



Improvements in Gas Turbine Performance via Novel Plasma Spray Coatings Offering Protection Against Ingested Species



a proposal submitted to

**UK-India Research Initiative on
Advanced Manufacturing**



What are we trying to accomplish?

To develop an improved understanding of how ingested species can degrade performance of ceramic coatings in gas turbines and identify effective measures to counter these effects.

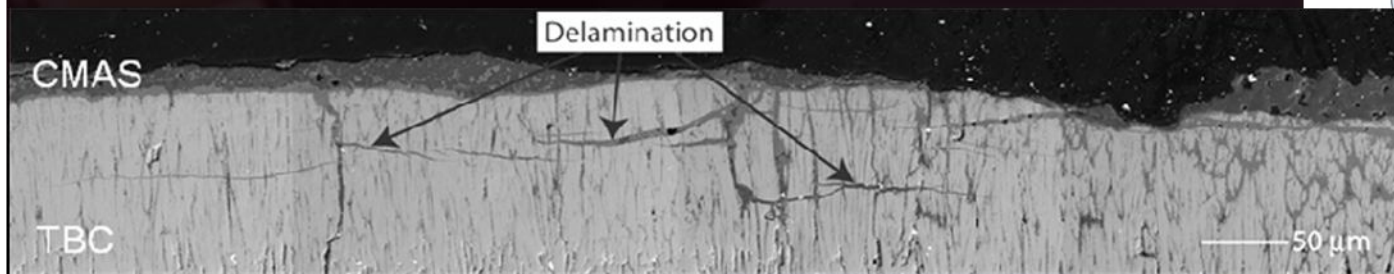
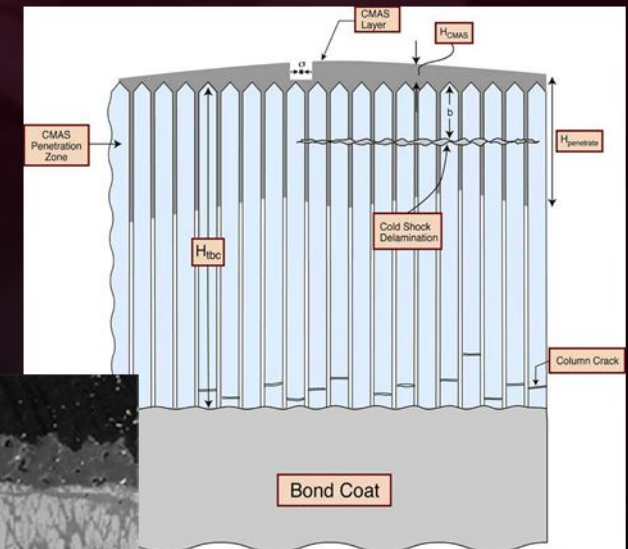
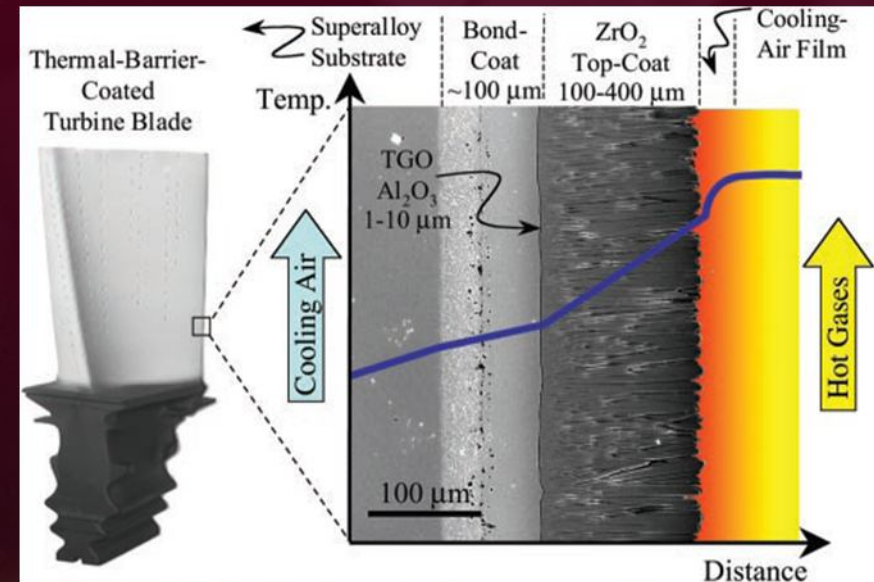
To study the impact and adhesion of ingested particles on substrates in the turbine area (on both stator and rotor components) and establish the regimes (operating conditions, particle characteristics etc.) in which such adhesion is likely to occur

To explore the scope for using variants of the conventional plasma spray process, notably Solution Precursor Plasma Spray and the over-spraying of “scavenging” outer layers, in order to counter sintering effects within protective coatings (promoted by ingested species) and hence to improve their thermo-mechanical stability.



Why is it important ?

- Thermal barrier coatings (TBCs) play a key role in aero, marine and power generation gas turbines; but improvements in TBC performance required to allow higher turbine entry temperatures and associated gains in engine efficiency
- TBCs vulnerable to attack by ingested particulates, often called "CMAS" (Calcium-Magnesia-Alumina-Silica) which are main ingredients ceramic particulate matter
- Sources of trouble: Volcanic ash (VA) for aero-engines; salt in marine environments; sulphur in fuel used by power plants





Relevance : Aero engines



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Volcanic ash grounds UK flights

15 April 2010 | By [Ellie Zolfaghari](#)

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A NOTE FROM ROCCO PENDOLA

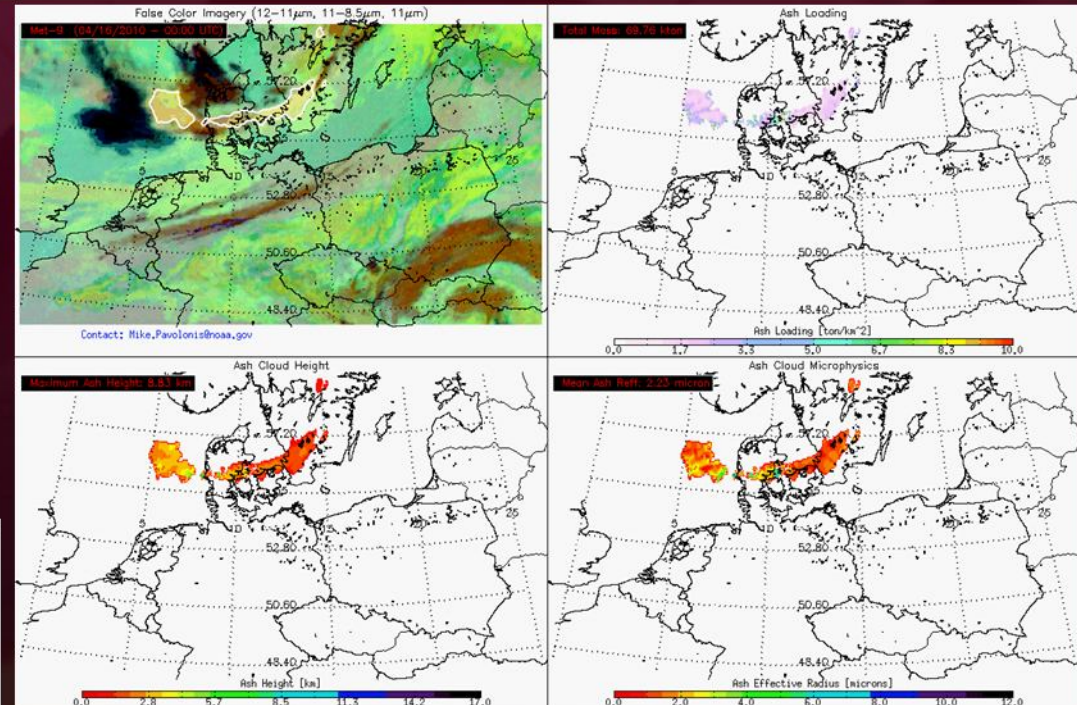
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Transportation

Volcano Impact on Airlines: \$200M a Day

By Andrea Tse 04/16/10 - 02:51 PM EDT



Spreading of volcanic ash clouds from Iceland through the Europe

- During the early 1980s, ash clouds spewing from Galunggung Volcano on Indonesia's Java island, a British Airways flight lost power on all four engines
- Another 747 encountered similar problems while flying through the ash clouds over Mt. Redoubt, Alaska.
- At least 10 Jumbo jets and 10 DC-10s suffered multiple engine failures in 1991 from ash from Mt. Pinatubo in the Philippines.

Image courtesy: Satellite Applications for Geoscience Education



Formation of volcanic ash

Large variations in physical properties

For
 SiO_2 - KAlSi_3O_8 - $\text{NaAlSi}_3\text{O}_8$
systems,

$T_m \sim 1000\text{-}1300^\circ\text{C}$

$T_g \sim 700\text{-}900^\circ\text{C}$

Decompression of rising
magma, gas- bubble growth
and fragmentation

Explosive mixing of
magma with ground/
surface water

Fragmentation of
surrounding rocks by rapid
expansion of steam and
superheated water

Particle size highly
variable - from mm
to nm range

iStockphoto.com/Jochen Scheffl

Sources: T.J.Casadevall, Geological Survey (U.S.), Air Line Pilots Association (1994) "Volcanic ash and aviation safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety"- articles "Volcanic Ash and How it Works" by G.Heiken, "Melting Properties of Volcanic Ash" by S.E.Swanson and J.E.Beget

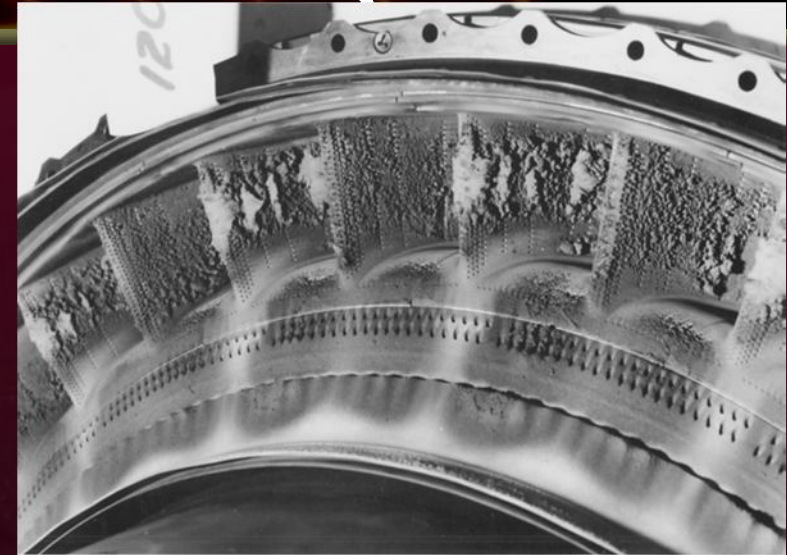
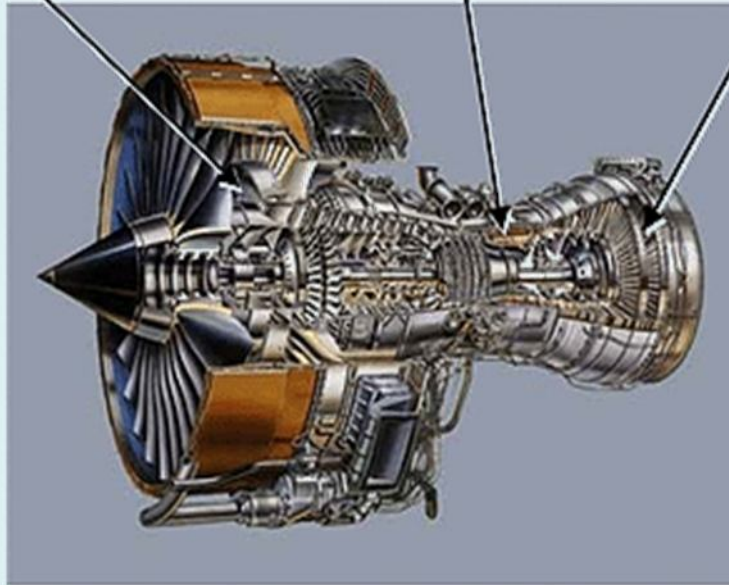


Effects of volcanic ash deposition

Abrasive particles can erode compressor blades edges, reducing compressor performance

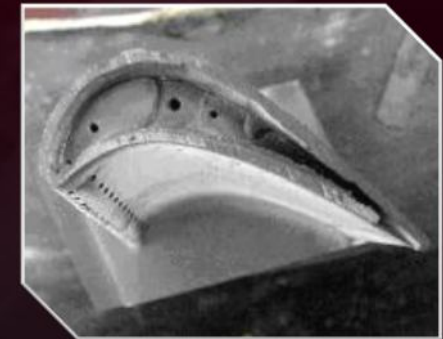
Glass particles will melt in the combustion chamber, if high thrust rating is used

Melted material will cool down in the turbine and deposit on the turbine vanes



Volcanic ash deposits on turbine vanes

*Image courtesy: IOP,
Ahmad et al, J Prop
Power, 2006*



- ◆ Airborne particles impact turbine surfaces to cause erosion damage at low temperatures
- ◆ At typical operating temperatures of gas turbines, particulates melt and adhere to the surfaces
- ◆ Ingestion can damage ceramic layers, particularly TBCs, mainly by promoting sintering and, hence, making them prone to premature spallation

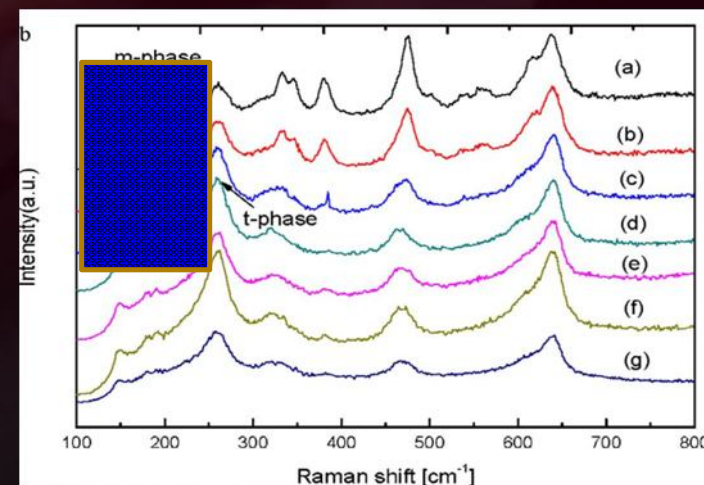
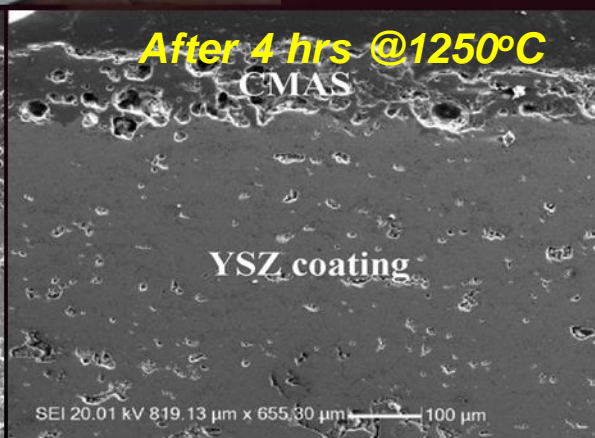
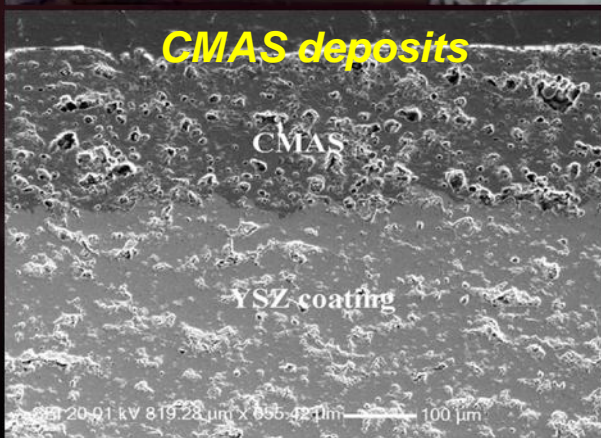


Relevance : Land-based gas turbines

BHEL 250 MW GT



- ★ Air-borne CMAS particles melts $>1100^{\circ}\text{C}$ and adheres to the surface coating on turbine blades of land-based GTs or aero-engines
- ★ CMAS reacts with YSZ to modify $t\text{-ZrO}_2$ to $m\text{-ZrO}_2$ (identified by Raman Spectra)
- ★ Pores are filled up with molten CMAS to reduce strain tolerance
- ★ Further penetration leads to reaction with bond coat and substrate susceptible to corrosion



m-ZrO₂ forms within 4 hrs of CMAS interaction

Ref: J. Wu, J. Eur. Ceram. Soc., Vol. 31, 2011



Approach

⇒ Coating Techniques Proposed

- Vacuum Plasma Spray
- Atmospheric Plasma Spray
- Solution Precursor Plasma Spray

⇒ Materials

- Modification of YSZ chemistry to increase the crystallinity
- Deposition of an active functional layer resisting CMAS/VA penetration
- Novel composite TBC with additional role towards CMAS resistance
- Use of vermiculite as CMAS and/or NaCl salt

⇒ Substrates

- Ni based super alloy with a standard bond coat
- Laser roughened Al_2O_3 substrates

Step 1

Assessment of CMAS Particle Adhesion

- Using AMT Pegasus Jet engine, deposition characteristics of CMAS to be evaluated
- Effect of particle size distribution, adherence level, penetration depth under varied turbine speed, inlet temperature, fuel consumption rate, engine thrust

Step 2

Modelling of CMAS Particle Impact and Adhesion

- Development of computational models to understand phase transformations during impact, associated particle deformation and bonding mechanisms with coatings
- Prediction of particles in different forms (solid, liquid, porous-solid), etc
- Validation of experimental results with Jet Engine and computational results to achieve better understanding

Step 3

Effect of CMAS on Sintering and Spallation of TBCs

- CMAS infiltration with standalone top coat at varied time-temperature profiles
- Microstructural assessment on elemental and phase distribution
- Thermo-mechanical monitoring of specimens to understand the sintering kinetics
- Similar approach with TBCs deposited on roughened alumina substrates

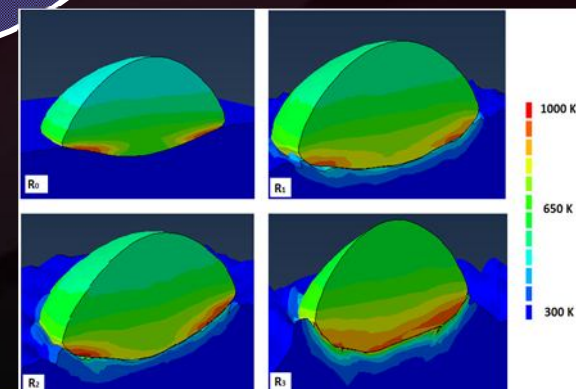
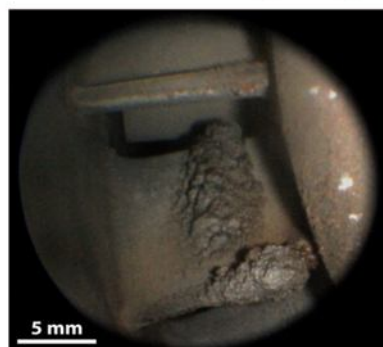
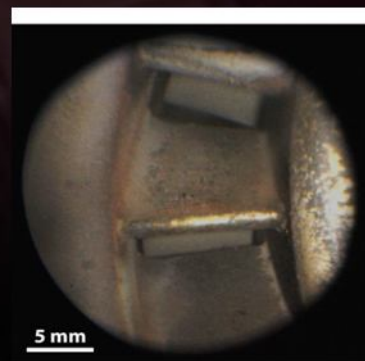
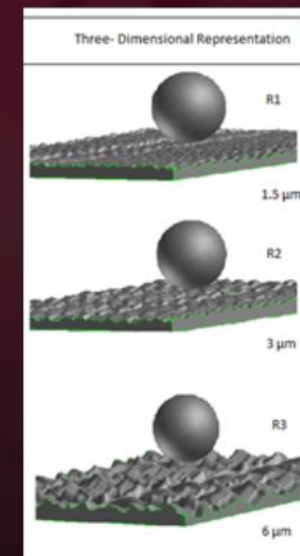
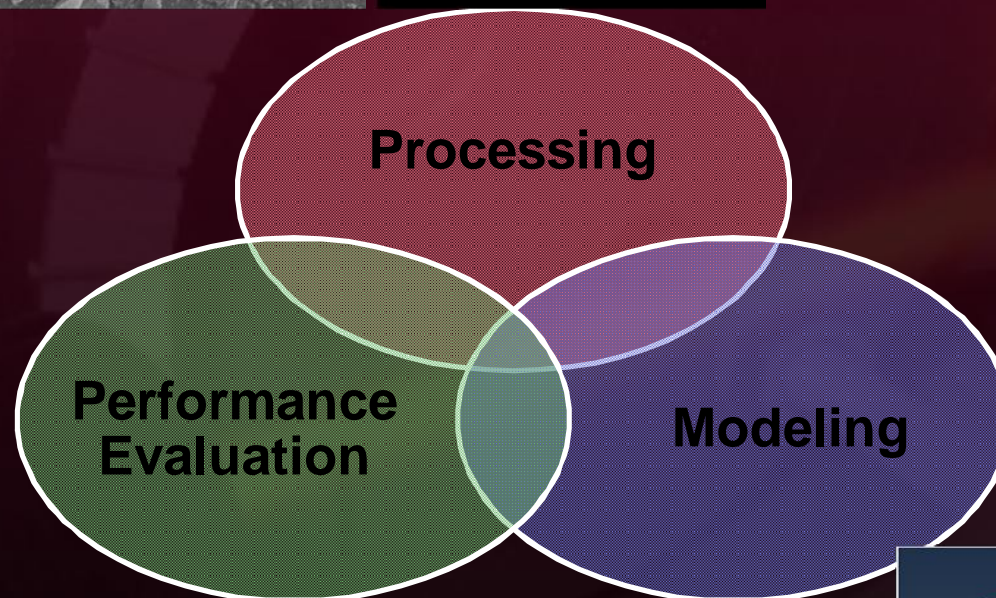
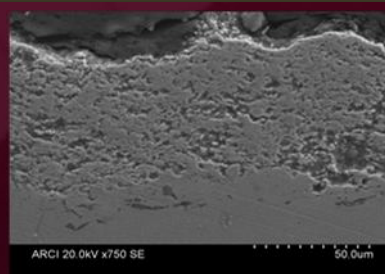
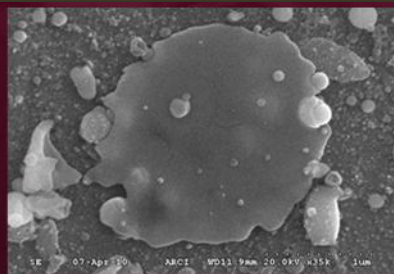
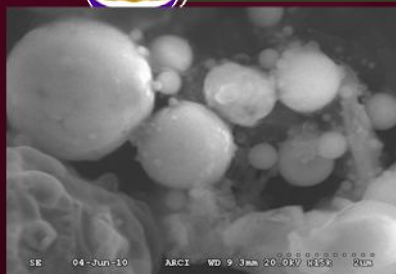
Step 4

Development of CMAS-Resistant TBC Formulations

- Based on the scientific understanding developed on the infiltration dynamics, parallel development of coatings to resist CMAS
 - Modelling of SPPS process for precursor and powder particle injection
 - Novel coating formulations with SPPS process
 - Modification of coating architecture through secondary treatments



Uniqueness in the collaboration





Confluence of Niche Expertise

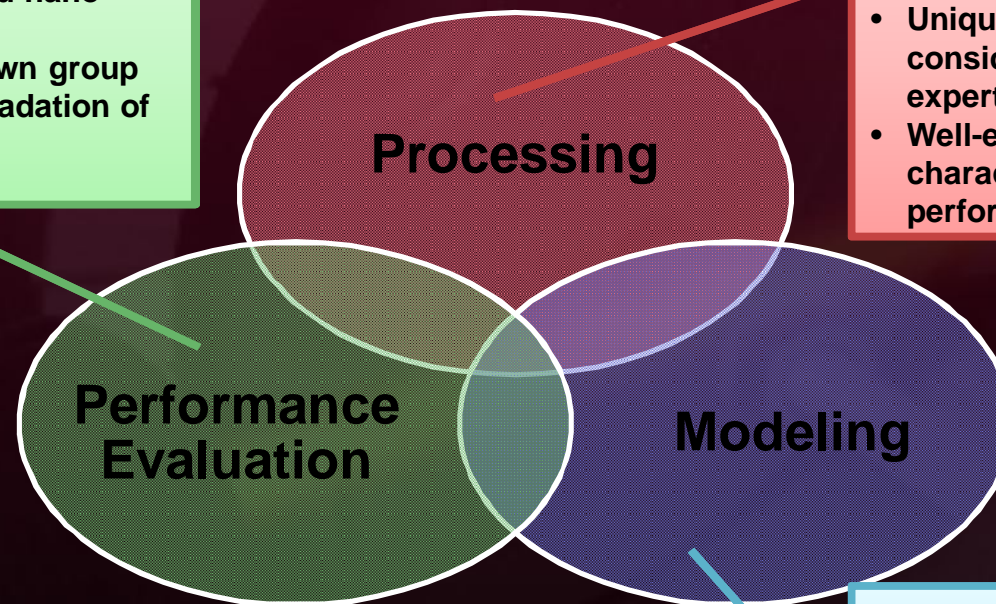
UNIVERSITY OF CAMBRIDGE:

- Substantial prior experience on thermo-mechanical characterization of coated systems on macro- and nano-scales
- Probably the best-known group for CMAS-related degradation of TBCs



ARCI:

- A leading group in the field of surface modification technologies, with history of technology development & transfer
- Unique coating facilities, considerable processing expertise
- Well-equipped for characterization and performance evaluation



CRANFIELD UNIVERSITY:

- Substantial expertise in computational analysis of coating processes,
- Considerable prior work on impact dynamics of various engineering phenomena





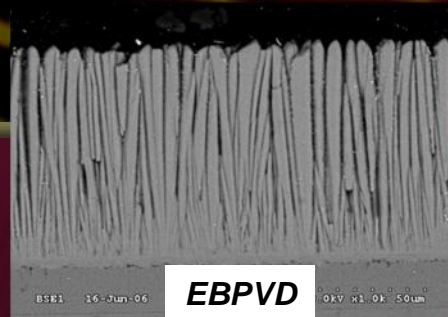
Confluence of Niche Expertise

INDUSTRIAL PARTNERS

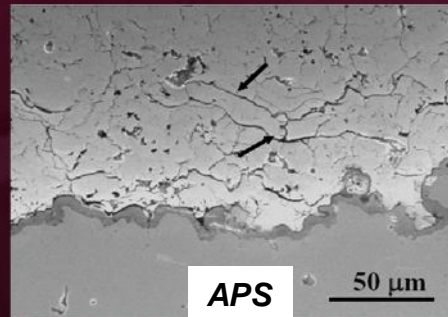
- **AMT, Netherlands**
Designs and manufactures small gas turbines for the propulsion of radio-controlled aircraft, experimental aircraft development, acoustic studies and full size gliders
- **Monitor Coatings Limited, UK**
Provides high quality coatings to demanding industries such as aerospace, oil & gas exploration, steel and many others where high performance is required in problematic hostile environments
- **Associated Plasmatron, India**
Leading thermal spray job shop in India
- **Bharat Heavy Electricals Limited, India**
A major Indian land-based gas turbine company
- **Gas Turbine Research Establishment, India**
An aero-engine development agency



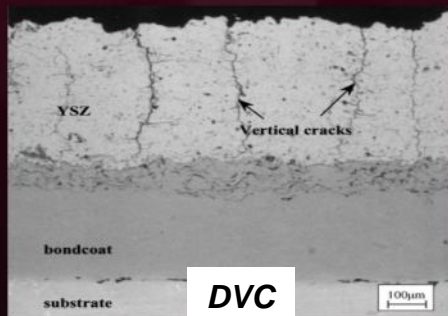
Present TBC architecture



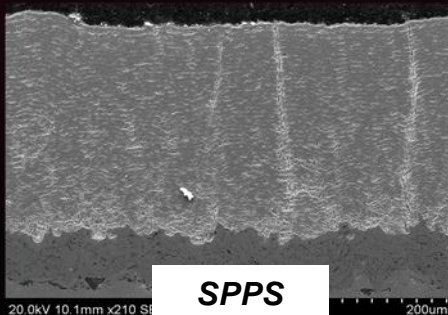
- Columnar grains, porosity, vertical cracks
- Higher strain tolerance
- Higher thermal conductivity
- Longer spallation life
- More expensive
- No hole coverage



- Porosity, horizontal cracks, splat boundaries, rough interface
- Lower strain tolerance
- Lower thermal conductivity
- Shorter spallation life
- Less expensive



- Porosity, vertical and horizontal cracks, splat boundaries, rough interface
- Better strain tolerance
- Moderate thermal conductivity
- Moderate spallation life
- Less expensive



- Porosity, vertical cracks, small sized splats, rough interface, nanostructured grains
- Better strain tolerance
- Acceptable thermal conductivity
- High spallation life
- Less expensive

Jordan & Padture, DoE report, 2006
Xie et al, Surf. Coat. Technol. 201, 2006



TBC processing: Unique capabilities



Cold Spray Coating



Detonation Spray Coating



Conventional Atmospheric Plasma Spray



Solution Precursor Plasma Spray



Electron Beam Physical Vapor Deposition

Bond Coat

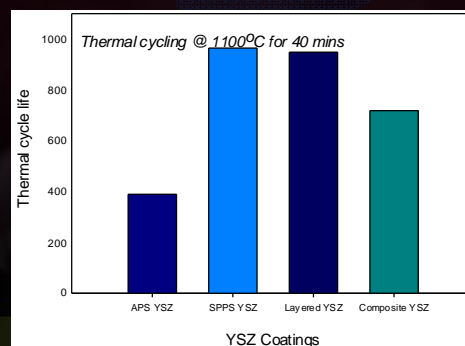
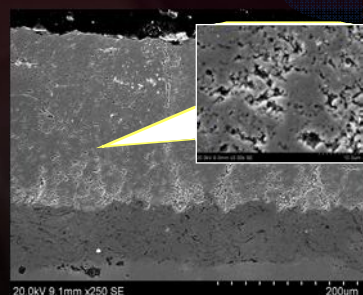
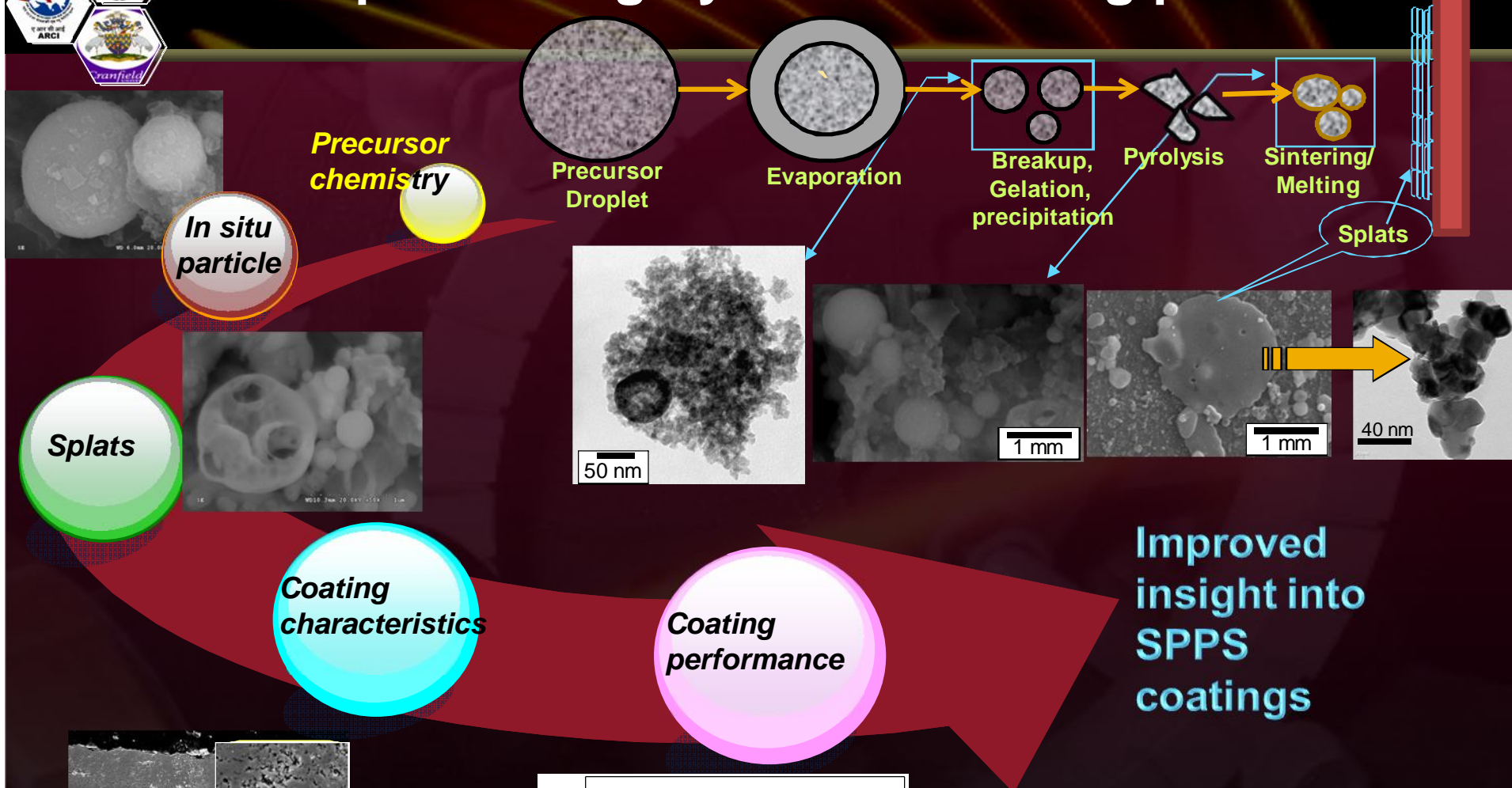


Vacuum Plasma Spray

Bond Coat + Ceramic Top Coat



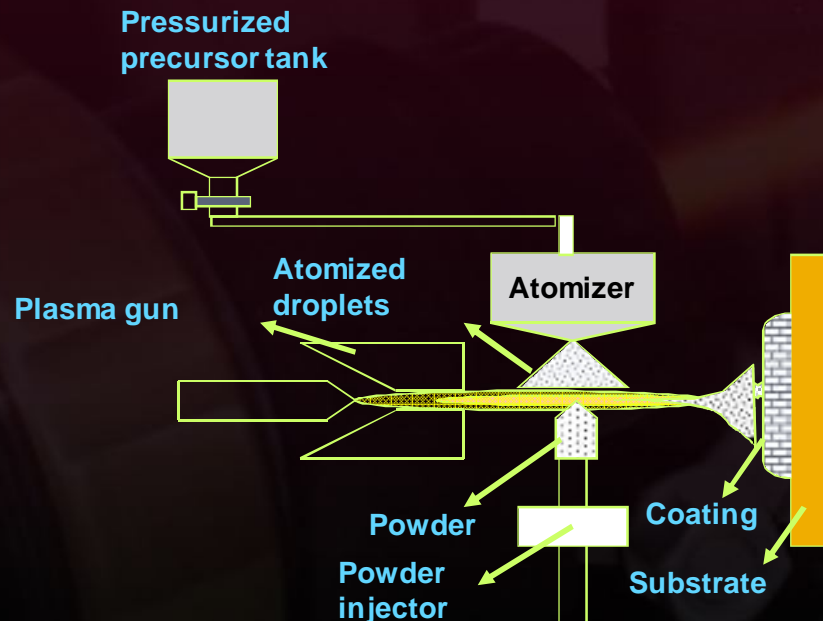
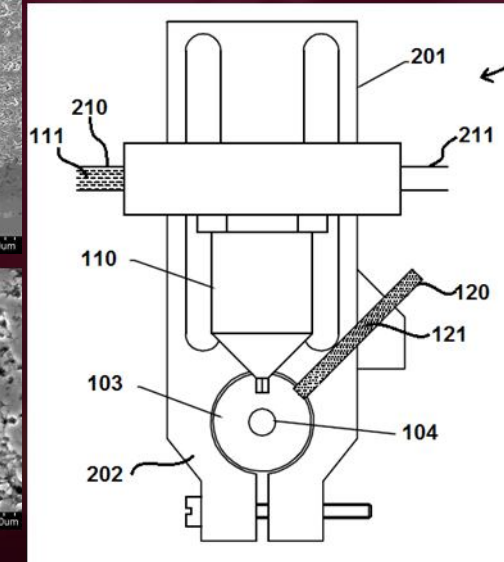
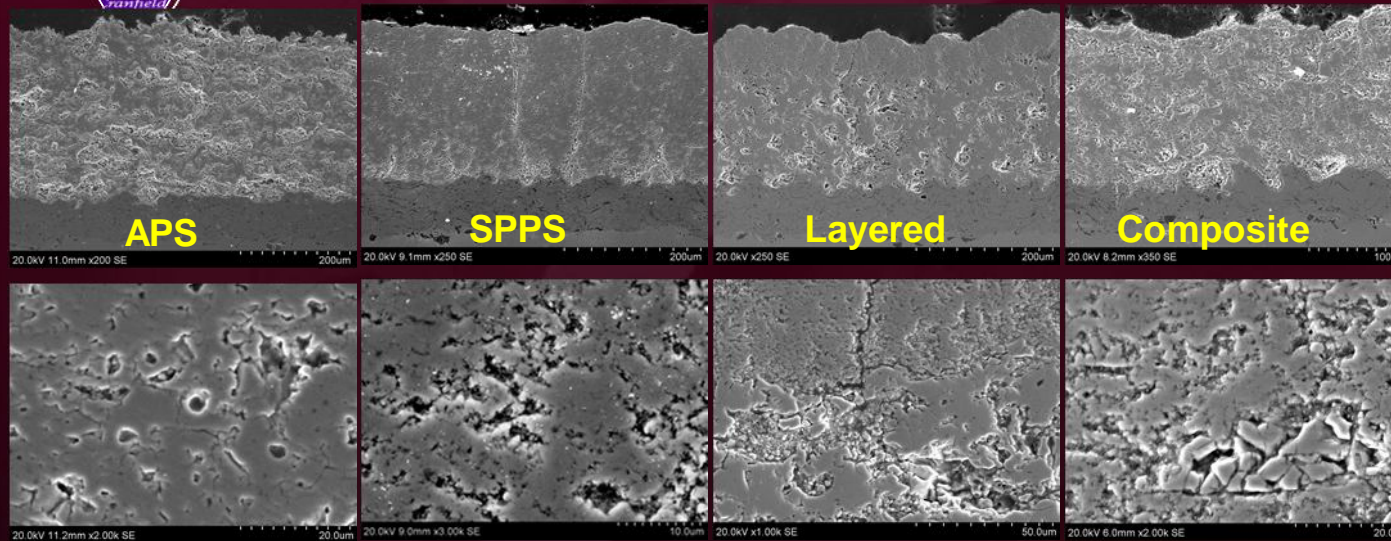
TBC processing by SPPS: Exciting possibilities



- Vertical crack formation & fine pores can be tailored
- Presence of vertical cracks along with optimum porosity assist in enhanced durability of SPPS YSZ TBCs



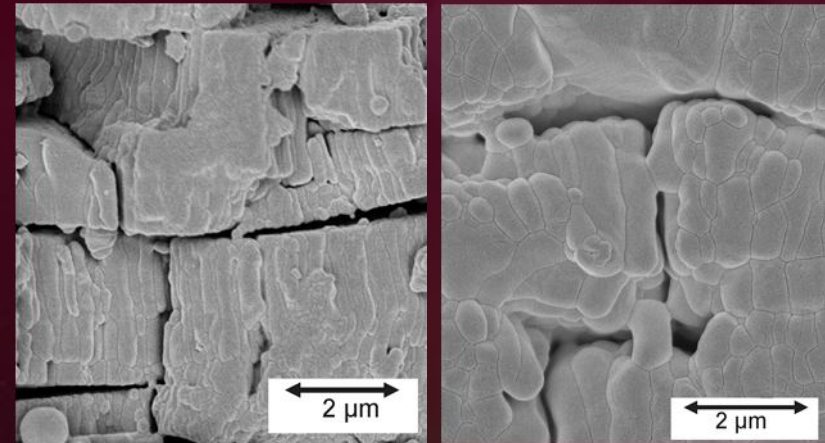
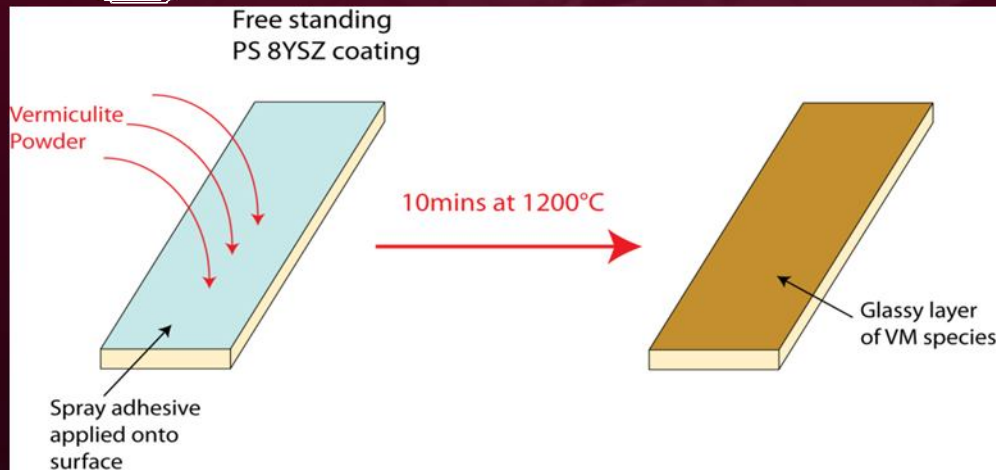
Controlled microstructure, novel architecture, new formulations



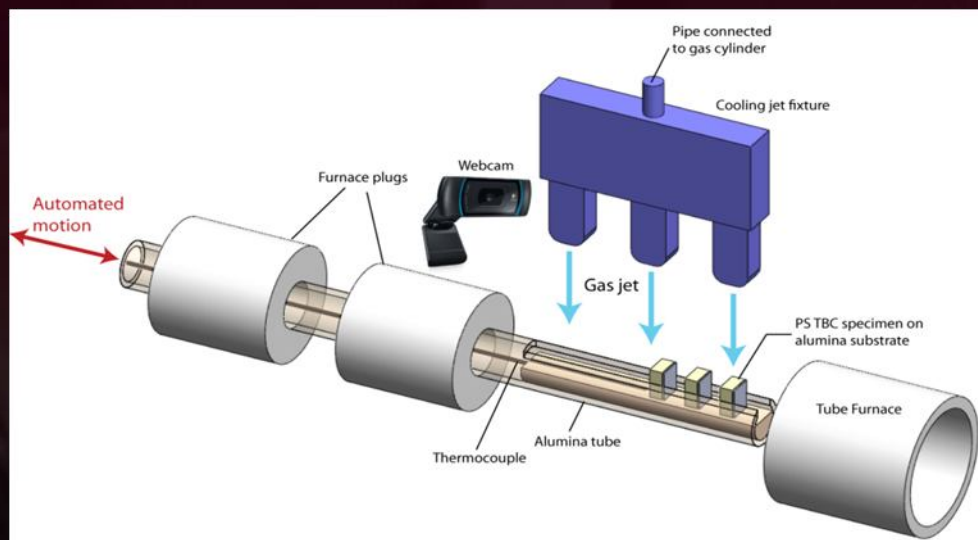
- ★ Patented process to enable simultaneous feeding of solution & powder feedstock to tailor unique microstructures - layered, composite and gradient structures
- ★ Nano-sized features from solution and micron-sized from powder feedstock mix well to form bimodal features
- ★ New formulations easily processed by appropriate choice of precursors



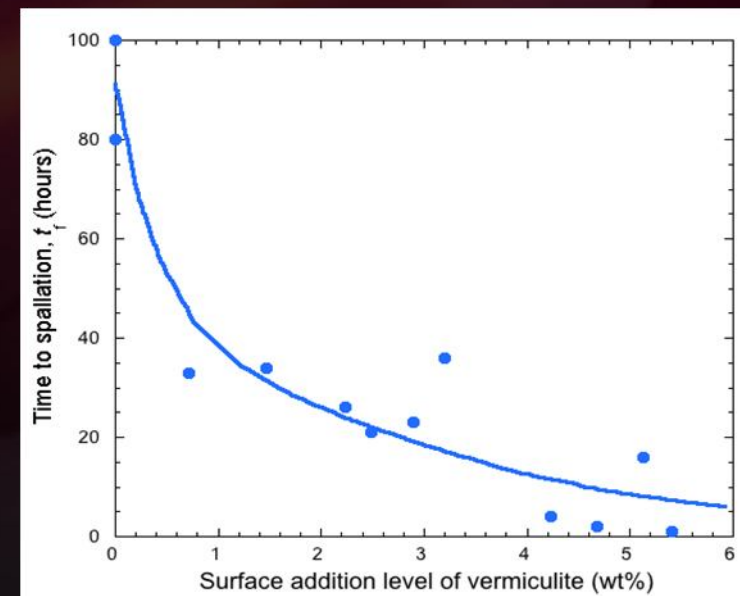
Understanding TBC degradation



Effect of exposure to high temperature



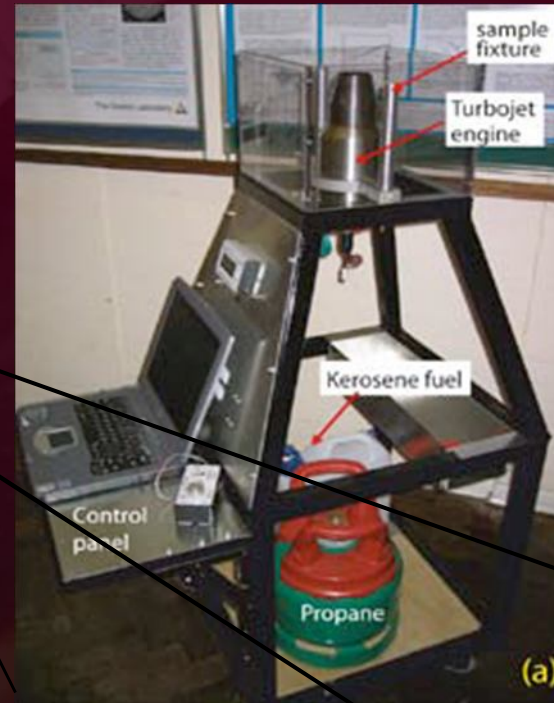
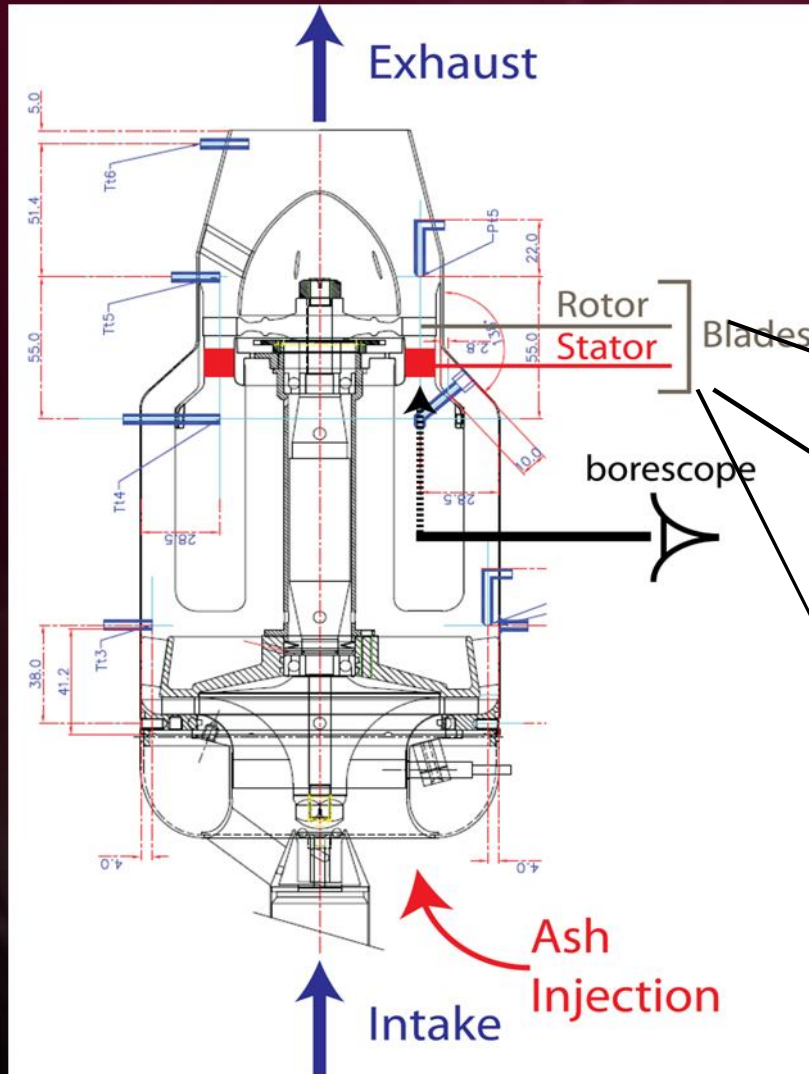
Periodic quenching arrangement



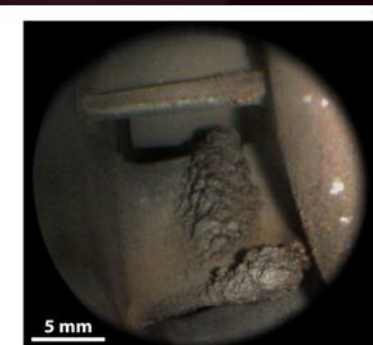
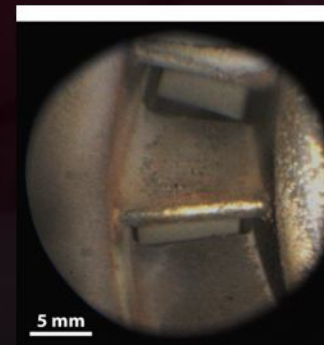
Thermo-mechanical characterization tools for coatings, composites, under simulated test conditions



Testing under simulated conditions using small jet engine



VA injection rate	~ 15g/min
Engine speed	120,000 RPM
Turbine entry temp.	~ 1200°C
Average VA particle size	~ 50 μm

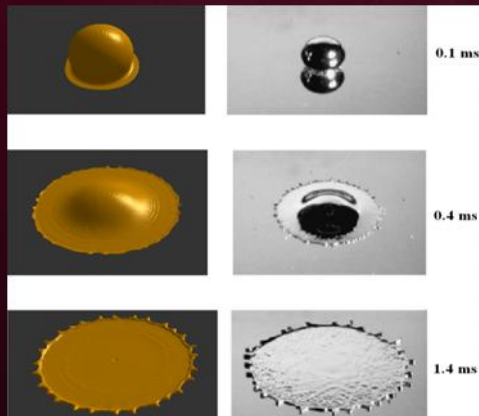


Studies of VA deposition rate in a Small Jet Engine and *in situ* observation through optical fibre

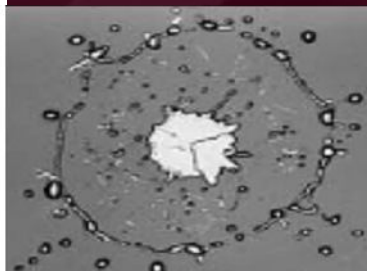


Modeling solid/liquid/porous-solid droplet impingement

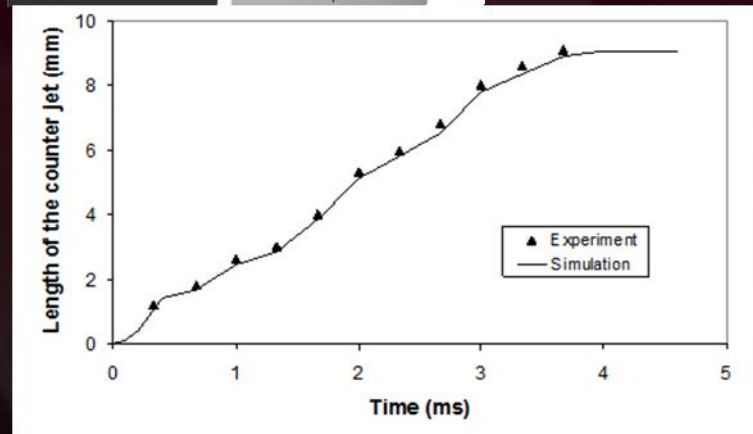
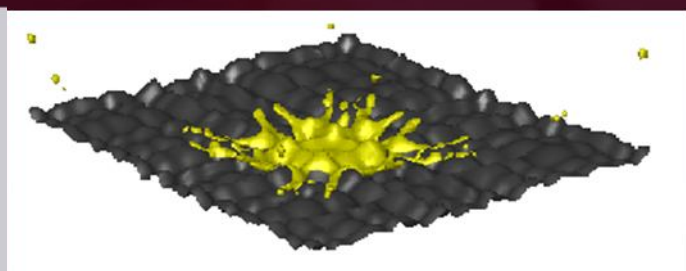
Dense droplets



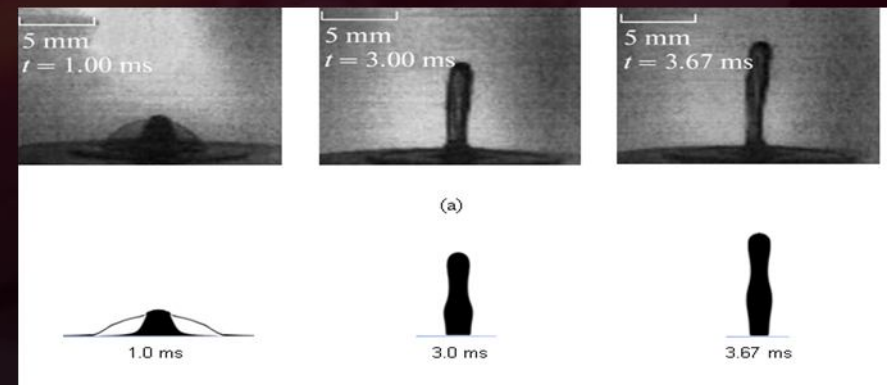
Dense droplet with solid core



Droplets on rough surface



Hollow droplets



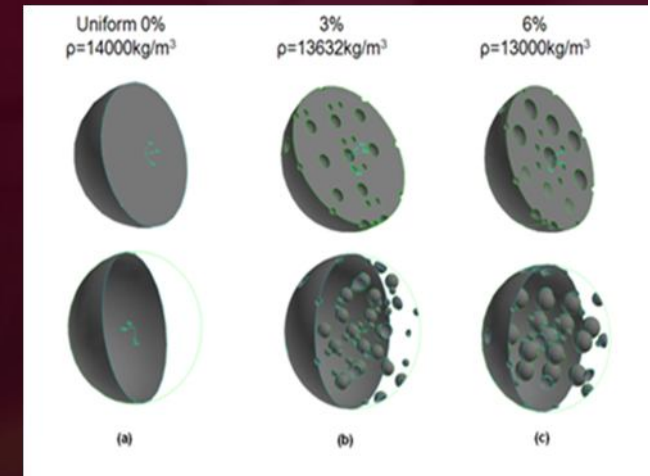
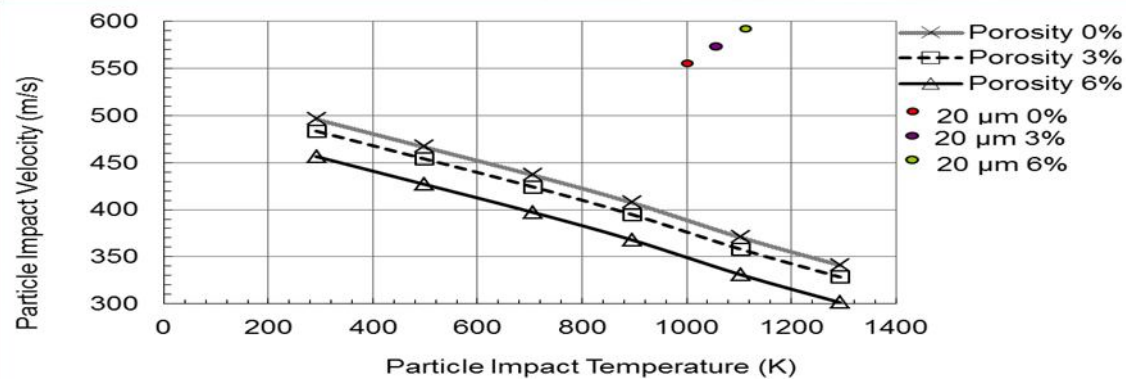
Arvind Kumar, Sai Gu, Spyros Kamnis, Simulation of impact of a hollow droplet on a flat surface. *Applied Physics A: Materials Science & Processing* (2012)

H.Tabbara, S.Gu, Numerical study of semi-molten droplet impingement, *Applied Physics A: Materials Science & Processing*, 104:1011–1019 (2011).

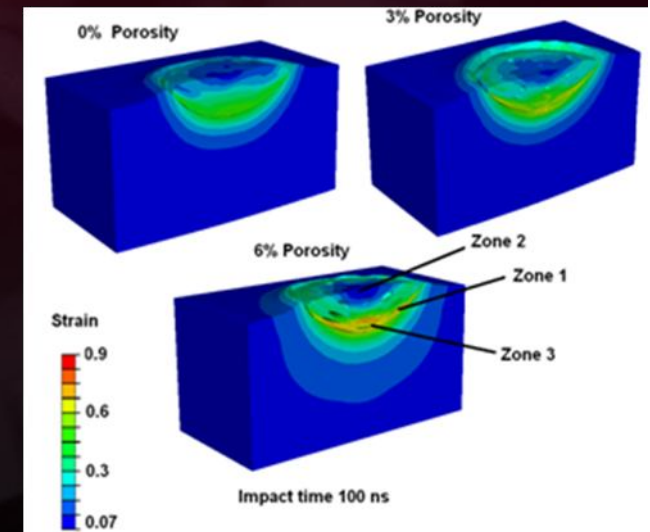
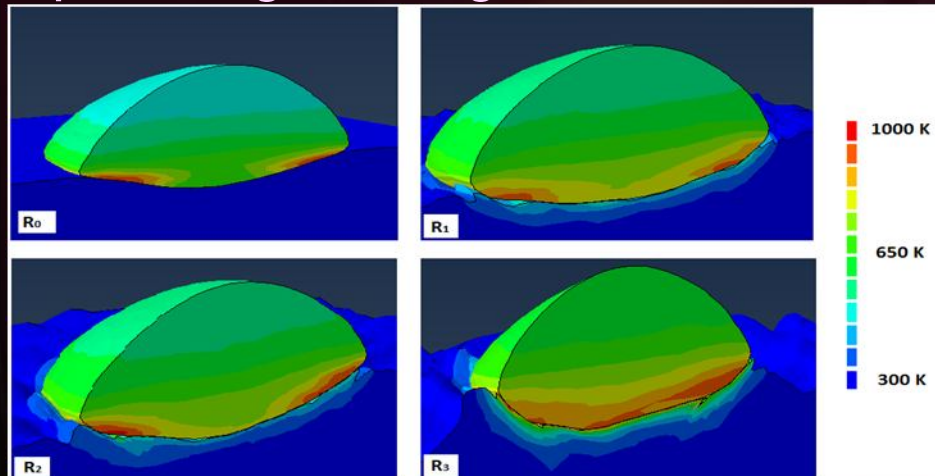
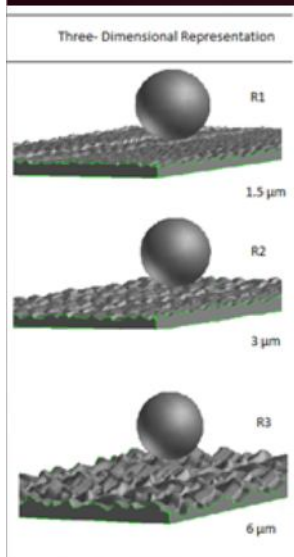


Modeling to support both SPSPS processing and impact of ingested particulates

Porous solid particle Impact Dynamics



Spreading on rough substrate



-S.Kamnis, et al, Metall. Mat. Trans. A, 2010



Facilities with Collaborating Partners

ARCI

- Solution based thermal plasma spray
- 6 kW Diode laser
- Thermal spray oven
- FE SEM, EBSD, TEM, XRD, FIB, SAXS
- ICP for in situ residual stress measurement during loading
- Nanoindentation
- Raman Spectroscopy
- Automated thermal cycling furnace
- Erosion tester

University of Cambridge

- Vacuum plasma spray
- Particle size analyser
- Mercury porosimetry
- BET surface area analyser
- Dynamic and static rigs for measurement of elastic constants
- Surface profilometer
- Raman spectrometer
- Nanoindenter (vacuum / high temperature)
- Periodic quenching furnace

Cranfield University

- High speed computing cluster
- Abacus software
- FLUENT software



Industry Partner 1 : AMT NETHERLANDS

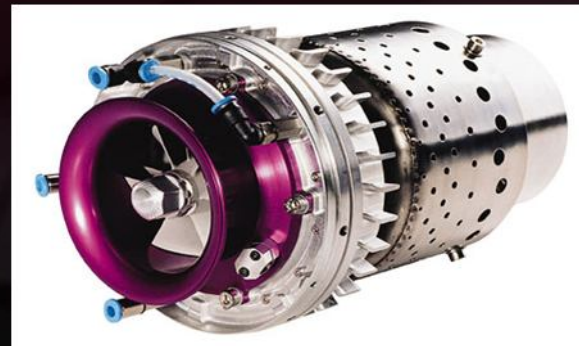


AMT Netherlands designs and manufactures small gas turbines for the propulsion of radio-controlled aircraft, experimental aircraft development, acoustic studies and full size gliders. Turbines are also used in research and education projects at universities around the world.

- Established in 1991, and managed by Bennie van de Goor, AMT Netherlands has over 20 years experience in the development and flight demonstration of high performance jet powered aircraft.
- Based in Geldrop, in the Netherlands, AMT has been growing steadily over the last 18 years to cater for the increased demand for micro turbines in all markets.



Nike (max thrust of 780N)



Pegasus HP
(max thrust of 170N)

For further details visit:
www.amtjets.com



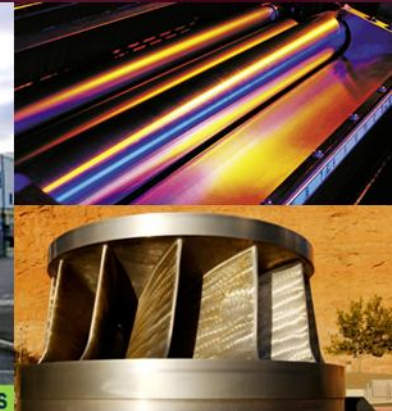
Industry Partner 2 : MONITOR COATINGS LTD.



MONITOR COATINGS



SURFACE ENGINEERING IN EXTREME ENVIRONMENTS



Monitor Coatings Limited is a privately owned company with over 30 years experience of providing high quality coatings to demanding industries such as Aerospace, Oil & Gas exploration, Steel and many others where high performance is required in problematic hostile environments.

- Provides a wide range of coatings and surface engineering disciplines to combat various chemical, physical and mechanical environments
- Based in North Shields, UK, Monitor has one of the largest Low Pressure Plasma Spraying (LPPS) facilities in Europe.

For further details visit: <http://monitorcoatings.com/home>



UK-India Research Initiative on Advanced Manufacturing



Industry Partner 2 : MONITOR COATINGS LTD.

Monitor Coatings Group - A Global Network





Industry Partner 3 : Associated Plasmatron Pvt Ltd

PLASMATRON
An ISO 9001 2000 Certified Company

Gas Turbine Components

Comprehensive coating and finishing facilities

Routinely deposit

- Carbides
- Ceramics
- Metals & Alloys
- Cermets
- Colmonoy
- Stellite

These coatings can be finished as per specific finish and dimension requirements.

List of gas turbine components routinely coated:

- Turbine Blades
- Rotor Shafts
- Fretting/Wearing Rings

www.plasmatronindia.com



Plasma spray coatings for gas turbine components



Industry Partner 4 : Bharat Heavy Electricals Limited



BHEL - the largest Gas Turbine manufacturer in India, with the state-of-art facilities in all areas of Gas Turbine manufacture provide complete engineering in-house for meeting specific customer requirement. With over 100 machines and cumulative fired hours of over four million hours, BHEL has supplied gas turbines for variety of applications in India and abroad. BHEL also has the world's largest experience of firing highly volatile naphtha fuel on heavy duty gas turbines.

Will get them on board at an appropriate time !!!

www.bhel.com



Gas turbine rotor on assembly bed at BHEL, Hyderabad



Industry Partner 5 : Gas Turbine Research Establishment



Gas Turbine Research Establishment is one of the pioneering Research and Development Organizations under the Ministry of Defence, Government of India. The main charter of the Establishment is to design and develop gas-turbine engines for military applications, besides carrying out advanced research work in the area of gas-turbine sub-systems. In addition, the Establishment is responsible for establishing the requisite computational, prototype manufacturing and test facilities for components and full-scale engine development. The Establishment has a strong team of over 1200 personnel drawn from various faculties for science and engineering which includes aeronautics, mechanical, electronics, computer science, materials science, applied mathematics, etc. and support services.



Will get them on board at an appropriate time !!!



Outcome of the Project

- Improvement of performance of protective ceramic coatings in gas turbine engines (for both propulsion and power generation)
- Improved understanding of the mechanisms by which ingested species (such as sand, ash, salt etc.) can cause degradation and debonding of these coatings
- Evaluation of some promising counter-measures (which have not previously been investigated for this purpose)
- Determining a surface engineering protocol that will provide an optimal solution



Dream !?!

- Improved understanding of degradation of TBC systems under actual engine conditions
- Ability to “tailor” material/coating combinations for future generations of aero-engines, land-based gas turbines to combat CMAS attack
- Industrial project partners capable of, and interested in, implementing counter measures



**TECHNOLOGY
LEADERSHIP**



Thank You!