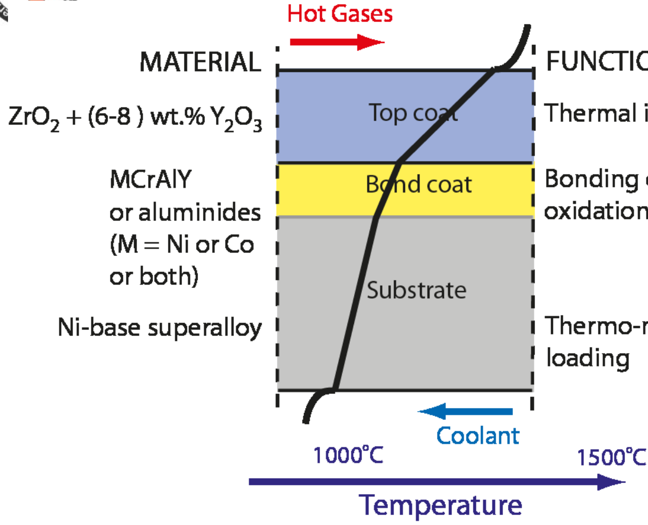
Image courtesy of the University of Cambridge

Thermal Barrier Coatings - Concept



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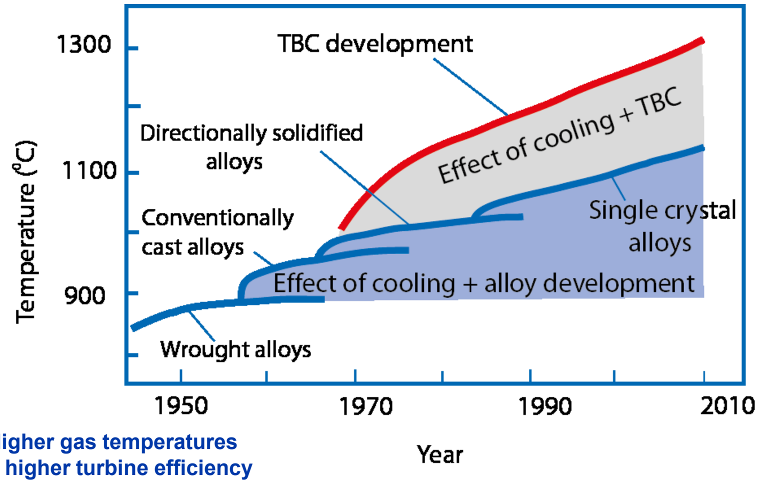
Thermal Barrier Coatings - Advantages



Higher gas temperatures = higher turbine efficiency

Image courtesy of Wiley

Material Properties required for TBCs

Material Properties - Bond Coat

- Must form an α-Al_2O_3 thermally-grown oxide (TGO)
  - Provides bonding of TBC to bond coat and slows subsequent oxidation (0.3-1.0 µm thick)
- High temperature corrosion resistance:
  - High temperature oxidation resistance
  - Resistance to hot combustion gases
  - In some cases impurities in the fuel can cause a more complex corrosive environment (e.g. molten salts, in some industrial turbines)
- High strain tolerance
- Thermal expansion coefficient
  - Preferably somewhere in-between that of the substrate and that of the ceramic top coat
- High melting point & thermodynamically stable

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Bond coat compositions and deposition methods

- MCrAlX (γ+β)
  - M = (Co,Ni)
  - X = (Y,Hf,Si,Re,Ru,…)
    - Air Plasma Spraying (APS)
    - EB-PVD
- β-NiAl; Pt-modified β- NiAl
  - Electroplating
  - Pack cementation
  - Chemical Vapour Deposition (CVD)

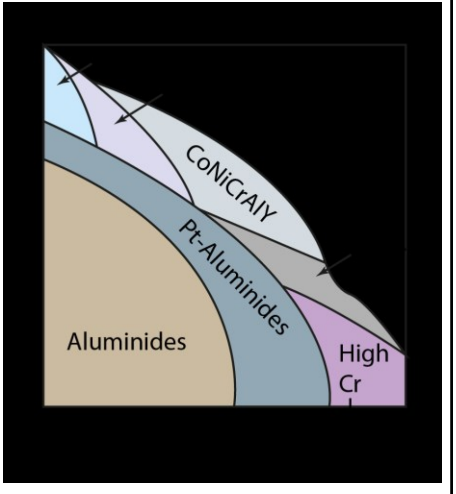
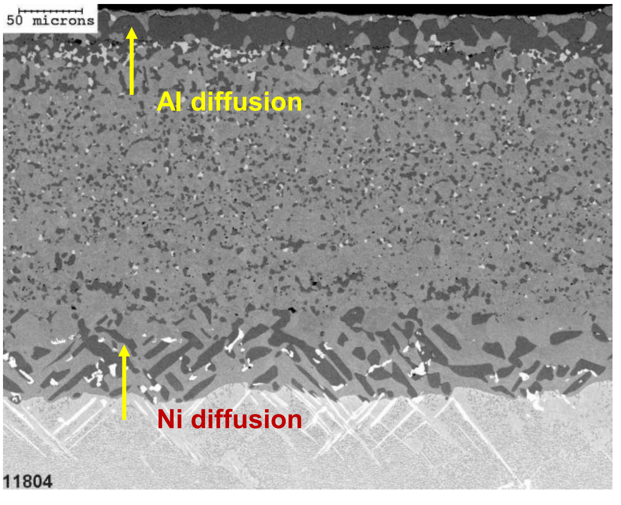


Image courtesy of Woodhead

Typical bond coat microstructure



Thermally grown oxide (TGO) layer

HVOF MCrAlY layer

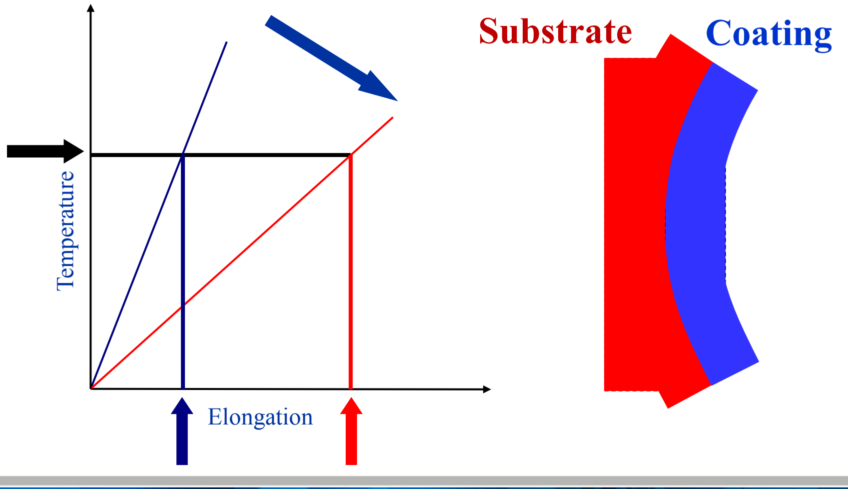
Aluminised layer

Ni alloy substrate

Material Properties - Top Coat

- Low thermal conductivity at operating temperatures
  - Preferably, thermal conductivity should be relatively temperature-invariant
- Low density (especially for aviation engines)
- High melting/softening point
- Compatibility with the bond coat

Thermal expansion coefficient and strain tolerance/stiffness



Thermal shock resistance and thermodynamic stability

- Pure ZrO_2 is monoclinic at room temperature but has tetragonal (t) or cubic (c) phase structure at higher temperarures:
  - Phase changes cause volume changes during thermal cycling - can cause undesirable cracking.
  - Desirable - a structure that allows a more consistent volume throughout operating range.

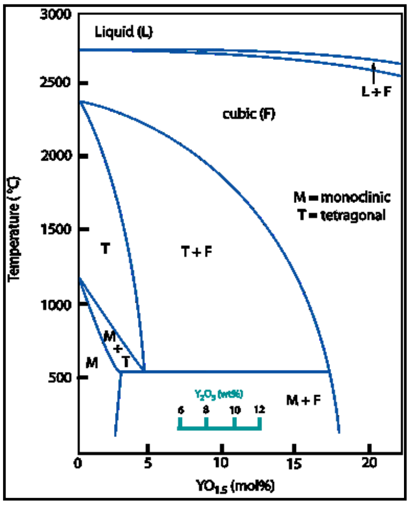


Image courtesy of Scott, *J. Mater. Sci.*, 1975, 10, p 1527-1535

Thermal shock resistance and thermal stability - use of stabilised zirconia

- Oxide additives used to stabilise cubic and/or tetragonal phases in ZrO_2
  - Typically: magnesium oxide (MgO), yttrium oxide (Y_2O_3), calcium oxide (CaO), cerium oxide (CeO_2 / Ce_2O_3).
  - Recently: dysprosia (Dy_2O_3), gadolinia (Gd_2O_3) and ytterbia (Yb_2O_3) have also been used.
- "Classic" TBC: Yttria-stabilised zirconia YSZ
  - 6-8%Y_2O_3 creates a partially-stabilised zirconia; 20%Y_2O_3 creates a fully-stabilised cubic zirconia
  - Recent research has also evaluated replacing some or all of the ZrO_2 with HfO_2.

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Achieving optimal properties: Microstructure of the top coat

- Engineering the microstructure to achieve the required properties:
  - 10-25% porosity
  - Vertical cracks/pores give more lateral compliance
  - Horizontal cracks/pores to provide lower conductivity

Deposition methods for TBCs

Deposition of MCrAlX bond coats

- Typically 100-150µm thick
- Vacuum/Low Pressure Plasma Spray (VPS/LPPS)
  - Much more costly but bond coat can be deposited entirely oxide-free in vacuum chamber
  - Followed by topcoat
  - Done sequentially using same equipment
- Cold Spray
  - Compares favourably with LPPS in terms of properties and is lower cost
- HVOF
  - Some oxides present
- EB-PVD
  - Costly, only makes sense if top coat is also EB-PVD

Deposition of TBC top coat: EB-PVD

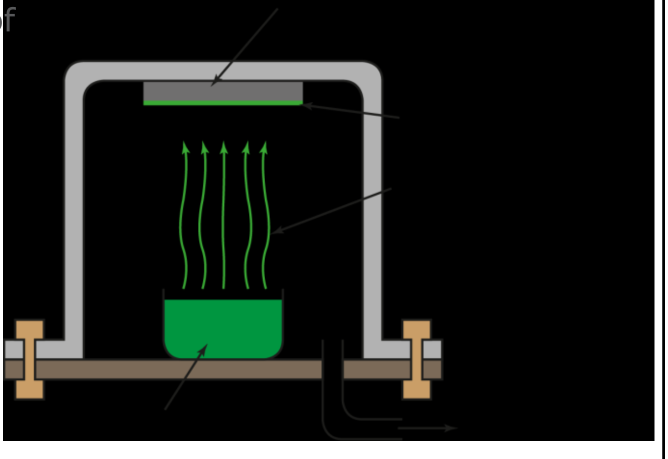
- Typically 100-250µm/250-500µm thick
- EB-PVD
  - More expensive than APS
  - Component size is limited
  - Coating performance is better and a thinner TBC is possible due to the **columnar coating structure**
  - Preferred for blades and vanes in aero engines
- Directed vapour deposition EB-PVD

What is PVD?

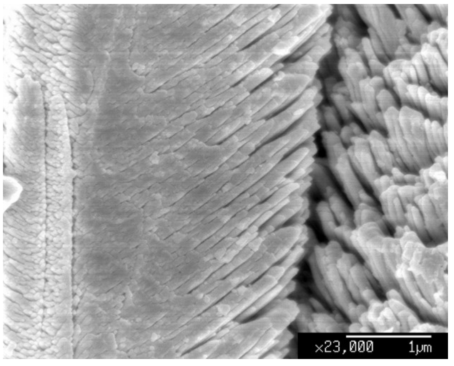
- Physical Vapour Deposition (PVD)
  - Electron Beam Physical Vapour Deposition (EB-PVD) is the most commonly used non-thermal-spray method

Physical Vapour Deposition

- Condensation of vapour
- Various heat sources
  - Plasma
  - Laser
  - Electrical (arc, resistance)
  - Electron Beam



Typical EB-PVD TBC



- Different types of pores
- Feather-like structures
- Columnar grains
- Inter-columnar porosity

Image courtesy of the University of Cambridge

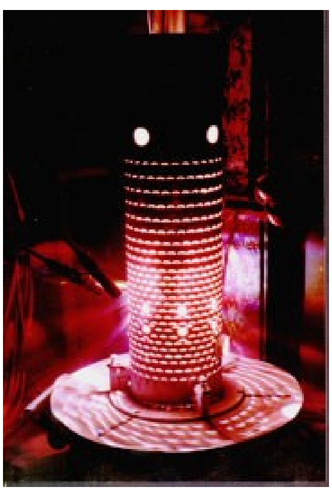
PVD variant

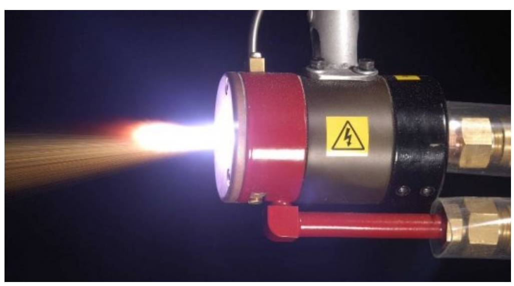
- Directed Vapour Deposition (DVD)
  - A stream of inert gas impinges on the PVD vapour and changes its angle of deposition onto the surface
  - By changing this angle constantly, a structure that is somewhere between the columnar PVD structure and a layered thermal spray coating structure, is obtained

Deposition of TBC top coat: APS

- Typically 100-250μm/250-500μm thick
- Air Plasma Spray (APS)
  - Combustor parts and shrouds in aero engines.
  - Most of the parts in stationary gas turbines
  - Preferred for coating large surfaces and/or thicker TBC
- APS variant
  - 'Dense vertically cracked' (DVC) TBC
  - An attempt to get some of the advantages of the PVD microstructure

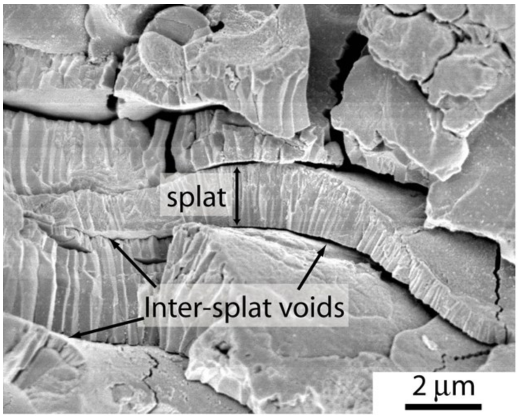
Plasma spraying





Left:
Internal surface of combustor can being coated with zirconia 'thermal barrier' coating

Plasma sprayed TBC structure



Different types of pores

Vertical and horizontal cracks and micro cracks

Columnar grains within the splats

Image courtesy of the University of Cambridge

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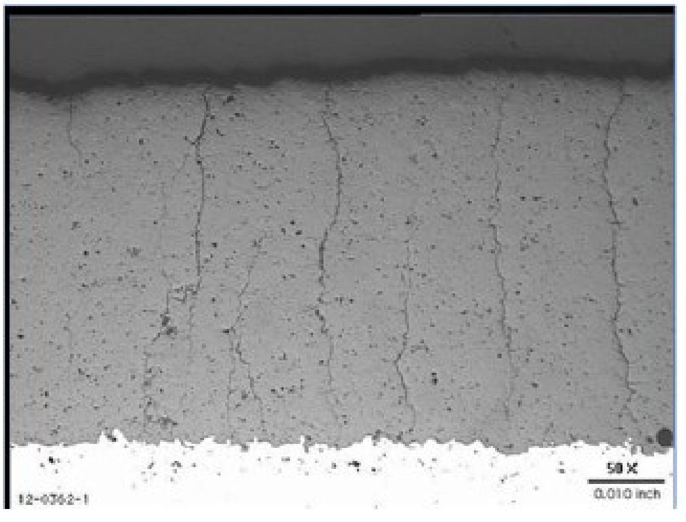
DVC TBC



From: Hardwick and Lau, JTST 2013 Vol 22[5] p564-576

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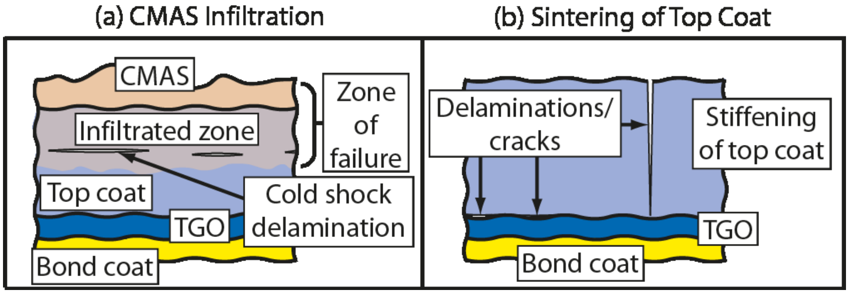
TBC Degradation Mechanisms

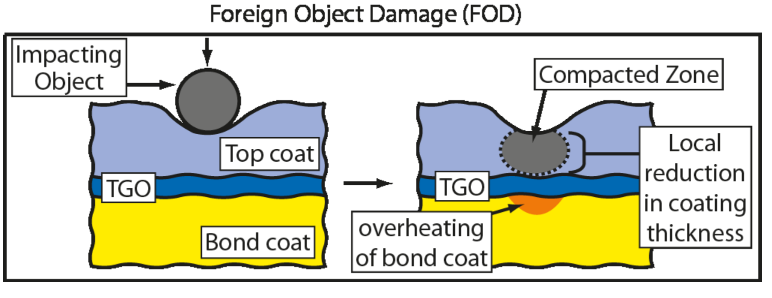
TBC degradation mechanisms

- Changes in the bond coat
  - Growth of the thermally grown oxide (TGO)
  - Rumpling/spalling of TGO
  - Depletion of important elements eg Cr, Al
  - Embrittlement
- Degradation of the top coat
  - Sintering due to high temperature excursions e.g. during take-off and reverse thrust at landing
  - CMAS infiltration (CaO MgO Al_2O_3 SiO_2) from solid particulates entering the engine
  - Phase changes
- Mechanical impact e.g. foreign object damage (FOD)

Changes in the top coat



Impact damage



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Abradables

Introduction

- Gas turbines(and more recently also steam turbines)
  - Rotating compressor blades or turbine blades inside compressor/turbine casing
  - Expansion/contraction depending on temperature
  - Abradable coating allows the blade to cut its own gas seal, minimising losses and improving fuel efficiency
- For the hotter turbine sections, honeycomb seals are an alternative technology to thermal spray coatings

Required properties

- Abradable coatings have to satisfy two conflicting requirements:
  - Must be **abradable**: Porous, friable microstructures (low shear strength)
  - Must be **mechanically stable** in the harsh operating conditions of a gas turbine
- On low-pressure turbine stages with moderate temperatures, both ceramic and metallic coatings have been used
- For high-pressure turbine applications, mainly ceramics

Abradables

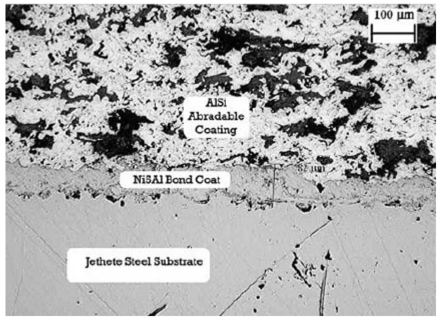
- Abradables are composite materials composed of:
  - A metal phase (e.g., Al-Si, Cu-Al, Ni, Ni-Cr, Ni-Al, Ni-Cr-Al, MCrAlY)

    or
  - An oxide ceramic

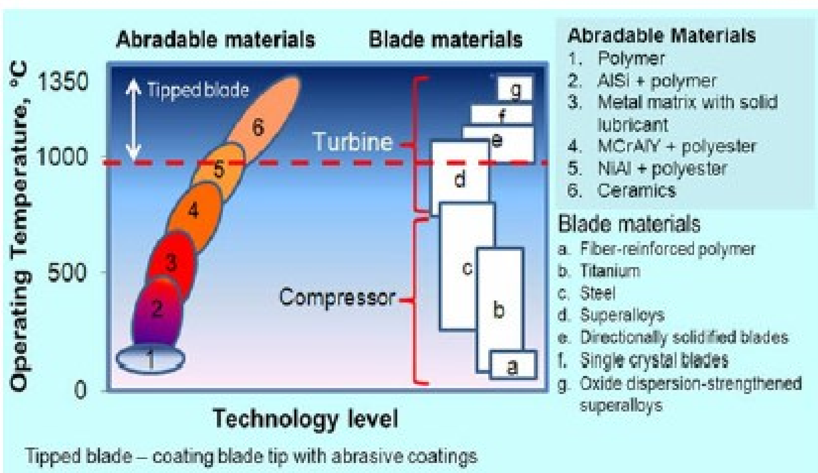
    and
  - A self-lubricating non-metal phase (e.g., BN, graphite composites, bentonite) ***(not used in all cases)***
  - A polymer or a polymer composite to generate porosity ***(not used in all cases)***

Moderate temperature abradable design

- Compressor sections of gas turbines
- Composite materials:
  - Metal phase + self-lubricating nonmetal + a polymer (for porosity generation)
- e.g.:
  - AlSi-polymer
  - AlSi-hBN
  - Ni-graphite
  - CoNiCrAlY-BN-polymer



Applicable temperature ranges



From: Hardwick and Lau, JTST 2013 Vol 22[5] p564-576

High temperature abradable design

- Yttria stabilized zirconia (YSZ)
  - For moderate temperature applications, YSZ is used as a composite material with addition of organics and a solid lubricant
  - For high-temperature applications it is used as full ceramic coating. Limited to ≈1200°C in long-term applications.
  - Can have additions of BN and polyester (the polymer controls porosity and is burnt off before use)
- Yb_2O_3–ZrO_2 based abradables
- Magnesia-based spinels
  - Good abradability
  - Resistance to high thermomechanical loading
  - Service temperatures above ≈1300°C

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Thank you

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