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TOwards design and Processing of advanced, comPetitive thermal barrier COATing systems

TOPPCOAT

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PU	**Public**	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

0. Preface

This publishable summary describes the scientific work performed in the STREP 6 project

T O P P C O A T.

TOwards design and Processing of advanced,
comPetitive thermal barrier COATing systems

This report gives an overview of the work performed in the eight foreseen work packages to achieve the main objective of the project, namely to achieve significant improvements to thermal barrier coating (TBC) systems used for gas turbine applications by introducing a number of key innovations.

1. Content

2. Participant List

Table 1: Project participants

Partic. Role*	Partic. no.	Participant name	Short name	Country	Date enter project**	Date exit project**
CO	1	Forschungszentrum Jülich, IEF-1	FZJ	GER	month 1	
CR	2	Avio	Avio	IT	month 1	
CR	3	Snecma Moteurs	SNECM	FR	month 1	month1
CR	4	Snecma Services	SNECS	FR	month 1	
CR	5	Alstom	ALSTOM	SUI	month 1	
CR	6	Turbocoating SpA	TURBO	IT	month 1	
CR	7	Treibacher Industrie AG	TIAG	AUS	month 1	
CR	8	Southside Thermal Sciences. Ltd.	STS	GB	month 1	
CR	9	Volvo Aero Corporation	VAC	SWE	month 1	
CR	10	Högskolan Trollhättan/Uddevalla -	HTU	SWE	month 1	
CR	11	ERSE S.P.A.	ERSE	IT	month 1	
CR	12	National Physical Laboratory	NPL	GB	month 1	
CR	13	National Aerospace Laboratory	NLR	NL	month 1	
CR	14	Rolls-Royce Deutschland	RRD	GER	month 1	
CR	15	Sulzer Metco AG	SM	SUI	month 1	
CR	16	Onera	ONERA	FR	month 1	

CO:= Coordinator

CR:= Contractor

3. Description of the project

In general, TBCs consist of an oxidation resistant (Co,Ni)CrAlY bondcoat and a insulating yttria-stabilized zirconia topcoat. To apply the ceramic topcoat, two process routes can be used: the atmospheric plasma spraying (APS) or electron-beam physical vapour deposition (EB-PVD). In the APS process, the material is deposited from the molten phase, while EB-PVD uses deposition from the gas phase. The use of the much more expensive EB-PVD process for highly loaded parts results from the columnar structure of the coatings giving improved strain tolerance and improved reliability. The in-service life of these coatings is now around 8000 hours.

3.1. Objectives:

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 material for thermal barrier systems with a capability exceeding the performance of EB-PVD coatings.

In both cases, a major impact on TBC performance, manufacturing and maintenance costs and hence competitiveness of European aviation gas turbine manufactures is expected.

3.2. Scientific approach – concept overview

Segmented or columnar structures within the TBC in combination with excellent bonding are expected to improve the durability and reliability of TBC systems.

Preliminary investigations on the development of 3D interfaces by some of the consortium partners had already shown that improvements to bonding can be obtained. This study was continued but the 3D profiling was also investigated as a method to control the microstructure of the TBC layer. A precise control of the microstructure was possible as the location of the segmentation cracks was directly correlated to micro-structural features on the substrate and this was used to initiate segmentation cracks in the coating. By this technique it was expected to gain significantly higher segmentation densities than by using only thermal spray technique on conventional rough substrates.

In order to take full advantage of this, the use of advanced spraying techniques both to initiate the segmentation cracks and to control the coating process in order to obtain desired reproducibility was essential. This included on-line particle diagnostic systems, precise substrate temperature control as high substrate temperatures and the use of advanced APS gun technology. All were essential for control segmentation crack formation.

Within the project the developed segmented APS coatings were compared with standard EB-PVD coatings. It is anticipated that this route will lead to TBC systems with performance close to that of EB-PVD but at a fraction of the cost having impact in both new component and repair businesses.

The project was aimed towards the next generation of TBC systems. In addition to the techniques developed above, further innovate steps were investigated. There are new, emerging technologies which showed the potential to produce highly strain-tolerant coatings in a cost-effective way. The processes that were identified as having the most potential are; thin film - low pressure plasma spraying (TF-LPPS), plasma enhanced chemical vapour deposition (PE-CVD), nano-phase suspension plasma spraying and hollow cathode gas sputtering PVD (GS-PVD). Investigations determined the single most promising process for the deposition of TBC systems. Also new, advanced TBC materials such as aluminates and modified spinels were included.

Background for the understanding of the performance of EB-PVD and APS coatings

In order to make a step forward in TBC systems it is important to have a detailed understanding of the reasons for the long lifetimes of EB-PVD compared to APS coatings. In fact, two basic differences between the coatings can be observed which appear to provide the main reason for the failure and hence for the lifetime of the coatings (Table 1):

	EB-PVD	APS
A) Microstructure	columnar structure	horizontal micro cracks
B) Interface	smooth	rough

Table 1 Major differences between APS and PVD coatings.

These two major differences were tried to overcome by the methods described in the proposal.

3.3. Microstructure

This section will first explain the effect of segmentation cracks and will then discuss, how they can be produced with outstanding micro-structural control.

Influence of segmentation cracks on performance – Why do they help?

Looking at the micro-structural issue it is known from thick TBCs that segmentation can provide large improvements in cyclic life-time. This behaviour can be understood in terms of critical energy release rates; this energy is available for crack growth in a system and it increases linearly with coating thickness. This means that more energy for crack propagation is stored elastically in the coating. Especially critical are the tensile stress levels during fast cooling of the coatings by compressed air. These tensile stress levels are reduced in a segmented coating since the segmentation cracks can open during tensile loading and release stress. For thin coatings the critical tensile stress levels are lower but, even so, segmentation is advantageous during fast cooling.

Segmentation also has a second effect on the stress state in coatings. Generally, plasma-sprayed coatings are in a tensile stress state at high temperatures due to the higher thermal expansion coefficient of the substrate. This tensile stress states will be relaxed (in typically micro cracked coatings) after some time. A subsequent cooling to room temperature will then lead to compressive stresses in the coatings which are critical for crack growth and hence life time. In a segmented coating the high temperature stress states will not be generated (or at least to a much lesser extent). This is because the segmentation cracks can simply open further under tensile stress. Similarly, no (or at least low) stresses will exist during cooling. This argument only holds if the distance between segmentation cracks is at least comparable to the coating thickness resulting in an advantageous crack density above 5 mm^{-1} for 200 to 300 µm thick coatings. This high density is certainly above the state-of-the-art (below 4 cracks mm^{-1})

However, the situation becomes more complex when additional strains due to external forces and the temperature gradient through the metallic blades are considered. As the coating of these blades is most critical these strains are considered to play a key role for the improved life-time of PVD coatings. Typically, compressive stresses are generated at high temperatures at the metallic surface of the blades because the surface cannot expand freely due to the cooler, inner core of the blade. As a result, especially for the hottest part of the TBC, its surface can reach a compressive stress level. Unfortunately, if the segmentation cracks become closed under these conditions, they start to sinter and the overall strain tolerance is lost. Thus, a certain crack opening is essential to provide a sufficiently long life-time for the coatings. Based upon this description of the failure mechanism, the following optimal coating features have to be obtained:

- High crack density to avoid high tensile stress levels in segments (> 5 cracks mm^{-1})
- Straight crack path to avoid blocking of crack opening and sintering
- Large crack spacing to avoid sintering at high temperatures

3.4. Physical background of the proposed crack initiation concept - why will it work?

High densities of segmentation cracks can be generated by adjusting “hot” spraying conditions with high substrate temperatures in combination with rather thick layers per spraying pass. Large segmentation crack densities have even been generated by use of a single spraying pass However; these techniques do not seem to be suitable to achieve sufficiently high, homogeneously distributed, segmentation crack densities (>5 cracks mm^{-1}), which are needed for the desired coating performance. From earlier investigations on the deposition of rather thin (about 100 µm) YSZ coatings (for solid oxide fuel cell applications) it is known that certain features in the substrate lead to the formation of segmentation cracks. While for this application these cracks are detrimental, the underlying mechanism offers a new degree of freedom in the design of segmentation in coatings. Both valley and hill type undulations might be suitable for crack initiation as both lead to stress concentration and hence crack initiation.

In our proposed interface promoted segmentation crack formation an upper limit of the segmentation crack density might exist as the formation of the cracks will lead to a stress relaxation and hence, to a reduced driving force for crack growth. One would expect a lower limit for the distance between segmentation cracks to be close to the coating thickness at the moment the segmentation cracks are formed. From earlier investigation this critical thickness seems to be below 100 µm and might be even lower for these artificially notched coatings. So, an establishment of segmentation crack densities even above 10 cracks mm^{-1} seems reasonable by the proposed process.

3.5. Interface

Design of the interface structure

The interface between the bondcoat and TBC in PVD systems is typically very smooth with roughness values below 2 µm. In contrast, bondcoats for APS systems are very rough (6-12 µm) to ensure a good interlocking between topcoat and bondcoat. It has been found in many investigations that roughness plays an important role for the failure of APS systems. The roughness leads to tensile and shear stresses in out of plane direction and these stresses often promote crack growth and hence failure.

In our, new approach bonding will not rely on the rather randomly produced roughness profiles (typically for conventional spray processes) but by well-defined 3-dimensional substrate surfaces. Investigations have indicated that a macroscopic 3D interface can improve the life of thick coatings by an order of magnitude when compared to standard methods for a MCrAlY bondcoat. Several techniques are available to produce such well-defined surfaces. These include selective etching; structured overlays attached to the surface by joining methods and modified coating deposition processes. In this project, these will be produced by subcontractors. The 3D interface will be designed in such a way that the bonding is enhanced and the tendency for crack initiation and growth reduced. This will be achieved by substrate modifications/undulations having distances from each other which will reduce the chance of crack interaction and coalescence.

In summary, the following issues will be addressed by features on the substrate and were investigated and developed in the project:

- Optimized interface design for excellent bonding and reduced driving forces for delamination crack growth
- Application of additional bonding (and protection layers)
- Initiation of the formation of segmentation cracks

The following table summarises the project objectives:

Objective	Action	Specific Improvement	Verification Process
To improve upon APS coating lifetimes to those approaching EB-PVD (i.e. 8000hrs)	Use of controlled 3D surface morphology	Increase in bonding, reduced stress levels	Rig tests , 4-point bending compared to standard
	Use of controlled 3D surface morphology	Increase segmentation crack density (> 5 mm^{-1})	Microstructure investigation
	Combination of all	Improved bonding, high segmentation crack density	Evaluation
To transfer advanced gas phase processes to industrial application	Coating of complex and 3D surfaces	Improved bonding, homogeneous coating thickness, availability of repair technology	Rig tests , 4-point bending compared to standard microstructure, thickness measurement application to repair parts
To provide a cost effective alternative to EBPVD	Optimum combination of the above	1.5% reduction in manufacturing costs	Cost benefit analysis
To increase temperature capability of coatings	introduce new coating materials by novel processes capable of depositing them; develop sintering resistant microstructures	Use of alumina based material; Use dense microstructures	Thermal gradient tests sintering tests
To increase engine efficiency	Optimum combination of the above	To increase turbine inlet temperatures (TIT) by 20-30K	Final evaluation

Table 2 Measurable and verifiable objectives

3.6. Project Organisation

The project was divided into 7 work packages as follows:

- WP Detail
- WP1 Technical specification, procurement of bondcoat and substrates
- WP2 Optimisation of starting powders and materials
- WP3 Interface modifications
- WP4 Advanced technology for manufacture of strain tolerant coatings
- WP5 Screening of key properties and full characterisation
- WP6 Transfer & application of technology
- WP7 Final evaluation

4. Short summary of the results

4.1. Work package 1

To have a large data base, the consortium decided to prepare 21 different TBC systems consisting of different bondcoats and topcoats. To compare the new specimen with state of the art TBCs, also an APS reference and an EB-PVD reference were produced. Beside the standard materials like spray dried YSZ, advanced materials like nano sized YSZ suspension and YSZ precursor in CVD processes were used. For all coating materials, detailed specifications were defined. Furthermore, the substrate material for the different TBC was defined, and samples from raw material like CMSX4 and IN738 were produced. For special geometries, hollow cylinders and massive pins were manufactured via electrical discharge machining.

4.2. Work package 2

The main objective in work package 2 was the production and procurement of powders and precursors. A large batch of fused & crushed YSZ powder was supplied by TIAG, and SM provide a large batch of spray dried YSZ powder. Besides these conventional materials, a YSZ powder with a small amount of Rare Earth was produced in order to use this material as sensor coating material. Further, a YSZ suspension with agglomerated, nano sized particles was developed and optimised by TIAG in collaboration with FZJ. Three batches of fused and crushed magnesia alumina spinel with slightly different contents of Al_2O_3 were produced also by TIAG. ONERA tested different precursor as starting material for PE-CVD coatings.

4.3. Work package 3

As mentioned in the project description, one route to achieve more strain tolerant coatings was the application of 3D interfaces on substrate surfaces. This surface modification was realised by using laser cladding technique. With this method it was possible to produce thin bars on the surface with a height of about 500µm as shown in the Figure 1.

The geometry of the surface structure was optimised. One main aim was the compatibility with the plasma spraying process, namely with the application of a bondcoat and the optimisation of the coating microstructure connected to the 3D interface. Further, the process of using 3D interfaces was transferred to real components.

Another field of activity was the computer-aided modelling of microstructure, spraying process and coating properties.

Figure 1: Cross section of a laser cladded structure.

The project established the laser cladding process to real components with very high coating/cladding rates. It could be shown that the model prediction concerning the coating microstructure was in very good agreement with cross sections of coated 3D samples.

4.4. Work package 4

Work package 4 was the largest work package in the project. The main objective was the development of strain tolerant coatings with different approaches to achieve this aim. The performed work can be divided into the following categories:

<u>Development of TBC with segmentation crack densities of about 10 cracks mm^{-1} using advanced conventional plasma spraying technique</u>

The activities in this field were successful. In summary, three different spraying methods were developed and revealed crack densities above 8 cracks mm^{-1}. One of the developed spraying ideas is filed as a patent. In Figure 2, an example for a highly segmented coating is depicted.

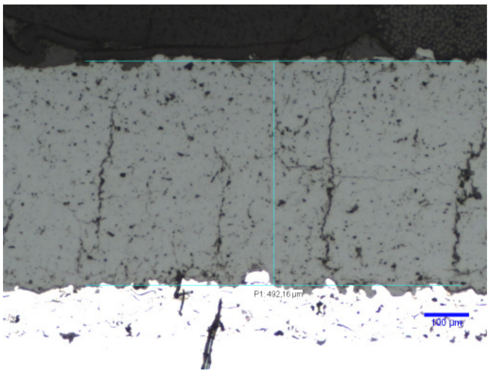

Figure 2: Microstructure of a highly segmented coating.

Development of TBC systems using new materials like nano sized powders

Especially by suspension plasma spraying, it was possible to prepare ceramic coatings with segmentation crack densities above 10 cracks mm^{-1}. The advantage of this technique is a combination of high porosity values within segmented coatings as presented in Figure 3. They showed a very good performance in long term furnace cycling tests.

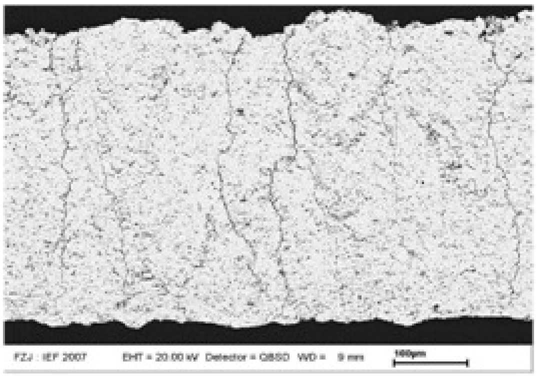

Figure 3: Cross sections of suspension plasma sprayed TBC .

Development of TBCs with columnar microstructure using new techniques like LPPS-TF, PE-CVD

In this part, it could be successful shown that the low pressure process LPPS-TF gives columnar microstructures comparable to EB-PVD coatings (Figure 4). The activities in the area of PE-CVD processes were stopped due to the very expensive feedstock (precursors) and difficulties with phase composition of PE-CVD coatings.

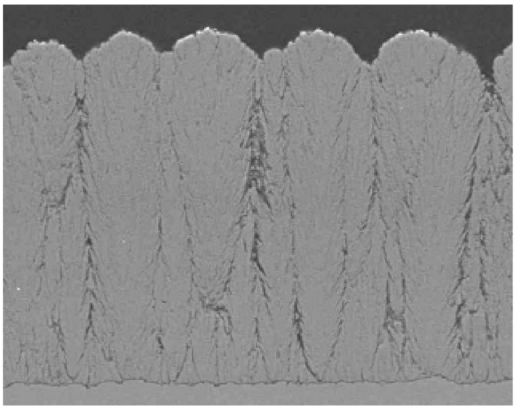

Figure 4: LPPS-TF coating.

Also a task of this work package was the first performance screening of the developed TBC systems. 21 different TBC systems were tested in a furnace cycling test and a burner rig test. These two tests and a comparison of all achieved microstructures was the base for the selection of five different, new TBC systems for further evaluations in the second project half. The five systems were:

- two systems with 3D interfaces, to be coated with TBCs produced with two different kinds of powders
- two highly segmented TBC systems produced with different powders and different spraying processes (F4 technology and TRIPLEX II technology)
- The LPPS-TF system showing a promising columnar microstructure

Beside the new coating types, two reference systems (EB-PVD and APS) were chosen to compare the results with state-of-the-art systems.

A minor part of work package 4 was the development of '*Thermal Barrier Sensor Coating'* for thickness measurements. This was carried out in close cooperation between TIAG (powder manufacturer), FZJ (coating manufacturer) and STS (IP owner[1], coating specification and measurements). When doped with rare earth elements a standard TBC can be made phosphorescent when illuminated with light. By using a layered coating structure of standard YSZ and rare earth doped YSZ it was shown that thickness measurements were possible based on luminescence attenuation. A method was successfully tested by STS which enables to use intensity ratios and consequently makes the system independent on stained or polluted optics.

Altogether, at the end of work package 4 more than 280 test samples with 4 different geometries were produced for tests in work package 5.

4.5. Work package 5

The main task in work package 5 was the evaluation of the developed new TBC systems. The consortium decided to use the following test methods:

- Furnace cycle test (ALSTOM)
- Burner rig test (VOLVO)
- Burner rig test (NLR)
- Corrosion test (AVIO)
- Impulse excitation and four-point bending test (NPL)
- Sintering behaviour (ERSE formerly CESI)
- Thermal conductivity measurement (ERSE formerly CESI)
- Solid particle erosion testing (ERSE formerly CESI)
- Sintering behaviour (ERSE formerly CESI)

<u>Furnace cycling test:</u>

Small coupons have been coated with various bondcoat – topcoat systems and were then tested for oxidation behaviour (in air) at ALSTOM. The coating systems were divided into three classes depending on the TBC thickness. To simulate the effect of the different TBC thicknesses on the bondcoat in an isothermal environment, higher temperatures have been selected for lower TBC thicknesses.

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[1] International publication number: WO2007/023292 A2, 'Measurement, coating and monitoring system and method';2005; Inventors; J Feist, J Nicholls , M Fraser , A Heyes.

The samples were cycled on a daily bases, five times a week. No cycling was performed on weekends, i.e. samples stayed at furnace temperature. The test was aborted for systems after major or total TBC spallation. The duration of the test was approx. one year (= 8760h).

Results:

For thin TBCs (and high cycling temperature), the EB-PVD reference system was the best performer

For thick TBCs (and lower cycling temperature), four developed TBC systems did not show any spallation after the complete test (e.g. highly segmented coatings, sensor coatings, >7000h), while the APS reference spalled off after 4000h.

The TGO growth as well as the BC depletion follows a parabolic behaviour, which is expected for both parameters.

Burner Rig Test (VOLVO)

The Thermal Shock Rig (TSR) is used to test the thermal cycling resistance. The test cycle is symmetric consisting of heating and cooling sections. The hot front side temperature rises up to 1250 ºC, hot backside temperature to 950 ºC. During cooling the test coupons cools down to 400 °C.

The determination of the coating failure was done visually. Two video cameras were used to record a heating position and a cooling position. Failure criterion was defined as 10 % spallation of the surface area regardless of the failure mode.

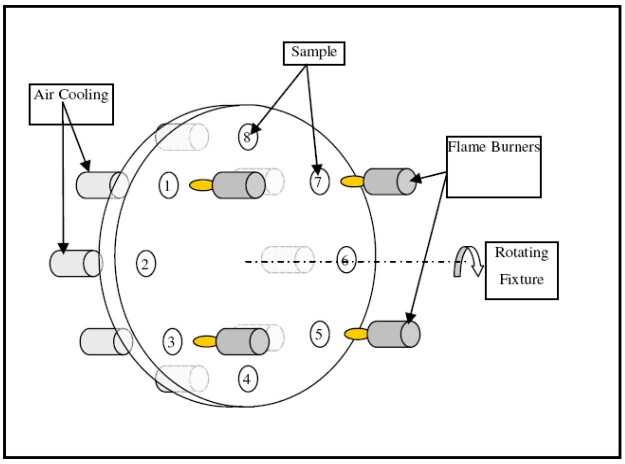


Figure 6: Schematic drawing of burner rig (VOLVO).

Results:

The test revealed a large scattering in results which is often observed in thermal shock tests. The best performers in this test were the highly segmented coatings sprayed with APS, the EB-PVD reference and the LPPS-TF coating.

Burner Rig Test (NLR)

The Burner rig test of NLR differs significantly from the one of Volvo: Round hollow bars with bondcoat and TBC on the outer surface, were heated by a flame from the outside and cooled with impingement technique from the inside.

Heating and cooling was adjusted to achieve a TBC surface temperature of approx 1200℃ and a thermal gradient of at least 100℃ over the TBC thickness.

Results:

The samples differ clearly with respect to TBC thickness and heat conductivity, both resulting in different TBC and substrate temperatures.

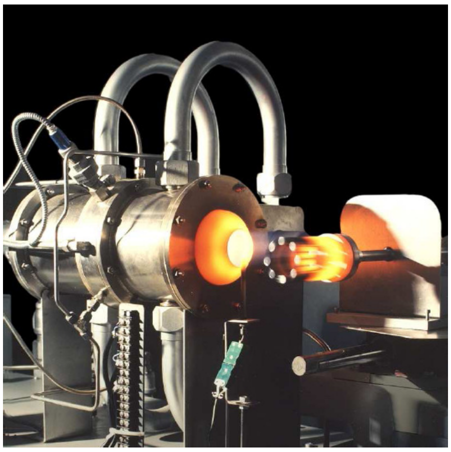


Figure 7: NLR Burner Rig.

The best performers were the EB-PVD reference system and the APS reference system. The most promising new coating was the highly segmented coating sprayed by APS.

Corrosion test

In total five samples for each coating system were delivered to AVIO for testing their corrosion resistance. Four samples were tested, and one was kept as a backup. Before starting the test, a small section was cut out of each cylinder and analysed using the optical microscope as well as the SEM – EDS to evaluate the microstructure and chemical composition. For corrosion testing the samples were put in a bath of melted salts (75 % Na_2SO_4 + 25 % NaCl) at 950 ℃. Microstructure analysis took place after fixed time steps up to TBC failure. Figure 8 shows the corrosion test set up.

Figure 8: Corrosion test set up.

All four samples were put in the corrosive environment for 8 hrs and were analysed thereafter. If any failure was detected, the test was ended. If not, two test bars were corroded further and then analysed.

Results:

The best performers in this test were the highly segmented coating which survived two times longer than the second best performer. Samples with columnar microstructure spalled off very quickly.

Impulse excitation and Modulus Measurements

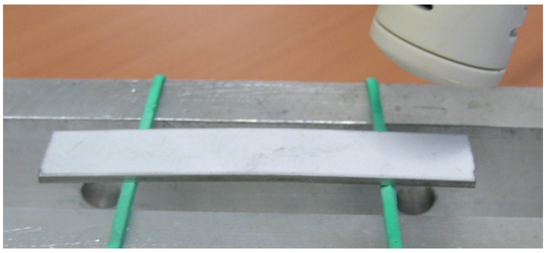
Impulse excitation is performed by mounting the specimen at nodal points and striking it in the centre so as to induce ringing of the fundamental transverse mode of oscillation. The physical arrangement is shown in figure 7a. This impulse excitation technique has been developed in order to obtain rapid non-destructive measurements of the modulus of elasticity for rectangular specimens of material using only a typical performance microphone and fine dimensional measurement instruments. Tight dimensional tolerances (uniformity and parallelism) are required in order to obtain modulus measurements with sufficiently small uncertainties.

In the four point bending test, specimen can be tested in compression (concave) or in tension (convex).

Results

The first thing to notice is that there is considerable spread in the modulus results. In all cases the measured modulus of the TBC coatings is much lower than the 200 GPa expected for bulk Zirconia. This is not particularly surprising since the microstructure of the coatings is very complicated involving considerable porosity and voids as well as micro cracks. In the light of the complications due to coating irregularities at the ends of some of the specimens it is encouraging that the data appears in broad clusters.

(a)



(b)

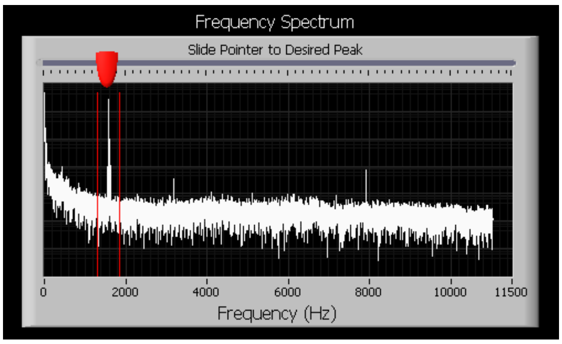


Figure 9: (a) Specimen supported for transverse impulse excitation, (b) Typical acoustic emission frequency spectrum

Although there is considerable scatter in the results, those obtained with impulse excitation are marginally higher than those from the four point bend test.

The two types of specimen showing the lowest modulus values were the EB-PVD specimens and the (free standing) highly segmented APS TBC. EB-PVD coatings have a columnar structure that adds virtually no stiffness in tension. These specimens were also coated on both sides, such that the bend test was always compressing at least one side of the specimen

Thermal conductivity measurement (ERSE formerly CESI)

Thermal conductivity and thermal diffusivity has been investigated in detail for five promising systems and two reference systems. Measurements have been performed at RT, 200°C, 400°C, 600°C 900°C 1000°C and 1100°C in Ar atmosphere by Netzsch LFA 527 (laser flash method)

Results:

The conductivity of the dense vertical cracked TBC is comparable to the columnar microstructure of EB-PVD coatings and more then twice than that of the porous APS-TBC reference system.

Higher conductivity was measured for the 3D systems, which contain metallic anchoring structures within the ceramic TBC to enable thicker TBCs.

Solid particle erosion testing (ERSE formerly CESI)

Solid particle erosion has been investigated in detail for five promising systems and two reference systems. Measurements have been performed with quartz powder (mesh ~100µm, impingement speed ~30m/s and impingement angle 90°) at temperature 700°C.

The best performance showed the LPPS-TF system in this test, as the highly segmented coatings show erosion rates better then the EB-PVD system.

Sintering behaviour (ERSE formerly CESI)

The kinetic of sintering was measured at room temperature by normalized thermal diffusivity. The Samples have been exposed in an FCT (23h hot dwell/1h cold dwell) at temperatures between 1000°C and 1100°C according given test procedure for the nominal TBC thickness.

The normalized thermal diffusivity increased for all samples with exposure time and cycles of the FCT. Most sintering occurred during the first 200h.

Thermal activation: The temperature during FCT seems to be less important than the microstructure of the applied TBC. Never the less sintering was observed already after 200h at 1000°C.

APS samples sinter more than EB-PVD even if the ageing temperature is lower.

Summary of evaluation

Within this work package, 24 bondcoat/TBC systems have been investigated. The systems were quite different with respect to bondcoat (composition, process, roughness, post–treatment) and TBC (composition, powder, process, porosity, thickness, segmentation). For performance evaluation various lab tests have been performed: Furnace cycle test, burner rig test on flat and curved samples, erosion test, measurement of physical properties such as Young's Modulus, thermal diffusivity and conductivity, characterisation of microstructure and degradation like sintering, depletion and oxide scale formation.

The overall evaluation showed that many systems have out-performing strengths but at the same time also some weaknesses. No system was the best in class in all tests. Several systems performed better than the EB-PVD TBC reference system, which was defined as goal of the project.

Based on all these investigations, the best TBC systems can be identified for specific needs only:

- If solid particle erosion is a predominant loading, the LPPS-TF TBC from SM shows the best performance.
- If corrosion is predominant, the dense vertical cracked TBC applied by FZJ with TIAG powder shows best behaviour.
- For loadings with thermal gradients, the porous APS and the highly segmented TBC will perform best.
- If rather isothermal loading is dominating, also highly segmented coatings are the best performers.

Combined loadings have not been considered for the evaluation.

4.6. Work package 6

The main objectives of work package 6 were:

- Implementation of plasma-sprayed coatings for combustion chamber, blades and vanes
- Delivery of mock-up samples (real components) for previous work packages.
- Delivery of coatings on real engine components (combustion chamber, blade and vanes)
- Implementation of repair technologies and repair procedures on worked engine components
- Delivery of samples obtained with repair technologies

The plan of the WP6 was organized as follows:

- Selection of the technologies to be transferred (WP5)
- Delivery of the components to be coated
- Technologies transfer
- Set-up deposition processes
- Coating of the Mock-up
- Coating of the real component
- Delivery of the coated real components
- Final evaluation (WP7)

<u>Thermal Spray Technology for coating Manufacturing</u>

The application of the innovative coatings on real components involves

- Tooling Design to mask and to hold the component in the industrial equipments
- Spray Programs design to coat the real component
- Spray Parameters design to adapt the developed parameters to industrial equipment
- Parameter Optimization to adapt the developed parameters to industrial equipment
- Deposition of the new coatings on real components
- Coating quality analysis

Several new TBC systems were applied on real components in order to proof if it is possible to use the spraying processes in industrial spraying facilities:

- A highly segmented coating was applied on a combustor splash plate. The developed spraying process was adapted to the industry equipment, and the coatings were in agreement with specifications concerning thickness, hardness and bond strength.
- VOLVO applied the developed bondcoat to a real flame holder strut.

The following real components were coated within the project end. Due to the end of the project, none of these TBC systems on a real component was tested. A first qualification test including metallographic investigations and a long term furnace cycling test will be performed by ALSTOM, and the results will be available for all project partner.

- RRD applied the 3D surfaces to real vanes in order to proof the transfer of the technique to real turbo machine parts. It could be shown that also on curved surfaces laser cladding is possible. The real components with 3D surfaces were coated with bondcoat and APS reference system (TUC).
- TUC delivered two real vanes as reference system.
- Two vanes were coated with LPPS-TF coating (SM).
- Two vanes were coated with highly segmented coatings (FZJ).
- LPT nozzles from SNS were partly coated with highly segmented coatings (FZJ).

Another objective of work package 6 was the development of a repair technology for EB-PVD coatings using the LPPS-TF technique due to the similar microstructure obtained by both processes. It could be shown that it is in principle possible to replace a spalled-off EB-PVD area by a LPPS-TF coating.

4.7. Work package 7

As described in the project proposal, the main objectives of this work package were the application of developed project coatings in real environments or as coating for real components.

VOLVO performed a first test of the developed bondcoat in a ground engine. Due to the test result without any damage of the test specimen, it was decided by VOLVO to expand the test. Parts of the test results will be available for the project partners.

Another test will be performed by RRD using some results of the optimisation of the 3D interfaces. The test will take place after the project. Some results will also be available for the project partners.

Non-destructive thermographic testing

Two different thermographic techniques have been applied on selected samples. Pulse thermography is a suitable technique for detecting TBC delaminations which are wide at least few square millimetres. Flash thermography is a technique that allows to measure thermal diffusivity of TBC. In this specific case this technique has been applied to monitor thermal diffusivity as a function of ageing cycles.

Thermographic inspections highlighted mainly the presence of delaminations along sample edges, even at early ageing stages. Delaminations are caused by the sharp change of geometry in the correspondence of the sample edges. Due to time limitations, tests have been performed just on a limited amount of samples aged up to 880 cycles.

Pulse thermography allows detecting fast and easily TBC delaminations on specimen and components. Since pulse thermography is a comparative NDT technique (a sound region has to be used as a reference) when a diffuse and roughly uniform damage all along the sample interface between TBC and BC takes place, its performance is reduced. In order to overcome these limitations, an alternative measuring approach was used.

Notwithstanding the different systems differed in TBC thickness and microstructure, they show remarkably similar trends. In particular, at an early stage an increase of thermal diffusivity is observed followed by an almost continuous decrease up to TBC failure. In the case of some samples the initial increase is not observed and thermal diffusivity starts decreasing even at early stages.

5. Impact of the project

The four project years revealed several promising results with potential to a commercial use.

In the field of spraying materials, two promising candidates were detected: the YSZ suspension and the fused & crushed YSZ powder, both produced by TIAG. Coatings produced by these two types of coating material showed good performance in comparison to other project TBC systems.

The activities in the research subject “3D interfaces” gave a deeper understanding in manufacturing 3D surfaces compatible with the plasma spraying process. These results can help to develop advanced coating systems for different application in gas turbines.

The development of more strain tolerant coatings with at least a performance equal to EB-PVD coatings in work package 4 was also successful and brought out some results that may be the base for further investigations and qualifications. Highly segmented coatings produced via advanced APS processes show some outstanding test results, while only the thermal conductivity in the same range as that of EB-PVD coatings is a disadvantage. The second innovative TBC system is the LPPS-TF coating, which is also a potential coating system to replace the expensive EB-PVD process.

Another remarkable achievement of the current project is the further development of APS Sensor Coatings. Beside the already known use of the Sensor TBC as a temperature indicator, an ageing detector or an early delamination sensor, another functionality has been proven throughout the TOPPCOAT project: thickness measurement capability. Further, to this the Sensor Coatings has shown remarkable durability during the cyclic oxidation tests which is comparable with the best coating morphologies tested during the project.

The performance of suspension plasma sprayed coatings was convincing especially in the long term furnace cycling test, and some partner decided to perform further research activities beside the project.

Evaluation of different new TBC systems on real parts could not be finalised within the project, but further qualification tests will show whether highly segmented coatings or LPPS-TF coatings are applicable in modern gas turbines. LPPS-TF TBCs as repair technology for EB-PVD coatings offers a promising solution for lower repair costs of turbine parts. Further, the engine test of a new developed bondcoat showed that costs can be reduced by using a HVOF bondcoat instead of state-of-the-art VPS bondcoats.

6. Project website

The coordinator was responsible for the project website

www.toppcoat.org

This site is still online and stores all relevant documents of the project. Due to the high level of confidentiality it contains only a small public section where the main project activities, the involved project partner and responsible persons are listed. The largest part of the site is strongly password protected. The site will be still online after the end of the project.