The Future of EB-PVD TBCs – Operational Side and Potentials for Further Improvements

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1. Introduction

The industrial application of Electron Beam-Physical Vapour Deposition Thermal Barrier Coatings (EB-PVD TBCs) on turbine parts started in the 1970s. A concept of a production EB-PVD coater was studied. The breakthrough of TBCs on turbine blades for aero engines succeeded at the beginning of the 1980s. Since then the acceptance of EB-PVD TBCs was becoming wider. Since the beginning of the 1990s scarcely a newly designed jet engine can be found without an EB-PVD TBC on high pressure turbine airfoils.

After 20 - 30 years of a successful service of such TBCs the question can be asked: How long will be EB-PVD TBCs still in service or how many years can be EB-PVD TBCs produced? This depends mainly on new developments of turbine materials including their protective/ bond coatings and on the configuration of the cooling system of turbine airfoils.

Yttria stabilized zirconia is the most used TBC material today. Several potentials are existing to decrease the thermal conductivity by structural and/ or chemical modifications. CMAS (calcium-magnesium-aluminum-silicate originating from ingested dust) requires other improvements of EB-PVD TBCs.

2. Status of the development on turbine airfoils

Two different techniques were optimized to improve the efficiency of the high pressure turbine (HPT):

- The cooling system with internal cooling channels, film cooling holes and the geometry of the cooling holes is optimized and has no further potential for other improvements or the potential is rather maxed out without a negative influence on the efficiency of the compressor which has to deliver cooling air.

- The improvement of Ni-based superalloys will not deliver big progress any more. The directly solidified (DS) or single crystal (SC) alloys are at a limit of approx. 1150°C part's temperature. 1150°c part's temperature means up to 1250°C coating's temperature. Fig. 1 shows the potentials of Ni base alloys.

The gas temperature before turbine entry is at approx. 1650°C. Fig. 1 lines out that an oxidation protective coating and a ceramic TBC have to be applied. Ceramic Matrix Composites (CMCs) are estimated to be available earliest within the next 5 years.

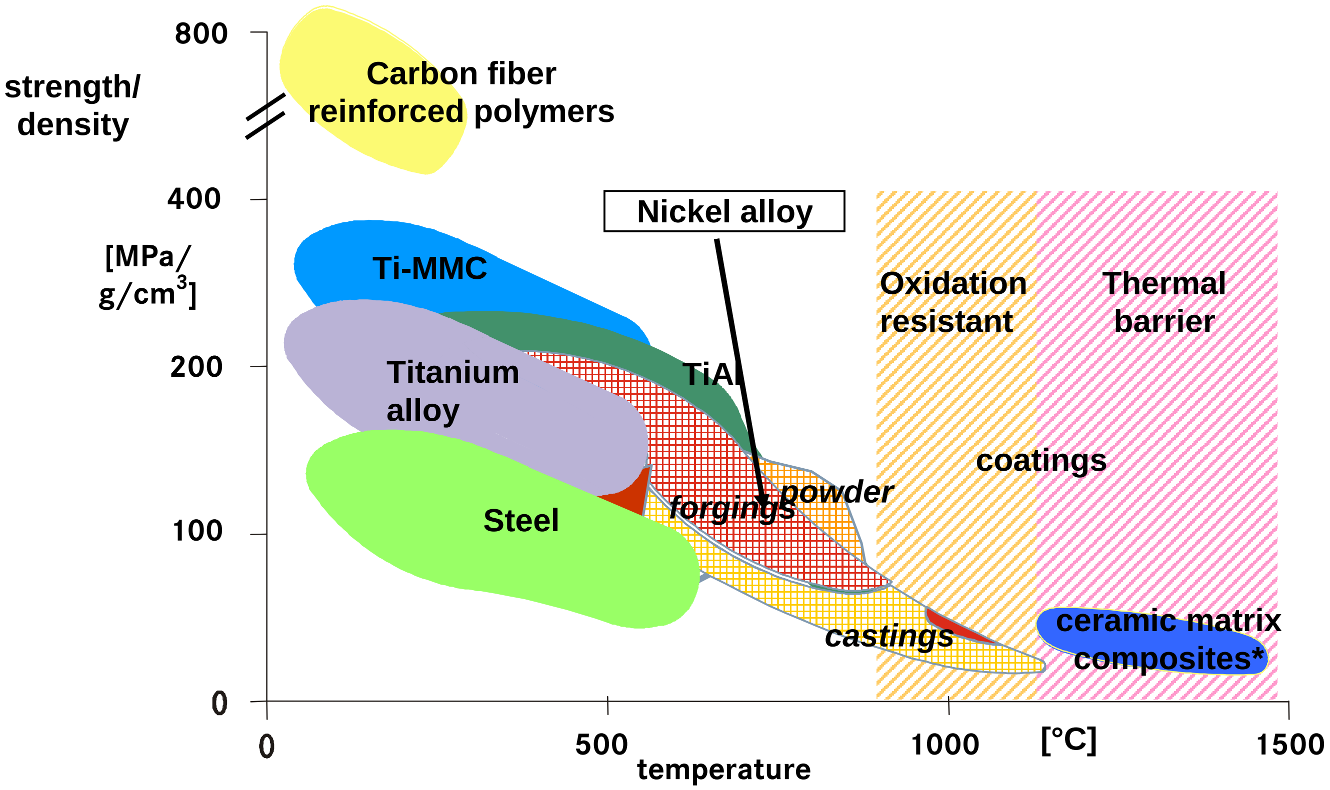

Fig. 1: Base materials for jet engine production (* first application estimated earliest within the next 5 years) [1]

3. Operational side of EB-PVD

The EB-PVD operation is the preferred choice for high-performance TBCs on high pressure turbine parts of aero engines and industrial gas turbines. Ceramic Coating Center (CCC - France) is a production facility which operates an EB-PVD coater. CCC is a joint venture between MTU Aero Engines and Snecma and was created in 1999.

3.1 Production facility

The EB-PVD coating process to apply ceramic coatings is a complex procedure in a vacuum chamber at temperatures up to approx. 1100°C. Fig. 2 shows the EB-PVD coater which is installed at CCC.

Fig. 2: EB-PVD coater at CCC in service

The coater constist of 1 central coating chamber and is equipped with 2 loading/preheating chambers allowing a continuous operation (coating from 1 side, loading/unloading from the other side).
The EB-PVD coater at CCC is able of coating approximately 150 000 blades per year.

3.2 Coating steps

The process comprises the following production steps:

- Cleaning the parts, which are already bond coated, in an ultrasonical aqueous or solvent cleaning process
- Activation of bond coat by dry grit blasting
- TBC coating in the EB-PVD coater :
  - ✓ Loading of parts inside masking tooling that are installed inside the loading chamber
  - ✓ Preheating phase under vacuum to heat up the parts. During this phase the creation of the TGO (Thermal Grown Oxide) begins
  - ✓ In the coating chamber the ceramic ingots are vaporized using the energy of 2 EB guns under vacuum. The parts are moving (rotating and tilting) allowing to meet the specified coating thickness distribution.
  - ✓ At the end of coating run (typically 10 to 30 min) the parts are removed from coating chamber and cooled down.

Fig 3 shows a EB-PVD coated high pressure turbine vane and blade of an aeroengine.

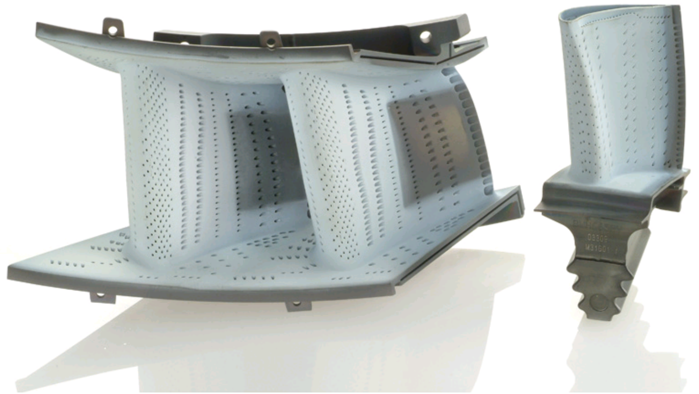

Fig. 3: EB-PVD coated high pressure turbine vane and blade

The EB-PVD coating thus obtained on the part has a typical columnar structure (see fig. 4).

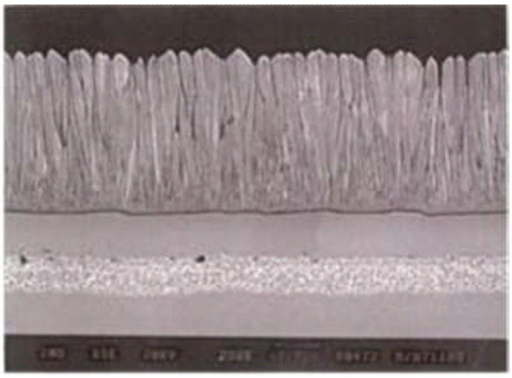

Fig. 4: The microstructure of a columnar structure of a typical EB-PVD TBC

4. Potentials for further improvements on TBCs

Further efficiency improvements in HP turbines require TBCs as an integral part of the component which necessitates reliable and predictable TBC performance. For so-called “designed-in” TBC solutions the coating is vital for the safe operation of the component. Therefore “prime-reliant” coatings are necessary that show performance beyond today's TBC generation. This requires a detailed knowledge of the correlation between process parameters, properties, and failure mechanisms.

It is obvious that any improvement of TBCs aims at three major directions:

- lower thermal conductivity (low K TBCs)
- increased temperature capability
- improved life time.

One more important issue concerns the overall cost of TBCs that are mainly caused by manufacturing but also by usage of TBCs in service. Other relevant TBC properties that should be improved are erosion resistance, and tolerance to foreign object damage. For the latest turbine generation that operates at very high temperatures exceeding 1250°C in the ceramic, the resistance to chemical reactions with deposits such as CMAS (calcium-magnesium-aluminum-silicate originating from ingested dust) is a challange. The following paragraphs give some examples for possible TBC improvements.

4.1 Low K TBCs

A reduction in thermal conductivity of the ceramic layer can be achieved by engineering the chemistry and/or microstructure of the coating. The thermal conductivity of a porous ceramic layer depends on both, the intrinsic thermal conductivity of the bulk ceramic, and on the pore structure [2, 3].

4.1.1 Manipulation of Coating structure

The architecture of the porous structure has a predominant effect on thermal conductivity, mainly due to volume fraction, geometry and distribution of the pores. One possibility to change the morphology of EB-PVD TBCs is the manufacture of inclined columns. This is by nature an inherent possibility for PVD line-of-sight grown films. Any deviation from a perpendicular vapour incidence on a substrate leads to inclined columns. The deviation can be achieved by several manipulations during EB-PVD processing. So-called “Zig-zag” or “Herringbone” structures (Fig. 5) provide reductions in thermal conductivity up to 40% [4].

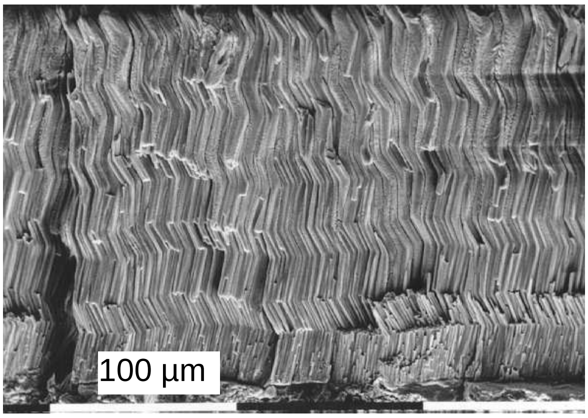

Fig. 5: Zig-zag structured EB-PVD TBC

The microstructure of EB-PVD TBCs is easily changed by varying the rotational speed and deposition temperature [2, 3]. Another effective way to lower thermal conductivity is to take advantage of the anisotropy of the columns in the vertical direction. Close to the substrate surface columns are very small, but with further growth only a few favoured columns become larger. Thus, the root area has a high boundary density with significantly lower thermal conductivity. The challenge is to maintain the microstructure of these thin layers throughout the whole thickness of the TBC.

4.1.2 Coatings chemistry

Changing the composition of zirconia should lead to a higher disordered crystalline lattice, achievable by either introduction of oxygen vacancies or by substitution of Y and/or Zr ions with ions of different ionic radius and/or different mass (mainly rare-earth metals). Of course, alternative ceramics (other than zirconia base) having intrinsic low thermal conductivity are also under development.

Alternative rare earth oxide stabilizers such as dysprosia (DySZ) and ytterbia (YbSZ) behave similar to yttria: 4 mol% additions create a metastable tetragonal phase while 12mol% additions create a stable cubic lattice. As shown in Fig. 6, a reduction of up to 40% in thermal conductivity can be achieved with an optimized version of 12Mol% DySZ [5].

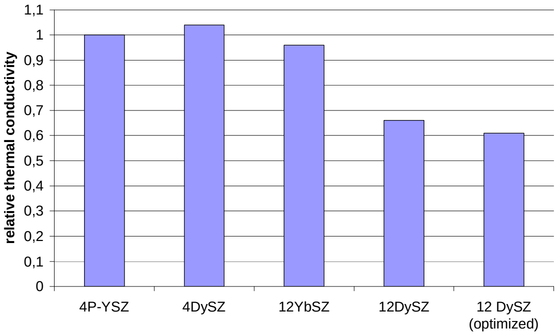

Fig. 6: Relative thermal conductivity of alternative zirconia TBCs at 1000°C, measured after a 2h/ 1080°C stabilizing tretment

Rare-earth zirconates (e.g. $La_2Zr_2O_7$) have a reasonable potential for TBC application. Reduced thermal conductivity as well as improved sinter resistance have been

found for EB-PVD pyrochlore TBCs, especially for $Gd_2Zr_2O_7$ [6] and $Sm_2Zr_2O_7$ [7]. Although not easy to manufacture and some fluctuation in composition encountered, doping $La_2Zr_2O_7$ with 3-10% yttria reduces the compositional scatter during evaporation [2, 3]. Due to the likely reaction of the pyrochlores with the alumina of the TGO, it may be necessary that these coatings are deposited on a thin P-YSZ bottom layer, which act as reaction barrier.

4.1.3 Multilayers

Multilayer structures with likewise reduced conductivity are obtained by two different chemistries (Fig. 7) or by variation in the processing conditions of 7 YSZ. In both cases however care has to be taken to stabilize the layered structure. Usually at higher temperatures an increase in thermal conductivity is observed which is attributed to the disappearance of the phase boundaries due to dissolution of the multilayer structure.

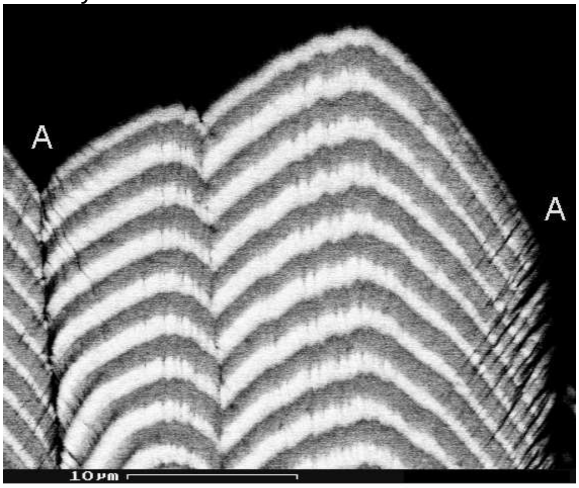

Fig. 4: Multilayered EB-PVD thermal barriers effectively reduce the thermal conductivity.

4.2 CMAS

The anticipated further temperature increase has revealed a new premature failure mechanism in the TBC caused by infiltration of molten calcium-magnesium-aluminum-silicate (defined as CMAS). These deposits can result from combustion products, formed due to dust ingestions through the air intake, particularly when engines are operated over sand and desert areas or in the vicinity of volcanic eruption plumes. Plugging of cooling passages has frequently been observed, and impact erosion of leading edges is another concern. The high-temperature interaction of the standard TBC 7YSZ with molten CMAS deposits destabilizes the top coat and finally leads to TBC failure. At temperatures above 1250°C CMAS can form a molten glass that rapidly penetrates into the open columnar structure of the EB-PVD coating. Chemical reactions of column tips with CMAS deposits are also promoted. Further-more, heavy reaction of CMAS with the TGO was observed. These mechanisms have the potential to reduce the integrity of the whole TBC.

5. Concluding remarks

The system Nickel base superalloy + oxidation resistant coating + TBC will be the standard system in the near future may be up to the next 15 years or longer. Today it is not clear whether CMCs do need TBCs also. Further improvements can be introduced with ceramic materials with lower thermal conductivity. Other improvements in thermal conductivity can be achieved by microstructural elements as pores or other vacancies whose formation are dependent on the coating parameters.

Oxidation resistant coatings as a bond coat for EBPVD TBCs could be improved if the growth of the oxide layer – also known as thermally grown oxides (TGO) - could be drastically retarded. The growth of the TGO is amongst others responsible for the life of EB-PVD TBCs.

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