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ADVANCED MATERIALS AND COATINGS FOR FUTURE GAS TURBINE APPLICATIONS

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Abstract

Advanced aeroengine design will focus 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 light-weight structures. Weight reduction of the aeroengine calls for new compact design of the compressor with a drastically reduced number of stages.

The need for ultra high specific stiffness/strength materials can only be met with design concepts employing reinforced composites. High strength and stiffness silicon carbon fibers in a high temperature titanium matrix are prime candidate materials the development of which will be outlined. For the high pressure turbine design concepts incorporating ceramic heat-shielding coatings, i.e. thermal barrier coatings, would overcome the natural limits given by the melting point of the Ni-based superalloy turbine blades.

Advanced evaporation processing by means of electron beam technology is the preferred choice of manufacturing these coatings on highly rotating parts. Major efforts are however still necessary to improve these coatings, make them more reliable and thus fulfill the designed-in philosophy to fully exploit their potential.

1 Introduction

During the design of a new aeroengine the impact on main engine characteristics like engine weight, specific fuel consumption (SFC), manufacturing costs, and maintainability need to be considered. For airlines the direct operating costs (DOC) of an aircraft are a prime qualification parameter. 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. This ranking is of particular importance for civil aircraft engines [1].

Apart from specific fuel consumption, the thrust-to-weight ratio is of considerable interest for military engines. The thrust-to-weight ratio has been significantly improved over the years accomplished through increased operating temperatures as well as improved structural efficiency. It is very obvious that advanced materials play a major role here. 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].

This paper will highlight two aspects of advanced materials technologies. The first addresses recent developments in the high-pressure compressor / low pressure turbine and focuses on light-weight titanium alloys, titanium aluminides and in particular titanium matrix composites (TMCs). The second touches on thermal barrier coatings (TBCs) for high-pressure turbine blades which try to eliminate a bottle-neck in the development of increased performance engines.

2 Challenges for Titanium Compressor Materials

The outstanding properties of titanium alloys include high specific strength and excellent corrosion resistance. Therefore, titanium alloys are found in aerospace applications where the combination of weight, strength, corrosion resistance, and/or high temperature stability of the classic light metal aluminum, high strength steel, or nickel-based superalloys are insufficient. In aero engines titanium alloys represent the most important class of materials for engine compressors. Some of the improvements made on conventional titanium alloys and titanium aluminides, as well as new design approaches possible with titanium matrix composites (TMCs) will be addressed.

2.1 Titanium alloys and aluminides

Today, approximately one third the structural weight of modern turbine engines is made up of titanium. Indeed, the first jet engines introduced at the beginning of the 1950s by Pratt & Whitney in the USA and Rolls-Royce in England contained titanium alloys. Since then the titanium content has steadily increased. Over the years an evolutionary trend in alloy design is observed from the $\alpha+\beta$ alloys to the elevated temperature near-α alloys.

Compressor blades were the first engine components to be made from titanium, titanium compressor disks being introduced next. The large front fan blades of modern jet engines are now often made from titanium alloys, too. Due to steadily increasing engine by-pass ratios, the newest blade designs exceed lengths of one meter. At these dimensions, fan blade flutter can become a serious problem since the blade tips may reach the velocity of sound and cause mixed supersonic / subsonic flow fields and associated shock waves. Advanced fan designs have improved blade stiffness through an increase in chord width and have led to a reduction in the number of blades by about one third. Today, these “wide chord fan blades” are employed in the latest generation jet engines. So the new engines for the Airbus A380 from both Rolls-Royce (Trent 900) and the GE/Pratt & Whitney Engine Alliance (GP7200) will have fan diameters of approximately three meters and will incorporate hollow titanium fan blades.

Fig. 1: Machined compressor disk „Stage 3 blisk“ made from TIMETAL 834; 40kg weight; 500 mm diameter (courtesy Otto Fuchs, Meinerzhagen, Germany)

Evolutionary engine design stresses the need to further decrease the weight of the compressor blades and disks, while extending component life or inspection intervals. This may be achieved using an integrally bladed disk, or "blisk", design. The finished blisk is a single assembly where disk and blades are metallurgically bonded together. For small blade heights it is more cost effective to machine a blisk from an oversized forged disk (Fig. 1). Larger blades are generally attached to the disk by linear friction welding. In addition to the weight reduction from a blisk design, the lack of a mechanical interface between the blades and the disks eliminates a common site for fatigue crack initiation, leading to extended inspection intervals. Blisk technology is now standard technology in low and medium size category compressors of commercial and military engines. In the Eurofighter's EJ200 engine, for example, all three stages of the fan section are a blisk design; the first two being manufactured using linear friction welding, the third by ECM (Fig. 2).

Fig. 2: Three stage blisk compressor (courtesy MTU Aero Engines, Munich, Germany)

Since fan blades and disks are used at low temperatures, they are normally manufactured from Ti-6Al-4V. The maximum temperature limit for this alloy is about 315°C. Therefore, in the high-pressure compressor only elevated temperature near-α alloys are used. Today, the maximum temperature limit for these alloys is about 540°C. This upper bound is not limited by the elevated temperature strength or creep resistance of the near-α alloys but by their moderate oxidation resistance, especially in comparison to nickel-based superalloys. In long-term elevated temperature applications titanium alloys form an "α-case" at the sub-surface, i.e. a zone with predominant brittle α phase caused by oxygen enrichment, which leads to drastic reduction in ductility and fatigue strength.

This temperature limitation for titanium alloys means the hottest parts in the compressor, i.e. the disks and blades of the last compressor stages, have to be manufactured from Ni-based superalloys at nearly twice the weight. Additionally, problems arise associated with the different thermal expansion behavior and the bonding techniques of the two alloy systems. Therefore, enormous efforts are made to develop a compressor made completely of titanium. Titanium alloys are required that can be used at temperatures at about 600°C or higher. This has been the impetus for the extensive research and development work in the area of titanium aluminides. These materials, based on the intermetallic compounds $\alpha_2(Ti_3Al)$ and $\gamma(TiAl)$, have been studied for their potential to raise the application temperatures of titanium alloys to 650°C and 800°C, respectively. Their excellent creep resistance is due to the ordered nature of the crystal structure. However, this structure also makes the intermetallics relatively brittle and correspondingly difficult to deform. Alloying with Nb, Cr, V, Mn or Mo and microstructural optimization are two approaches to gain increased ductility. Sufficient damage tolerance, a satisfactory oxidation behavior, and producibility (cost) are critical parameters that will determine the use of titanium aluminides in aerospace.

The prospect for potential application of TiAl-based alloys is much higher for jet engine components with less stringent damage tolerance requirements. Fig. 3 shows the fifth low-pressure turbine stage of the GE CF6-80C2 jet engine with turbine blades manufactured from a cast Ti-47Al-2Cr-2Nb alloy. Each of the 98 blades has a length of 50 cm, and, at 217 g, the blades are only about 55% the weight of a conventional nickel-based superalloy blade. The reduced weight of the titanium aluminide blades would further enable an even lighter weight design of the entire turbine due to the lower centrifugal forces imposed on the disk. Use of these alloys in a large jet engine like the GE90 could save more than 150 kg. Due to cost, the casting route is favored for the production of TiAl low-pressure turbine blades. At present the production of TiAl blades is delayed primarily due to cost considerations [3].

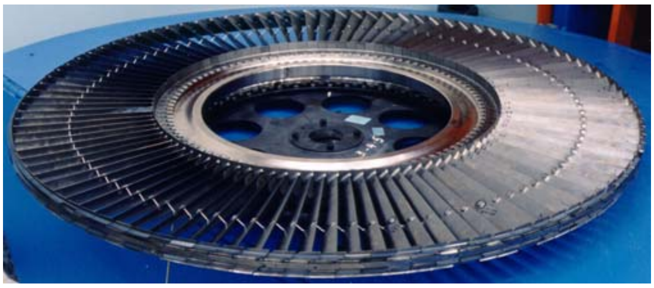

Fig. 3: LP turbine stage of the GE CF6-80C2 jet engine with turbine blades manufactured from a cast Ti-47Al-2Cr-2Nb alloy (courtesy GE Aircraft Engines, USA)

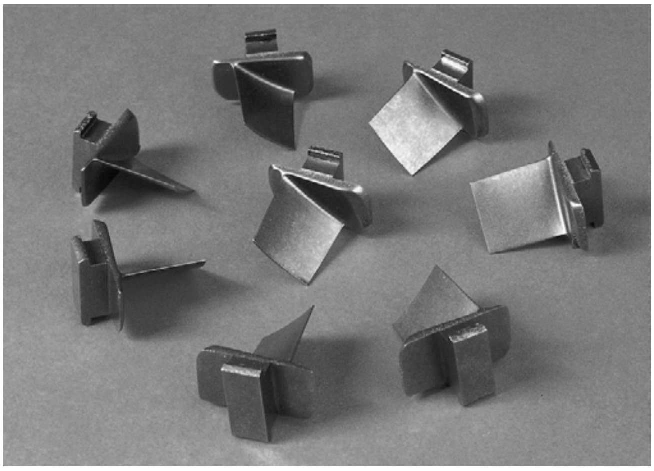

Fig. 4: Rotor blades from a gamma titanium aluminide alloy for the high-pressure compressor of a jet engine [5]

In a different approach for manufacturing turbine blades the wrought processing route involving closed-die forging has been followed in Germany as shown in [4]. As an example, the processing route for the fabrication of high-pressure jet engine turbine blades was jointly developed by Rolls-Royce Deutschland, ThyssenKrupp Turbinenkomponenten, and GKSS Research Centre. Processing involved extrusion of ingot material, subsequent isothermal forging in several steps, and a final heat treatment. Finishing of the blades was carried out by Leistritz Turbomaschinen using electro-chemical milling [5].

2.3 Titanium Matrix Composites (TMCs)

While titanium aluminides may broaden the spectrum to higher temperatures [6], the use of titanium-based composites in highly loaded components would prove to be a quantum leap for materials design, hence opening unknown possibilities to engine designers [7]. Such titanium matrix composites (TMCs) are obviously an innovative materials concept that combines the high strength, stiffness, and creep resistance of silicon carbide (SiC) monofilaments with the damage tolerance of titanium alloys and titanium aluminides. Moreover, introducing SiC fibers into a titanium matrix further reduces the density of the material.

2.3.1 Fabrication Processes

Due to the high reactivity of titanium alloys with the SiC monofilaments, fabrication processes that take place with the least possible thermal load on the composite during manufacturing are given preference. Thus, processes based on vapor deposition and solid state formability are considered.

Today the favored route is the matrix-coated fiber technique. The starting product is a homogeneously matrix-coated fiber (monofilament) that allows fabrication of composites with excellent fiber arrangement and microstructure of the matrix. The coating fabricated by magnetron sputtering is deposited from the vapor phase. Due to the higher deposition rate electron beam physical vapor deposition (EB-PVD) is also used but limited to matrix alloys of simple composition.

Magnetron sputtering is a very versatile process to produce coatings of almost any chemistry, first explored in the early 1980's as a deposition process for titanium matrices on monofilaments [8]. Matrix deposition onto the fibers is the first step of a multiple step processing chain, shown in Fig. 5. The fiber volume content of the composite can be easily adjusted by the matrix coating thickness.

In the second step, the matrix-coated fibers are bundled or arranged using, for example, winding techniques to achieve the desired component geometry, encapsulated, and subsequently hot-isostatically pressed at temperatures around 950°C and pressures of about 2000 bar. In the last step, the component is machined to its final geometry.

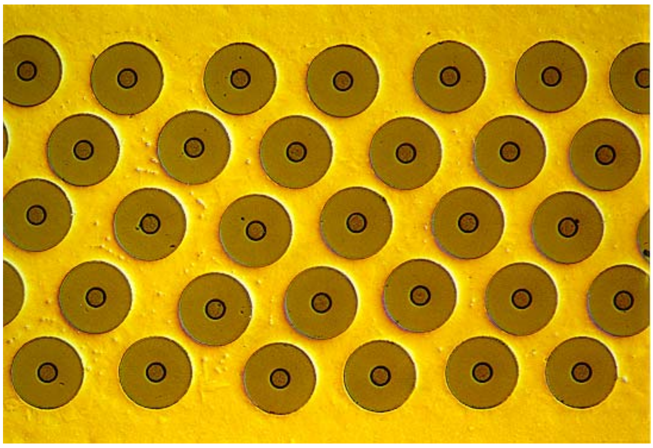

Fig. 5: Titanium matrix composite manufactured by matrix coated fiber technique via magnetron sputtering.

2.3.2 Properties

In general, composite properties strongly depend on the properties of the single constituents. Knowledge of the interaction between the constituents is the basis for successful materials system development; optimization of the composite properties almost always relies on the optimization of these interactions.

High strength and stiffness in the longitudinal direction up to elevated service temperatures are certainly the most outstanding properties of unidirectionally reinforced TMCs. Strength, or more precisely specific strength, i.e. strength related to density, is a key parameter for lightweight structures and is an important property of major interest to the designer.

The specific strength data of typical aerospace materials and TMCs are displayed in Fig. 6 for maximum service temperatures up to 800°C. While the specific strength (or the rupture length) of classical near-α titanium alloys, α_2-Ti_3Al or orthorhombic (Ti_2AlNb) titanium aluminides, γ-TiAl alloys as well as nickel-based superalloys (here IN 718) range from 10 to 30 km at room temperature and from 10 to 15 km at 800°C, the maximum specific strength of TMCs is between 40 and 55 km at room temperature and still as high as 50 km at 700°C. The maximum strength strongly depends on the fiber volume fraction; maximum values were obtained from 40% fiber volume fraction. For SiC/TIMETAL 834, a room temperature tensile strength of 2400 MPa can be reproducibly obtained, which is in good agreement with the calculations according to the rule of mixtures.

Strength of TMCs at high temperatures is not limited by insufficient strength of the fiber – the fiber is stable far beyond 800°C – but by the high temperature capability of the matrix material. The service temperature limitations of the matrix are caused by the loss of strength and, much more importantly, by environmental degradation of the matrix material. Therefore, the choice of matrix material determines the service temperature limit of the composite. Similar to the environmental protection required by monolithic titanium alloys at elevated temperatures, the full potential of TMCs at high temperatures can only be used if sufficient environmental resistance of the matrix, e.g. by the use of protective coatings, is provided [9].

The use of TMCs in rotating components of future jet engine compressors requires fatigue resistance; where fatigue behavior under high stress loading is one of the most important design criteria. Fig. 7 shows the cyclic strength of unreinforced and SiC-fiber reinforced

TIMETAL 834 under tension-tension loading at room temperature and 600°C, respectively. The application of TMCs has a positive effect, particularly at 600°C where the high strength of the fibers dominates the behavior. The maximum cyclic stress for TMCs in the LCF (low cycle fatigue) regime as well as in the HCF (high cycle fatigue) regime is at least 100% higher than that of the unreinforced material. While the endurance limit of the unreinforced alloy is about 400 MPa, SiC/Ti reaches an endurance limit of more than 1000 MPa at 600°C.

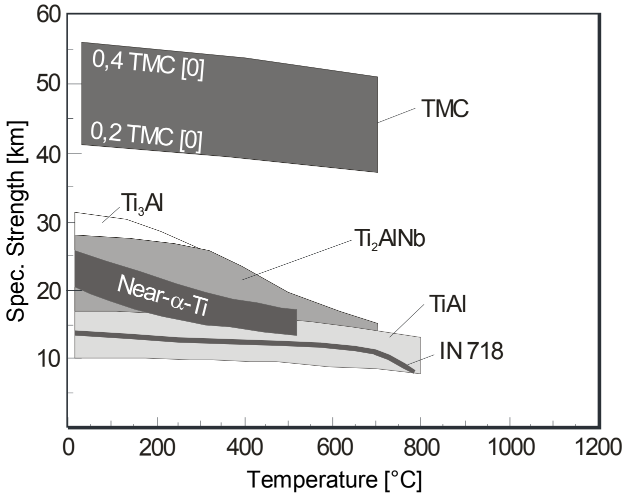

Fig. 6: Specific strength and stiffness of TMCs and other aerospace materials and their temperature dependence

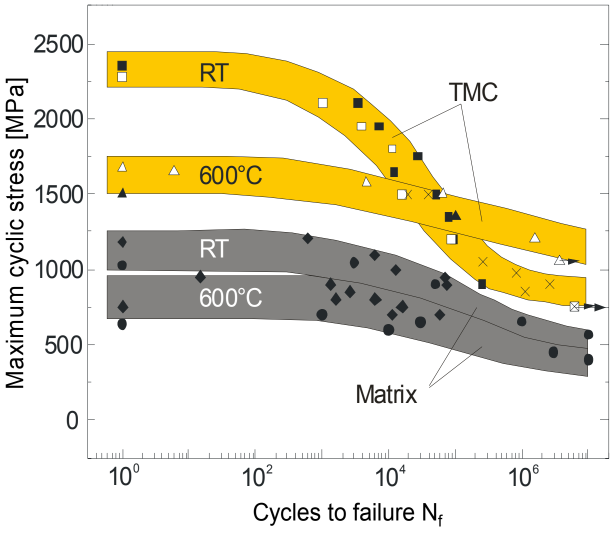

Fig. 7: Fatigue strength of TMCs in comparison to the unreinforced matrix material in the tension-tension mode.

Furthermore, the creep resistance of TMCs is significantly greater compared to that of the unreinforced matrix material which is of particular interest for aeroengine applications in rotating parts. A detailed discussion of the micromechanical behavior and the fracture mechanics exceeds the purpose of this paper and can be found in the literature [7, 10].

2.3.3 Applications

The development of TMCs has been decisively spurred by the requirements of the gas turbine engine industry. With increasing demands placed on lightweight properties in engine design, development of materials operating at elevated temperatures for long times, providing damage tolerance and extreme mechanical properties has become necessary. In the USA, the IHPTET program (Integrated High Performance Turbine Engine Technology) was among the most powerful programs for the development and introduction of TMCs into aerospace applications. To date, a number of different components have been developed with TMCs, such as hollow airfoils, compressor rotors, casing structures, connecting elements, and actuators. With the introduction of the F-22 for the U.S. Air Force, TMCs have arrived in the operational world. Pratt & Whitney’s F119 engine that powers the F-22 has TMC actuators used for nozzle control. Recently, fan airfoil design concepts for rotating components have been developed based on a locally TMC-reinforced airfoil. Due to the high stiffness of the airfoils, innovative aerodynamic designs can be approached that reveal significantly improved efficiency and higher specific performance than achievable with monolithic titanium alloys today.

Many attempts have been made to realize the bling (bladed ring) concept that aims to revolutionize current compressor design. Along with extended design limits in the compressor, substantial weight savings are feasible by replacing the heavy compressor disks by bladed rings. In these components, the benefits of TMCs can be used in an ideal way since loading is mainly unidirectional. It is expected that weight savings of the order of 50% relative to conventional compressor design can be realized. However, these rotating components would be high-risk applications, since in the case of failure the entire engine might be damaged. Reliability of the materials and the components are therefore of uppermost importance. Moreover, a reasonable balance between the expenditures necessary to produce high-quality TMCs and the final direct operating costs must be found.

Shafts are a further example of safety-relevant components in gas turbine engines. Again, fiber reinforcement would result in a significant increase in component stiffness and strength. Particularly for large-scale components, marked technical hurdles must be taken before high quality shafts can be manufactured that meet all the materials and design requirements.

3 Thermal Barrier Coatings for Increased Turbine Efficiency

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 in the order of 1 MW/m^2, thus reducing the overall fuel efficiency of the engine. The necessity of a close control of materials temperatures can be expressed by the simple rule that blade life on creep is halved for every 10 to 15°C increase in temperature [11].

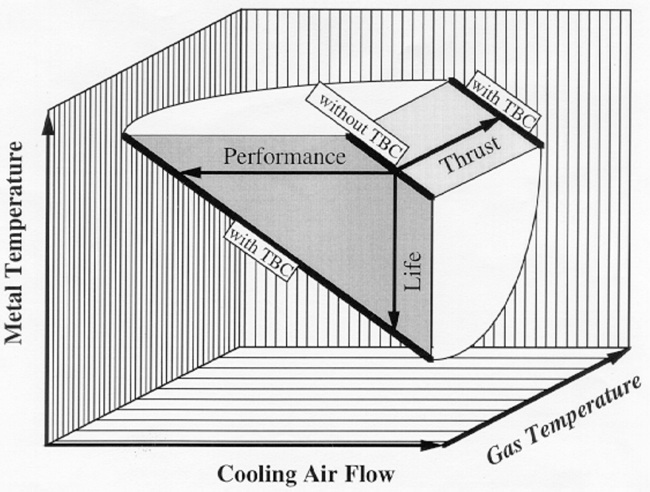

Fig. 8: Thermal barrier coatings (TBCs) allow increased engine performance and/or life extension

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 deposition (EB-PVD) thermal barrier coatings (TBCs) [12].

TBCs consist of thin ceramic layers of low thermal conductivity - typically partially stabilized zirconia - which are applied on aerofoil surfaces that just have a metallic corrosion resistant coating. The coating imparts good adhesion of the ceramic to the substrate. Application of the TBCs enables increasing engine performance/thrust by either increasing the gas temperature or reducing the cooling air flow [13]. Alternatively the lifetime of the turbine blades can be extended by decreasing metal temperatures as schematically outlined in Fig. 8.

Plasma-sprayed (PS) TBCs have been widely applied to hot components like burner cans since the sixties while in recent applications to 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 with 2 to 25 µm in diameter. The main advantage of this structure is its superior tolerance against

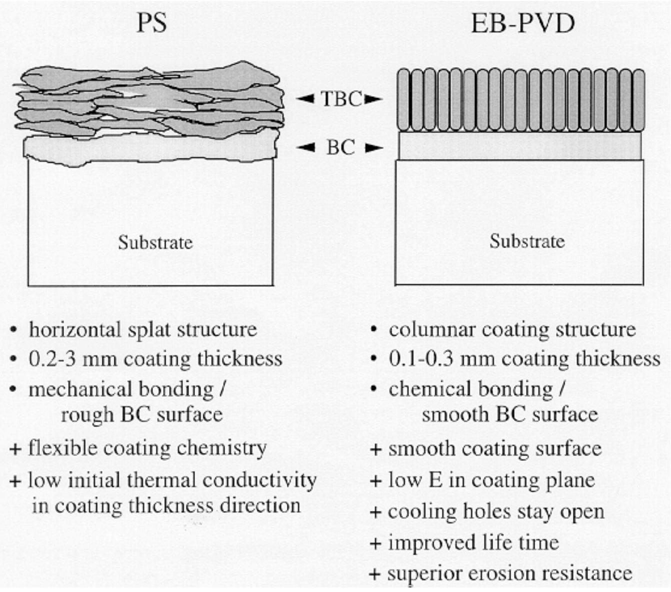

Fig. 9: A simplified comparison of properties for plasma sprayed (PS) and evaporated (EB-PVD) TBCs (schematic)

straining and thermoshock, thus giving it a major edge in lifetime.

During EB-PVD processing a high energy electron beam melts and evaporates a ceramic source 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 aerodynamically 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. Typical characteristics and major advantages of thermally sprayed and on-evaporated TBCs are schematically compared in Fig. 9. Fig. 10 shows an EB-PVD TBC on an aircraft engine turbine blade produced at DLR using a semi-industrial size dual-source 150kW von Ardenne EB-PVD coater (Fig. 11).

Since the late 1990s the first generation of EB-PVD thermal barrier coatings have 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 to fully integrate TBCs into the blade design and not only use 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 [14, 15].

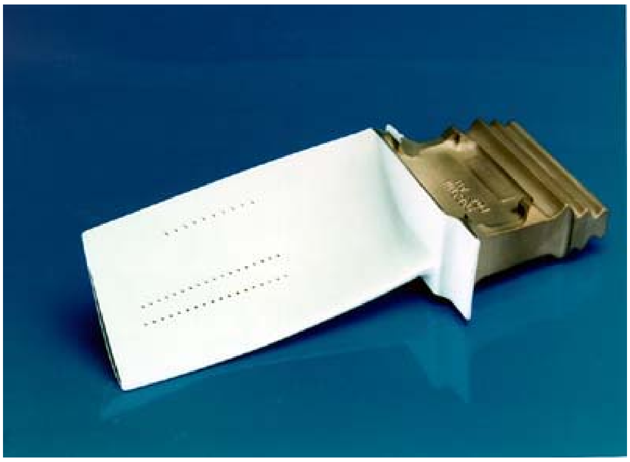

Fig. 10: EB-PVD thermal barrier coating on high pressure turbine blade, manufactured at DLR

Future applications of TBCs aim at blade surface temperatures well beyond 1250°C where aircraft engines as well as industrial turbines will operate. However, today’s state-of-the-art TBC material, partially stabilized zirconia (PYSZ), exhibits destabilization of the tetragonal t' phase to monoclinic and cubic on extended exposure at temperatures above 1200°C, and sintering phenomena become predominant [16, 17]. Alternative ceramics will be needed with reduced sintering rates, better phase stability and lower thermal conductivity. Besides changes in zirconia stabilizer content and type, new ceramics compositions with more complex crystallographic structures, such as pyrochlores, garnets, and magnetoplumbites are under investigation [18]. The need for advanced ceramic materials will force EB-PVD processing development to overcome pertinent materials restrictions. Multiple-source high rate evaporation will be a valuable tool in this context to enable the production of complex TBCs which are composed of "low" and ”high” vapor pressure components. Advanced bond coat compositions may also contribute to the manufacture of safer TBC systems.

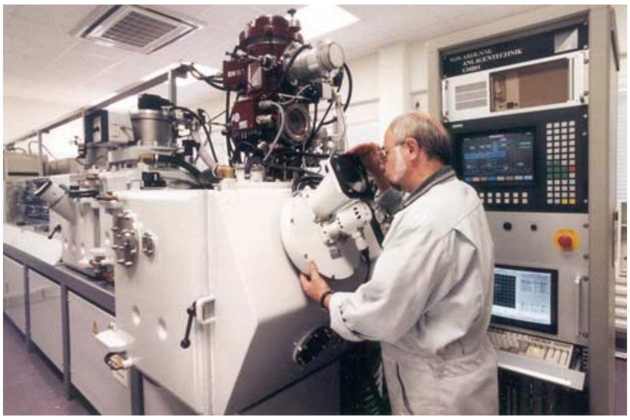

Fig. 11: 150 kW EB-PVD pilot coater (von Ardenne Anlagentechnik, Dresden, Germany) operated at DLR

Generally, research on EB-PVD TBCs has become highly dynamic. New microstructures encompass compositionally graded, density graded and multilayered arrangements where, especially in the last case, reduced heat conduction may allow the application of thinner overlays [19-22]. CVD techniques can attribute their particular thin layer virtues. In any case basic and applied research capabilities have to focus on alternative materials and processing routes while earnestly guarding all cost requirements. Finally, non-destructive testing and life-prediction methodologies for TBC systems have to be furnished.

4 Conclusions

Advanced materials technologies are essential for future aircraft engine design. Near-α titanium alloys are the prime choice for elevated temperature applications up to 500°C in current aircraft engines. Titanium aluminides are at the edge for commercial applications and will further expand the range of application of light-weight high temperature components made of titanium base materials.

Outstanding mechanical properties including high strength, stiffness, creep and fatigue resistance make continuously fiber reinforced titanium matrix composites (TMCs) ideal materials for demanding high technology applications, e.g. in gas turbine engines. Due to high materials costs and lack of knowledge on materials properties, their use has so far been limited to niche applications. Current activities have to improve the affordability of the TMCs to increase the acceptance in the industrial market. While today most TMC applications are focused on low or moderately elevated temperatures, high temperature applications are likely the future of TMCs.

For thermal highly loaded rotating parts such as high pressure turbine blades, EB-PVD thermal barrier coatings (TBCs) exhibit the highest potential to increase turbine efficiency. TBCs represent a complex system consisting of (at minimum) 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. The complex and often dynamic thermal, thermo-mechanical, and mechanical loading situation, including thermal gradients and cyclic effects, further complicates the situation.

Future research is directed towards improved lifetime, reduced thermal conductivity, improved temperature capability, lower manufacturing cost, and ability for repair.

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