ADVANCED COATINGS FOR ROTATING AERO ENGINE COMPONENTS

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ABSTRACT

Advanced aero engine design focuses on reduced specific fuel consumption and increased thrust-to-weight ratio. This ultimately calls for increased pressure ratios as well as higher operating temperatures and certainly represents a major challenge to the structural design and the materials employed. Increased high temperature capability materials are required as well as extremely lightweight structures.

Ceramic thermal barrier coatings (TBCs) offer the potential to significantly improve efficiencies of aero engines as well as stationary gas turbines for power generation. On internally cooled turbine parts temperature gradients of the order of 100 to 150°C can be achieved. Today, state-of-the-art TBCs are mainly used to extend lifetime of components. Further efficiency improvements require TBCs being an integral part of the component which, in turn, requires reliable and predictable TBC performance. For so-called "designed-in" TBC solutions the coating is vital for the safe operation of the component. Coating failure then essentially marks the end of component lifetime. Therefore "prime-reliant" coatings are necessary that show performance beyond today's TBC generation. The performance improvements needed require a systems approach, including consideration of environmental resistance and mechanical properties of each part of the TBC system and their interplay and changes in the system during service.

Presently, TBCs produced by electron beam physical vapour deposition (EB-PVD) are favoured for high performance applications. Based on extensive knowledge available from field and laboratory tests, the paper will focus on both research and development status as well as trends devoted to future generation EB-PVD TBCs with significant improvements in performance and reliability, particularly looking for sophisticated systems with reduced thermal conductivity. Finally an outlook on advanced coating systems for titanium-based aluminides will be given.

1. INTRODUCTION

During the design of a new aero engine the impact on main engine characteristics like weight, specific fuel consumption (SFC), manufacturing costs, and maintainability need to be considered. For airlines the direct operating costs (DOC) of an aircraft are of prime concern. Engine design dependent costs may amount to 40% and above. Hereby it is important to note, that the sensitivities of the DOC with respect to the engine characteristics are quite different. While a 1% lower DOC of a 100-seater regional airplane requires an approximately 10% lower engine weight or engine price, only 5% reduction in SFC yields to the same reduction in DOC [1].

For military engines the thrust-to-weight ratio is of considerable interest. It has been significantly improved over the years accomplished through increased operating temperatures as well as improved structural efficiency. Here obviously advanced materials play a major role. In fact, modern aircraft engines represent some of the most demanding and sophisticated applications for structural materials in any engineering system manufactured today. This has been manifested by the steady increase in service temperature, product reliability and usage of lightweight materials [2].

Blades and vanes of the high pressure turbine section of aircraft engines are among the most highly stressed parts in engineering components. Internally cooled aerofoils of state-of-the-art Ni-base superalloys operate at temperatures of about 1000°C with short-term peaks yielding

even 1100°C which is close to 90% of the alloys' melting points. These temperatures are maintained in service due to a highly sophisticated cooling technology by which, however, thermal energy is withdrawn from the aerofoils thus reducing the overall fuel efficiency of the engine. The necessity of close control of material temperatures is obvious: Blade life on creep is halved for every 10 to 15°C increase in temperature [3].

Future development of gas turbines clearly aims at increased gas turbine inlet temperatures (TIT) passing well beyond 1600°C. There is no doubt that this ambitious goal can only be met by usage of uneconomically extensive cooling techniques or by advanced high temperature materials and in particular through extended usage of electron-beam physical vapor deposited (EB-PVD) thermal barrier coatings (TBCs) [4].

At the same time a new class of high-temperature titanium alloys – titanium aluminides - is at the edge of being introduced into the latest military and civil type aero engines. First potential applications are as blade material in the last stage of the HP compressor or LP turbine. In both cases Ni-base superalloys are going to be replaced with substantial weight savings. Therefore ways to protect this new class of alloys are also highlighted.

2. THERMAL BARRIER COATINGS

Thermal barrier coatings (TBCs) are currently used in the hot gas path of aero-engines and land-based gas turbines. TBCs are utilized in the high pressure turbine section for lifetime improvement of highly loaded turbine blades and vanes and to increase turbine efficiency. They typically comprise of a thin ceramic top coating of low thermal



Fig. 1: Thermal barrier coatings (TBCs) allow increased engine performance and/or life extension

conductivity - typically partially stabilized zirconia - that reduces the metal temperature and smoothens the temperature peaks during the transient stage of turbine operation, and of a metallic bond coat for oxidation protection of the underlying superalloy part. The coating imparts good adhesion of the ceramic to the substrate. Application of TBCs enables increasing engine performance/thrust by either increasing the gas temperature or reducing the cooling air flow [5]. Alternatively the lifetime of the turbine blades can be extended by decreasing metal temperatures as schematically outlined in Fig. 1.

There is ample literature available about TBCs, e.g. their manufacture, properties, and behavior in service, life time prediction, and failure modes. Overview papers describe aspects of the whole coating system, the several interactions between the constituents, and new development trends [6-9]. The key features required for a material to become a thermal barrier coating are a reasonably low thermal conductivity, sufficient high temperature capability, and chemical and mechanical compatibility with the underlying layers. In the early days of thermal barrier application, the major research and development focused on feasibility and reliability issues, since coatings tended to spall and thus lost their protective properties. Today, TBCs are well-engineered systems that can survive several ten thousands of hours in service, although there is still a tremendous potential for improvements of TBC life time e.g. by bond coat optimization.

Already since the 1960s plasma-sprayed (PS) TBCs have been widely applied to hot components like burner cans while in recent applications on more pretentious parts like turbine blades EB-PVD technology is favored. Contrary to plasma spraying, EB-PVD processing offers the opportunity to generate coatings having a unique columnar microstructure. The main advantage of this structure is its superior tolerance against straining and thermoshock, thus giving it a major edge in lifetime. Furthermore, cooling hole closure will be prevented and aerodynamic design of the blades is maintained. In Fig. 2 micrographs of PS and EB-PVD processed TBCs are compared.

Since the late 1990s the first generation of EB-PVD thermal barrier coatings has been introduced onto aircraft engine airfoils, primarily to extend the lifetime of the blades. However, to exploit the full potential of TBCs further work has in particular to be directed to efforts which determine critical failure mechanisms more accurately based on detailed understanding of dynamic changes of the entire TBC systems during service. This would allow fully integrating TBCs into the blade design and not only using them as 'bandage'. The progress in the manufacture of more reliable TBC systems on single crystal materials will address the design of favorably microstructured TBCs with superior strain tolerance on advanced bond coats with predictable formation of adherent thermally grown oxide scales. Detailed knowledge of the correlation between process parameters, properties, failure mechanisms, and lifetime helps to tailor TBC systems with improved durability [10, 11].

During EB-PVD processing a high energy electron beam melts and evaporates a ceramic so-called ingot in a vacuum chamber. Ingots are bottom fed into the crucibles during evaporation to ensure continuous TBC growth. To achieve defined stoichiometry of the zirconia a controlled amount of oxygen is bled into the deposition chamber. Preheated substrates are positioned in the vapor cloud where the vapor is deposited on substrates at deposition rates of 3 to 20 µm/min. Typical columnar microstructures and aero-dynamically smooth surfaces are obtained without the need for final polishing or conditioning of cooling holes. Due to the columnar microstructure the life time of the TBCs is prolonged and the damage tolerance improved. Fig. 3 shows EB-PVD TBCs on a selection of aircraft engine turbine blades produced at DLR using a semi-industrial size dual-source 150kW von Ardenne EB-PVD coater (Fig. 4).



Fig. 2: Micrographs of plasma sprayed (PS) versus evaporated (EB-PVD) TBCs [5]

EB-PVD processing offers the opportunity to generate coatings having a unique columnar microstructure with 2 to 25 μ m in diameter. The main advantage of this structure is its superior tolerance against straining and thermoshock, thus giving it a major edge in lifetime.

3. GUIDELINES FOR TBC IMPROVEMENT

It is obvious that any improvement of TBCs aims at three major requirements: lower thermal conductivity, increased temperature capability, and improved life time. One more important issue concerns the overall costs of TBCs that are mainly caused by manufacturing but also by usage of TBCs (e.g. on blades for special handling and inspection requirements, quality control, new repair strategies etc.). Other relevant TBC properties that should be improved are erosion resistance, tolerance to foreign object damage, and resistance to chemical reactions with gas impurities or deposits.



Fig. 3: Thermal barrier coating on high pressure turbine blade; the EB-PVD process takes care that cooling holes are not closed.



Fig. 4: DLR operates a 150 kW EB-PVD dual-source pilot plant coater which allows processing of advanced graded or multilayer type coatings.

During the last decade research activities world-wide aimed at improved ceramic top coats [12]. In the following, examples to improve the ceramic top coats - mostly via reduced thermal conductivity - will be given. Only EB-PVD processing will be looked at, since this is the common practice for aero engine turbine blades today.

4. OPTIMIZED CERAMIC COATINGS

Thermal conductivity is the key physical property of a TBC. Today, increasing TBC insulation capability clearly emerges as a technical and economical challenge for engine manufacturers [13-15].

The benefits from low conductivity coatings are quite obvious. They allow increased engine performance by improving the combustion efficiency (higher turbine entry temperature), reducing specific fuel consumption and internal cooling, lowering metallic component temperatures, and extending lifetimes. If thinner coatings are deposited, lower parasitic weight and hence less centrifugal loads on rotating blades result. The external surface temperature of the ceramic increases notably with decreasing thermal conductivity, partly explained by the fact that the heat flux is kept constant. Increased external surface temperatures may adversely affect the high temperature stability of the ceramic by enhanced sintering which in turn results in thermal conductivity increase of the coating.

The thermal conductivity of a porous ceramic layer depends on the intrinsic thermal conductivity of the bulk ceramic, which is linked to its composition and structure. The architecture of the porous structure has a predominant effect, mainly due to volume fraction, geometry and distribution of the pores. Moreover, in the case of a multiphase ceramic material (for example a multilayer coating or a phase mixture), thermal boundary resistance and phase topology have to be taken into account [16, 17]. Thus lowering thermal conductivity of the ceramic layer can be achieved by engineering the chemical composition and/or coating microstructure.

Changing the composition of zirconia should lead to a higher disordered crystalline lattice, achievable by either introduction of oxygen vacancies (e.g. by increasing the total amount of stabilizer) 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.

5. DEVELOPMENT OF ADVANCED EB-PVD CERAMIC TOP COATS

Improved morphologies of EB-PVD P-YSZ TBCs

EB-PVD TBCs deposited at high chamber pressures and low substrate temperatures possess a low density. The microstructure shows low density characterized by large gaps between the columns and an increasing column diameter with thickness [18].

The effect of temperature on density is quite obvious: the lower the substrate temperature the lower is the ability for

diffusion of the condensed particles into stable lattice positions, leading to a disordered and imperfect microstructure with low density. The correlation between density and thermal conductivity is nearly linear, offering a reduction potential of about 15% by microstructural tailoring. Larger reduction in thermal conductivity and improved cyclic lifetime have been found for TBCs deposited at high chamber pressure of $1.5*10^{-3}$ mbar by usage of mixtures of oxygen and an inert gas [19].

Generating inclined columns is by nature an inherent possibility for PVD line-of-sight grown films. Any deviation from a perpendicular vapor incidence on a substrate leads to inclined columns. The deviation may be caused by axis tilting [20], off-axis part positioning, or substrate tilting [21]. So-called "Zig-zag" or "Herringbone" structures (Fig. 5) provide reductions in thermal conductivity up to 40% [22].



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

The microstructure of EB-PVD TBCs can be tailored by taking advantage from the four basic processes during film growth which are shadowing, surface diffusion, volume diffusion and desorption. In practice and for rotated components, the most important EB-PVD process parameters that rule the microstructure are substrate temperature, rotation speed, chamber pressure, and pattern and angle of vapour incidence in conjunction with deposition rate [23, 24]. The resulting microstructural features of EB-PVD manufactured TBCs are a result of their columnar morphology and pore architecture. The pores can be categorized in [25] inter-columnar gaps between the columns, voids between feather-arms, and intra-columnar pores and pore-arrays that are mainly caused by substrate rotation. The interplay between these pore types finally determines thermal conductivity. A lower density TBC promotes a lower thermal conductivity.

Since shadowing occurs primarily along the plane of vapor incidence, columns are significantly wider in the direction parallel to the rotation axis than perpendicular to it, leading to an anisotropy of the in-plane compliance with notable consequences on Young's modulus. It is expected that similar in-plane anisotropy exists for thermal conductivity, but this has been difficult to validate experimentally so far. Moreover, it is not relevant for the application case since the heat flux in TBCs is primarily perpendicular to the surface. Interestingly, no big difference was found between in-plane and through thickness thermal conductivity values in [26]. The feather arms, aligned under angles between 35 to 50° (often 45°) towards the main column axis, might partly transform into lines of small nanometer sized globular pores already during deposition, mainly driven by minimization of surface energy, overshadowing effects and gas entrapment.

The variation of thermal conductivity due to microstructure differences is quite large. At a measurement temperature of 1000°C, the difference between the smallest and largest values (feathery and coarse) is about 30% and after ageing still 17%. It is largest for the version with the lowest starting value (feathery, increase by 19%) and smallest for the fine microstructure (only 3% increase). A detailed analyses of the role of each individual pore family present in EB-PVD TBCs by applying 3D diffraction methods revealed that not the general sintering behavior and changes in the total surface area are important, instead the evolution in shape and density of the individual pore fractions is responsible for the thermal conductivity during service at high temperature [25, 27]. To get a low thermal conductivity, EB-PVD TBCs rely mainly on feather-arms and intra-columnar porosity while intercolumnar porosity is obviously less effective.



Fig. 6: Thermal conductivity values at different Laser flash measurement temperatures of EB-PVD P-YSZ TBCs as a function of thickness. Measurements were done after an initial 2h/1080°C heat treatment [28].

Most easily the microstructure of EB-PVD TBCs is changed by varying the rotational speed [23, 29]. Generation of a club-like columnar structure by additionally modifying the deposition temperature on EB-PVD processing results in TBCs with very low Young's modulus [30]. Another effective way 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 favored columns become larger. Thus the root area has a high boundary density with significantly lower thermal conductivity [21, 31]. As shown in Fig. 6 the thinnest layer (52μ m) has a 35% lower conductivity compared to a 350μ m TBC.

A similar approach to provide a microstructural improvement by layering at a much finer scale (i.e. layers of about 1µm thickness) is to periodically switch on and off a strong BIAS voltage within a plasma atmosphere. This procedure changes the density of the alternating layers and provides up to 37-45% reduction in thermal conductivity at room temperature [31]. Similarly, layered structures with likewise reduced conductivity are obtained with multilayered structure developed by two different chemistries (Fig. 7). In both cases however care has to be taken to stabilize the layered structure. Usually at higher temperatures an increase of thermal conductivity is observed which is attributed to the disappearance of the phase boundaries due to dissolution of the multilayer structure.



Fig. 7: Multilayered EB-PVD thermal barriers effectively reduce the coating's thermal conductivity

6. ALTERNATIVE TBC COMPOSITIONS

Ceria stabilized zirconia (CeSZ) is considered as a potential EB-PVD candidate material, providing a good corrosion resistance and superior phase stability at high temperature. Furthermore, the thermal conductivity is found to be lower than for P-YSZ, and benefits for lifetime and thermocyclic resistance are reported [31-36]. As the vapor pressures of zirconia and ceria differ considerably, the evaporation from one source containing both zirconia and ceria turns out to be critical. Two source evaporation was identified to offer a possibility to overcome the problem.

Other 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. 8, a reduction of up to 40% in thermal conductivity was achieved with an optimized version of 12Mol% DySZ [37, 38]. The cyclic lifetime of these new EB-PVD TBCs was comparable to the standard P-YSZ version.

Hafnia containing compositions

Hafnia containing TBCs are easy to manufacture by EB-PVD. The crystal lattice of zirconia and hafnia is isomorphous; a complete solubility exists. Although the vapor pressure of zirconia is slightly higher than that of hafnia, no major problems have been found in terms of composition up to now. No significant influence of the hafnia content was found in cyclic life time tests [12].

Larger additions of hafnia, e.g. 40wt% zirconia+ 40wt% hafnia + 20wt% yttria, reduce thermal conductivity further but the largest effect of 30% reduction at high temperature was reported for zirconia free 27wt% yttria-stabilized hafnia [39]. The latter showed a much denser and fine columnar microstructure and was less susceptible to sintering. Similar favorable lower shrinkage rates have been found for EB-PVD 7.5wt% yttria-hafnia that was not rotated during deposition [40]. Own experiments on 32wt% yttria-hafnia (FYSHf) TBCs showed similar results. Evaporation from one source was possible without notable problems with nearly the same composition in both ingot and TBC (Fig. 9).



Fig. 9: Microstructure of EB-PVD yttria-hafnia (FYSHf) TBCs in fractured cross section

The FYSHf possesses only 66% of the theoretical density for this composition while P-YSZ has around 80% of the theoretical density. Due to the higher porosity, the heavy element hafnium did increase the total density by only 15% compared to the standard material (5.5 g/cm³ compared to 4.8g/cm³). This is a clear advantage for this TBC version if the low density is maintained during service.

Pyrochlores and other approaches

Rare-earth zirconates (e.g. $La_2Zr_2O_7$) have reasonable potential for TBC application. Reduced thermal conductivity as well as improved sinter resistance have been found for EB-PVD pyrochlore TBCs, especially for $Gd_2Zr_2O_7$ [41] and $Sm_2Zr_2O_7$ [42]. Although not easy to manufacture and some fluctuation in composition encountered, a recent study has shown that doping La₂Zr₂O₇ with 3-10% yttria reduces the compositional scatter during evaporation [43]. Morphologically La₂Zr₂O₇ based coatings are similar to cubic structured EB-PVD TBCs. Although the microstructure changed significantly after 100h of annealing at 1300°C, thermal conductivity remained low at about 1.4Wm⁻¹K⁻¹ [44]. Due to the likely reaction of the pyrochlores with the alumina of the TGO, it may be necessary that these coatings are deposited on relatively thin (50 - 100 µm) P-YSZ bottom layers, which act as reaction barrier.



Fig. 8: Relative thermal conductivity of alternative stabilized zirconia TBCs at 1000°C, measured after a 2h/1080°C stabilizing treatment.

A combination of the morphology approach by microlayering with new compositions yields multi-layers of different chemistry. Alternating layers of, e.g., zirconia and alumina [45, 46], P-YSZ and yttria stabilized hafnia [47], P-YSZ and yttria-ceria or P-YSZ and gadolinia stabilized zirconia [48], P-YSZ and dysprosia stabilized zirconia [35] have been investigated. For these systems at least two factors contribute to a reduced thermal conductivity: firstly, thin films have been reported to exhibit lower thermal conductivities than the respective bulk materials, and secondly, additional boundaries are incorporated perpendicularly aligned to the heat flux. Especially the long term high temperature stability of the thin multi layers has to be proved.

7. TITANIUM ALUMINIDES

Recent trends in aerospace as well as in automotive industry have led to the use of light weight materials especially applied in highly stressed components [49-52]. Thereby titanium aluminides become more and more interesting because of the attractive mechanical properties, such as low density, high stiffness, high yield strength and good creep resistance under service conditions at temperatures up to 900°C. Owing to these advantages titanium aluminide alloys appear to have the potential to partly replace heavy steels and nickel-based alloys presently used in aeroengines. Titanium aluminides based on γ -TiAl have proven suitability as construction material for parts of automotive engines [51, 52] and have been successfully tested as low pressure turbine blades in aeroengines [53].

However, the oxidation resistance of γ -TiAl alloys decreases rapidly at temperatures above 750°C due to the formation of fast growing TiO₂ [54-58]. Reducing the formation of non-protective titanium oxide is the primary objective to improve the resistance of titanium aluminides against oxidation.



Cu plating Al₂O₃ scale Laves phase γ-TiAl phase substrate <u>5 μm</u>

Fig. 10: Oxide scale structure of an uncoated Ti-45Al-8Nb sample (a) and of Ti-Al-Cr coated Ti-45Al-8Nb base material (b) exposed to air at 900°C for 120h

The main approach is the formation of a continuous protective Al_2O_3 scale by means of coatings [54, 59-61]. One possibility is the deposition or formation of aluminum rich top coats [61-63]. Besides this most suitable approach, coatings with chromium and/or further elements can provide moderate oxidation protection [64-68].

Figure 10a shows an unprotected Ti-45Al-8Nb surface exposed at 900°C for 120h with an 8 μ m thick oxide scale on top consisting predominantly of porous titania and small amounts of alumina. Ti-Al-Cr coatings provide good oxidation resistance by the formation of a continuous Al₂O₃ scale on top as shown in Figure 10b. The Laves phase co-existing with the γ -phase promotes the formation of the protective oxide scale.

To extend the potential of titanium aluminides for high temperature applications the use of thermal barrier coatings on the light-weight material was discussed. Recent studies have demonstrated that thermal barrier coatings can be successfully applied on γ -TiAl alloys [69-74].



Fig. 11: Ti-45Al-8Nb specimen with oxidized Ti-Al-Cr coating and P-YSZ top layer exposed to air at 950°C for 300h

Moreover, a recently observed reaction zone between thermally grown oxide and TBC occurs if the Al_2O_3 layer is no longer present. This effect is not well understood, yet. Cations of titanium and aluminum seem to diffuse outwards and react with oxygen at the TBC-TGO interface forming a columnar-type structure. The TBC systems fail due to crack formation within the TGO. Therefore the development of long-standing oxidation resistant coatings forming a stable alumina scale as base for bonding of TBCs is elementary for using titanium aluminides in fields of long-term high temperature applications

8. OUTLOOK

So far, only few of the newly developed EB-PVD TBCs have been tested with an underlying standard P-YSZ ceramic layer, partly because of chemical incompatibility with the thermally grown oxide alumina as found especially for pyrochlores, and partly because the formation of the thermally grown oxide was altered and reduced life times were observed for bare new compositions. Such double layers have been explicitly reported for top coats of ceria-yttria, gadolinia-zirconia, dysprosia stabilized zirconia, and Sm-zirconate. The accompanied increase in cost and complexity of the TBCs are a major disadvantage for those new materials. On the other hand, if the benefits of thermal conductivity or high temperature capability outweigh the costs, those new TBCs may enter into production soon. Furthermore, oxidation resistant coatings are under development improving significantly the oxidation behaviour of TiAl above 900°C for applying thermal barrier coatings also on light-weight material for long-term use.

9. CONCLUSIONS

For high pressure turbine blades EB-PVD thermal barrier coatings exhibit a high potential to increase aero engine turbine efficiency. TBCs represent a complex system consisting of substrate, bond coat, thermally grown oxide, and ceramic top coat. Each of the constituents can influence the lifetime of the TBC with a strong effect of the processing conditions. A key development aspect of TBCs aims at low conductivity of the ceramic top coat. Improvements have been achieved by modifying both microstructure and chemistry, resulting in about 50% reduction in thermal conductivity and approximately 100 to 150K temperature capability increase in an optimistic scenario. Customized multilayer with multi-functionality seem to provide further progress, although a balance between all loads placed on the coatings and cost issues must be considered. Developing thermal barrier coating systems for titanium aluminides is the logical next step when introducing TiAl as structural material for very high temperature applications. Hitherto unknown interaction effects between thermally grown oxide and TBC have to be considered for a successful implementation of this material system on titanium aluminides.

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