High temperature oxidation and burner rig testing of different TBCs in the frame of the European Project TOPPCOAT: A summary of results

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High temperature oxidation and burner rig testing of different TBCs in the frame of the European Project TOPPCOAT: a summary of results.
TOwards design and Processing of advanced, comPetitive thermal barrier COATing systems
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Main objective of the Project

The major S&T objective of the project is the development of improved TBC systems using advanced bonding concepts in combination with additional protective functional coatings. The first specific objective will be to use these developments to provide a significant improvement to state-of-the-art APS coatings and hence provide a cost-effective alternative to EB-PVD. The second objective will be to combine these new concepts with new coating technologies to provide new, advance materials for thermal barrier systems with a capability exceeding the performance of EB-PVD coatings.
Segmented APS YPSZ TBC

Highly segmented f&c

Highly segmented spray dried

Nano -Suspension Plasma Spray
Layered or 3D interfaces segmented APS TBC

Double layered YSZ/spinel coating

3D interface YPSZ

classified

Reference APS porous YPSZ

HOSP ZY Guard

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Columnar structures and new compositions

- LPPS-TF
- PECVD YPSZ
- HS- PVD
- PECVD GdLAO
- Reference EB-PVD
Testing approach

**SCREENING TESTS:** LONG CYCLE FURNACE TESTS AND BURNER RIG (DISK GEOMETRY)
AFTER THE SELECTION, LONG AND SHORT CYCLE FURNACE TESTS AND BURNER RIG (CYLINDRICAL GEOMETRY)

IN LONG CYCLE FT MORE THAN 130 SAMPLES AND 25 DIFFERENT TBCs SYSTEMS (BC, 3D, TBC POWDERS, TBC THICKNESS, DEPOSITION PARAMETERS AND SUPPLIERS) HAVE BEEN TESTED AT 3 DIFFERENT TEMPERATURES.

MORE THAN 40 SAMPLES HAVE BEEN TESTED IN GKN AEROSPACE BURNER RIG (SAMPLE SIZE, BC, 3D, TBC POWDERS, TBC THICKNESS, DEPOSITION PARAMETERS AND SUPPLIERS)
Number of samples

- Define number of samples to be tested within the same experimental conditions for a statistically significant estimation of the lifetime of the different TBCs systems.

<table>
<thead>
<tr>
<th>Decision</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>fail to reject H0</td>
<td>correct decision $p = 1 - \alpha$</td>
<td>Type II error $p = \beta$</td>
</tr>
<tr>
<td>reject H0</td>
<td>Type I error $p = \alpha$</td>
<td>correct decision $p = 1 - \beta$</td>
</tr>
</tbody>
</table>

The probability ($p$) of making a Type I error is called \textbf{alpha} ($\alpha$) and is sometimes referred to as the \textbf{level of significance} for the test. When $H_0$ is false and you fail to reject it, you make a type II error. The probability ($p$) of making a type II error is called \textbf{beta} ($\beta$).

In our specific case the $H_0$ hypothesis is that the average lives of one TBC set differ by another by $X\%$. We fixed a level of significance equal to 5% (the two systems differ by $X\%$ but we reject the hypothesis) and a power of at least 95%.
Number of samples
Screening tests - GKN aerospace Burner rig

<table>
<thead>
<tr>
<th>Gas flow (SLPM)</th>
<th>Hot max frontside T [°C]</th>
<th>Hot max backside T [°C]</th>
<th>Max BC T [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.5 - 33</td>
<td>1200</td>
<td>920</td>
<td>1020 - 1100</td>
</tr>
</tbody>
</table>

Failure criterion: 10% spallation surface area as observed by two video cameras (hot and cold positions). Hot front side temperature increase.
Highly segmented f&c

Double layer
Highly segmented

Screening tests - Volvo Burner rig
Screening tests - Volvo Burner rig

Large coupons results

EB & HS PVD

PVD DySZ

3D+highly segmented
Screening tests - Alstom FCT

Temperature of samples during FCT

<table>
<thead>
<tr>
<th>0</th>
<th>250</th>
<th>500</th>
<th>750</th>
<th>1000</th>
<th>1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>Di</td>
<td>Mi</td>
<td>Do</td>
<td>Fr</td>
<td>Sa</td>
</tr>
</tbody>
</table>

- 4 cycles 23h/h + 1 cycle
- 7h/h at 1050°C/30°C
- approx. 30 cycles / 1000 h

Failure criterion: spallation area wider than 10%
Screening tests - Alstom FCT

No failure occurred
Screening tests - Alstom FCT

FCT @1100°C

<table>
<thead>
<tr>
<th>Method</th>
<th>Time to failure [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF-LPPS SM204 NS mod</td>
<td>3286</td>
</tr>
<tr>
<td>HS-PVD</td>
<td>2820</td>
</tr>
<tr>
<td>EBPVD</td>
<td>2793</td>
</tr>
<tr>
<td>TF-LPPS DSZ</td>
<td>2560</td>
</tr>
<tr>
<td>PE CVD n°1</td>
<td>1704</td>
</tr>
<tr>
<td>PE CVD YSZ</td>
<td>955</td>
</tr>
<tr>
<td>PE CVD GLAO</td>
<td>369</td>
</tr>
</tbody>
</table>

Average values:
- TF-LPPS SM204 NS mod: 3286 ± 591
- HS-PVD: 2820 ± 266
- EBPVD: 2793 ± 291
- TF-LPPS DSZ: 2560 ± 94
- PE CVD n°1: 1704 ± 188
- PE CVD YSZ: 955 ± 186
- PE CVD GLAO: 369 ± 47
Screening tests - Alstom FCT

**FCT @1050°C**

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 6 HCST 827.7</td>
<td>1470</td>
<td>182</td>
</tr>
<tr>
<td>System 4 SM ZYGuard</td>
<td>1063</td>
<td>229</td>
</tr>
<tr>
<td>System 4 TIAG f&amp;c</td>
<td>900</td>
<td>85</td>
</tr>
</tbody>
</table>
FCT tests - RSE Short cycle (2h)

Some samples have been tested up to the End of Life while the others have been stopped at shorter times for characterisation of the kinetics of TGO and Dext growth.

Failure criterion: spallation area wider than 10%
FCT tests - RSE Short cycle (2h)
Comments

• Although more samples would be needed for statistically sound conclusions:

  ✓ by increasing the temperature and reducing the cycle length a discrimination among different TBC systems is allowed

  ✓ failure mode of 3D samples differ from that of the other APS coatings

  ✓ 3D and porous reference APS samples seem to be the best performers*

  ✓ The PVD coatings perform similarly within the scatter of data, as pointed out also by long cycle FCT
FCT tests - follow up: modelling

\[
\frac{da}{dt} = A \left( G_{el} + \frac{1}{b} \times G_{TGO} \right)^m \\
G_{TGO} = \frac{E_{TGO} \times (1 - v_{TGO}^2)}{(1 - v_{TGO})^2} \times (\beta \times (1 + f_{ox}))^2 \times d_{TGO} \times Y^2 \times f(r)
\]

\[
G_{el} = \frac{E_{TBC}}{2} \times \left( 1 - v_{TBC}^2 \right) \times \left( (\alpha_{th}^{TBC} - \alpha_{th}^{Sub}) \times (DBTT - T_{min}) \right)^2 \times d_{TBC} \times Y^2 \times f(r)
\]

FCT tests - follow up: modelling

E vs. time for T

T=1100°C

E estimation

Pore Sintering

FCT tests - follow up: modelling

Different TBC powder

Estimated minimum EoL [h]  
Experimental EoL [h]

Time to failure [h]

Sys6 @1050°C 2 h  
21% porosity

Sys6 @1050°C 24 h

Sys 6§ @1000°C 24 h

Sys 6@1050°C 2h
15% porosity

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Failure criterion: spallation length >8 mm
• TBC SURFACE TEMPERATURE 1200°C
• 3 SAMPLES EACH SYSTEM
• 200 RPM COMPATIBLE WITH PYROMETER
• MINIMUM ACQUISITION TIME
• STOP EVERY 30 CYCLES FOR CHECK INTEGRITY OF TBC
NLR Burner rig
Thermal diffusivity measurements of TBC and substrate

Thermo-fluid dynamic modeling

TGO and Dext of FCT @1000°C and 1050°C

TBC thickness measurements

Thermo-fluid dynamic modeling

TBC surface and BC temperature estimation

TBC surface temperature measurements

BC temperature estimation
NLR Burner rig - modelling
NLR Burner rig

Although TBC and BC temperatures as estimated by the model of the samples show large variations (20 – 40°C) compared to the pyrometer and TGO&Dext estimations, respectively, the outcomes of the model are in line with the experimental data.

Possible causes for quantitative misfit could be:

• differences in **heat transfer coefficient** per coating system owing to **different roughness**.
• differences in **surface emissivity** of both the TBC and the metallic substrate
• **local differences in coating thickness**. For the calculations an average coating thickness was used. The thickness of the coating at the measurement spot of the pyrometer might differ more than ±10% as indicated by the measurements
• differences in **thermal conductivity** between coated test **pins and coated buttons**. This could be especially true for 3D interface samples. In fact thermal diffusivity estimation for such a complex sample could be affected by a higher uncertainty: TGO and Dext has been measured between 3D structure while thermal diffusivity and TBC thickness have been considered on the whole section.

Temperatures 3.5 cm far from the failure zones resulted 50 – 75°C lower (as estimated by TGO&Dext thickness)
SPE: the erosion rates

- LPPS-TF™ performs better than the other TBC systems at low speed
- HS APS performs similar to EBPVD TBC
- Erosion rate decreases with impingement angle. The increase from 30° to 90° is in the range 20% - 85%
- Erosion rate increases from 4 to 9 times increasing the speed
- The index $n$ estimated by comparing erosion rates @ two speeds is close to 2 (3 for bulk ceramics)

The results: $90^\circ \; v=40 \text{ m/s} \; 104 \text{ µm}$

- LPPS-TF performs better than EB-PVD and HS-APS (low speed)
- Erosion rate increases one order of magnitude from SiO$_2$ to Al$_2$O$_3$ for PVD and Segmented APS systems (the particle size distribution coarser for SiO$_2$)
- Porous APS is so poorly resistant that erosion rate is less sensitive to particle hardness (Samples supplied by another Lab!! Porosity 16% vs 23%)

The results: $90^\circ \ v=40 \text{ m/s}$

- Erosion rates decrease from coarse to fine particle size.
- LPPS-TF performs better than EB-PVD and HS-APS
- HS APS performs similar to EBPVD TBC
Erosion tests using Alumina mesh 150 powder @950°C

V_i = kE_i^1.4

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Conclusive remarks

Although the outcomes from the testing activity give some indications on the performances of the different TBCs systems, the number of samples tested in each experimental condition is not high enough be statistically significative, but a complete characterisation of all the tested samples was well beyond the efforts and the time scheduling of the project.

Some TBC systems have been tested during the development phase when not all the deposition parameters were completely optimized. This means that poor results cannot be considered as the final finding.
Thank you very much for your attention!