User case study

Cranfield University (United Kingdom)

High temperature tools for designing sustainable erosion resistant coatings

Overview

Cranfield University is addressing one of the critical challenges faced by aerospace engine manufacturers and operators in their journey to achieve net zero [1]. Their goal is to reduce both total life cycle costs and the environmental impact of their products.

This case study looks at Thermal Barrier Coatings (TBCs) as applied to the hot section of the gas turbine. Here, the environment in the turbine engine is extreme, rotating parts (12,000 rpm) operate at temperatures above 1200 °C and each blade experiences a suspended load equivalent to a double-decker bus. In service, the TBCs suffer damage caused by ingested airborne dust which erodes the TBC and limits operational life.

TBCs are comprised of a low thermal conductivity ceramic topcoat and a metallic bond coat offering oxidation protection to the underlying nickel superalloy substrate.

The industry standard ceramic topcoat (≈ 200 µm thick 7 wt.% yttria stabilised zirconia, 7YSZ) enables the surface of the blade to operate at temperatures up to 170 °C higher than that experienced by the blade itself and, at times, above the melting point of the substrate alloy. Such coatings are deposited by Electron Beam Physical Vapour Deposition. The processing conditions result in a strain compliant columnar microstructure as in Figure 1 a) and b).

However, new, multi-functional TBC materials and microstructures are required for the sustainable net zero journey. Such materials will enable combustion at higher temperatures, thereby increasing engine efficiency and reducing emissions. Suitable tools are needed to accelerate time to market development of new TBCs.

TBC systems are screened in Cranfield's erosion rig which consists of an air gas gun projecting particles at up to 200 m/s at the TBC coated substrates; this test closely simulates the damage observed in the engine. The NanoTest impact tool, Figure 1 c), is a timely addition to the engineer's toolbox enabling rapid simulations of erosion that can be fine-tuned to simulate the damage observed on actual components and in erosion tests. The tool also provides physical property data to facilitate the design of next generation TBC systems and supports modelling activities.

NanoTest Vantage platform configuration used:

- Nanoindentation
- Microindentation
- Nano-impact
- Micro-impact
- 850 °C hot stage

The NanoTest Vantage has been used to perform repeat micro-impact tests at the same position at a range of applied loads (500-3000 mN) using a calibrated spheroconical diamond probe with 25 µm end radius and 90° cone angle impacting at 90° to the surface accelerating from 50 µm above the initial coating surface. Randomised (statistically distributed) micro-impact tests at 500 mN were performed with a programmed number (50-500) of statistically distributed impacts within different sized regions (0.01-1 mm^2).

Randomised Impact Experiments

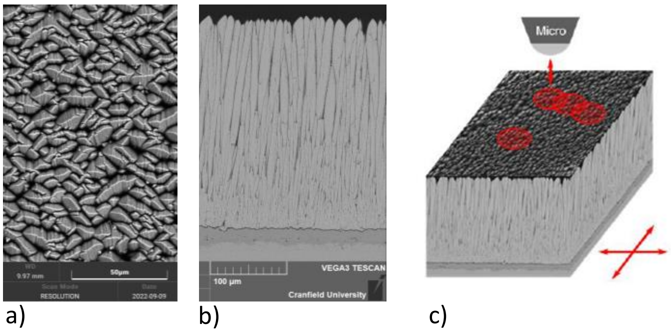

Figure 1. SEM images of TBC a) top, b) cross-section and c) Micro-impact tool graphic

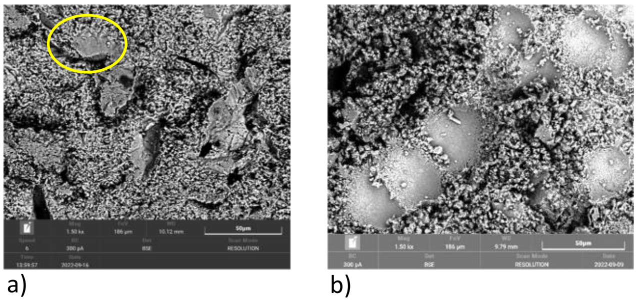

Figure 2. SEM images of surface TBC damage caused in a) Cranfield erosion test and b) random impact test on trial TBC.

Initial trials focused on exploration of impact test variables to best simulate damage features observed in erosion tests. Such variables included indenter geometry, impact load, impact angle, and density of random impacts. Figure 2 a) shows surface damage observed in erosion tests including column compaction, highlighted in yellow, and the considerable amounts of TBC debris from fractured columns accumulating on the surface. Figure 2 b) shows random impact damage of the same coating system with similar damage features. Here, more compacted regions are observed but at greater density than in the erosion test.

Cross-sectional images of damaged regions from the impact and erosion test methods strengthen the comparison, Figure 3. The impacted region, Figure 3 b), shows similar cracking across several columns but rather more compaction of columns in the surface region and some sub-surface column distortion which is less evident in the erosion test. This suggests that random micro-impact testing can generate the same damage mechanisms of erosion and further optimisation of the impact parameters could adjust the compaction vs cracking ratio.

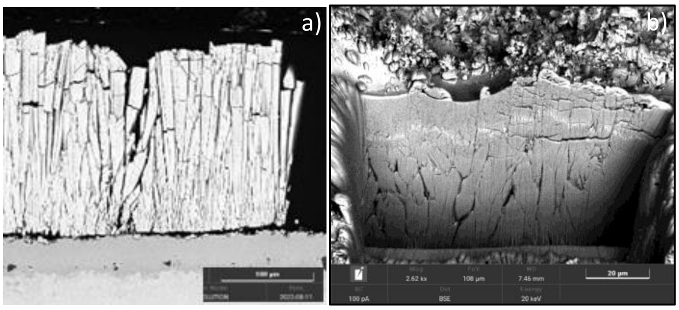

Figure 3. a) cross-section image of erosion test damage and b) FIB-SEM image of random impact test damage showing across column cracking.

Our joint research programme [2] with Micro Materials Ltd concluded with a set of ranking experiments comparing behaviour of reference and novel TBC systems (with material and microstructure variations) under erosion testing and impact testing. While erosion is ranked by the ratio of coating loss per amount of erodent in g/kg, impact test systems were ranked by impact volume. All TBC systems tested were correctly ranked except for TBC variant 2. Its anomalous but interesting behaviour merits further investigation and will support studies in the development of tougher new TBC materials and microstructures.

TBC Variant	Relative Erosion rate (g/kg)	Erosion rank	Random impact rank
TBC1	1	1	1
TBC2	6.3	2	4
TBC3	6.9	3	2
TBC4	20.0	5	5
TBC5	8.8	4	3

User profile

The Surface Engineering and Precision Centre team at Cranfield has many years' experience in the design, manufacture, testing and analysis of materials for extreme environments. The team has worked with Micro Materials Ltd on several Innovate UK projects using nanoindentation and related techniques at room and elevated temperatures. The group is part of the Henry Royce Institute based at Cranfield which offers many of its coating and testing facilities to SMEs and the academic community, free of charge, https://www.royce.ac.uk/ https://www.cranfield.ac.uk/centres/surface-engineering-and-precision-centre

Highlights from the user

- Damage created in cyclic impact tests is similar to that seen in eroded TBC samples.
- The same 'random impact' test can be used to test each TBC removing the uncertainty of the stochastic nature of erosion test and erosion experienced in service.
- Erosion testing is a time consuming, expensive, and intensive test technique. Micro-impact testing can be used for rapid screening of new coating systems.
- Data generated can be used to support Finite Element Analysis of ballistic impact. Such data can often be difficult to find in literature.

Quote from the user

"The micro-impact test speeds up our research by allowing us to rapidly screen novel coating systems for promising erosion resistance"

References and Acknowledgements

1. *Ceramic coatings for jet engine turbine blades carbonbrainprint@cranfield.ac.uk*
2. *This work was funded by an Innovate UK Smart grant 10020751 'High Temperature tools for designing sustainable erosion resistant coatings.*

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