# Conventional and advanced coatings for turbine airfoils

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## Abstract

This paper gives an overview over the types of coatings applied on turbine airfoils of modern jet engines. Due to increasing demands for engine efficiency and lifetime modern turbine airfoils have to be protected against high temperature oxidation and corrosion. As protection either pure oxidation resistant coatings or Thermal Barrier Coatings (TBC) can be used. Two examples of turbine airfoils are presented, where the different types of coatings are applied. This includes coating properties, manufacturing processes, operational experience and repair schemes.

## Introduction

The requirements for aircraft engines are high efficiency at low costs. This means, that prices for new engines have to be attractive and the operating costs have to be low. The operating costs are determined by low Specific Fuel Consumption (SFC), long Time Between Overhaul (TBO) intervals and low repair costs. One critical part in all engines is the high pressure turbine section, because the operating temperatures are very high. Figure1 gives an overview over a modern jet engine.

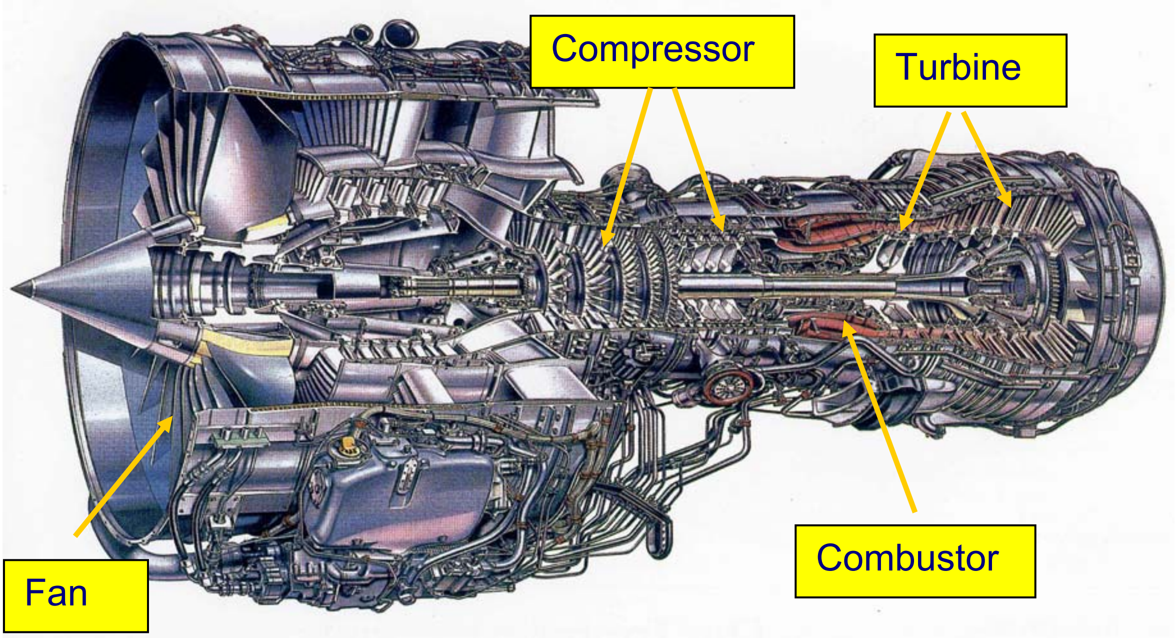

*Figure1:* Picture of a modern jet engine

The gases from the combustion chamber of modern civil aero engines enter into the turbine section with temperatures up to 1850 K and higher. Therefore advanced cooling methods and the use of advanced materials which are protected by advanced coatings are required to guarantee, that turbine airfoils can withstand those high gas temperatures for up to 20000 hours, before they are repaired or replaced. This presentation will describe the coating design, manufacturing processes and the coating properties for a turbine blade and a turbine vane and will also give information about flight performance and repair possibilities.

**Development of airfoil materials**

Due to the increased operating temperatures of modern aero engines the airfoil materials have changed from polycrystalline materials over to directionally solidified castings over to single crystal materials. In mature engines cobalt based materials were used for static vanes, which are now more and more changed to nickel based materials. For rotating blades only nickel based materials are used. Some typical materials for modern turbine airfoils are given in *table1*.

*Table1*: Materials used for modern turbine airfoils

| Materials | Polycrystalline | Directionally solidified (DSR) | Single crystals (SX) |
|---|---|---|---|
| Examples GE | Rene 80 | Rene 142 | Rene N5 |
| Examples PW | IN 713 | PWA 1426 | PWA 1484 |

**Development of airfoil coatings**

On the coating side one must differ between pure coatings for oxidation protection and Thermal Barrier Coatings (TBC) which are presently made of Yttria Stabilized Zirconia (YSZ). The function of the TBC is to reduce the temperature of the airfoil material, so that either the engine can be operated at higher temperatures or the lifetime of the parts is increased. YSZ is a good thermal insulator which has a thermal conductivity in the range between 1 and 2 $Wm^{-1}K^{-1}$, depending on the manufacturing process. The Thermal Barrier Coatings cannot be applied directly on the part but need a bond coat. This bond coat has the function to reduce the thermal expansion mismatch between the substrate and the TBC and to provide an oxidation resistant interface.

**Oxidation protective coatings**

The main types of coatings used for oxidation protection are:

1. Metallic overlay coatings of the composition MCrAlY with M=Ni, Co or a mixture of both elements. The cheapest process to apply those metallic coatings is Atmospheric Plasma Spray (APS). However, these layers tend to oxidize during the APS-process and are not very dense. Therefore APS sprayed MCrAlY-coatings are normally aluminized to increase their oxidation resistance. Better MCrAlY-coatings can be obtained by High Velocity Oxy-Fuel spray (HVOF) or by Vacuum Plasma Spray (VPS). These coatings have fewer oxides and are much denser. Manufacturing costs for HVOF coatings are comparable to those for APS coatings, whereas VPS coatings are more expensive.
   Another very expensive method to produce MCrAlY-coatings is by Physical Vapour Deposition, (PVD) in particular by Electron Beam Vapour Deposition (EB PVD). These coatings also show a very good performance because they are very clean and dense.

2. Aluminide diffusion coatings
   This type of coating consists of intermetallic compounds between Aluminium and Nickel or Cobalt of the base material. The coatings are obtained by placing the parts in a box, heating them up to temperatures between 760 °C and 1100°C and by supplying Aluminium containing species which decompose on the hot surface of the components under formation of a diffusion coating. Aluminium can be supplied either by a powder pack or by vapour phase processes. Depending on the coating conditions the morphology and to some extent the performance of the coating can be influenced by the coating process.

3. Noble element modified Aluminides, mainly Platinum Aluminides (PtAl)
   These coatings show a better performance than pure aluminide diffusion coatings due to the addition of a noble metal which in most cases is Platinum. The noble metal is normally applied by a plating process followed by diffusion heat treatment prior to aluminizing.

Examples for the application of oxidation protection coatings on turbine airfoils are given in table2.

*Table2*: Application of oxidation protection coatings on turbine airfoils

| | MCrAlY (EB PVD) | Aluminides (NiAl)) | Platinum Aluminides (PtAl) |
|---|---|---|---|
| Examples GE | not applied | CF6-80 Vane 1 | CF6-80 Blade 1 |
| Examples PW | PW2000 Blade 1 | V2500 Blade 1 | not applied |

**Thermal Barrier Coating systems**

As already mentioned before, every Thermal Barrier Coating requires a bond coat for sufficient life time. The main combinations used are the following:

1. VPS MCrAlY + APS TBC
   This was one of the first systems used especially on the platforms of turbine vanes. Plasma sprayed TBC's have a layered structure with a low thermal conductivity. Since the airfoils normally are not coated with Plasma sprayed MCrAlY's, an additional aluminide diffusion coating has to be applied to the airfoil to give sufficient oxidation resistance.
2. APS MCrAlY + APS TBC
   This coating is equivalent to the VPS + APS TBC system, but it is cheaper to manufacture, because no VPS equipment is needed. Due to the fact that the bond coat is not very dense, the required aluminide coating for the airfoil is applied to the whole part after spraying the bond coat, leading to improved performance of the bond coat/TBC system.
3. Aluminide + EB PVD TBC
   This was the first system used for EB PVD coatings. EB PVD TBC's have a columnar structure which is very strain tolerant resulting in a longer lifetime compared to plasma sprayed TBC's. As a disadvantage, they are denser than plasma sprayed TBC's which results in a higher thermal conductivity. EB PVD coatings have higher production costs than plasma sprayed coatings, because the coating equipment is very expensive.
4. PtAl + EB PVD TBC
   This coating combination improves the lifetime compared to the Aluminide + EB PVD TBC system due to the better performance of the PtAl bond coat. However the manufacturing costs are higher due to the additional platinum plating process.
5. EB PVD MCrAlY + EB PVD TBC
   This system also has a very good performance but a second EB PVD coater is required to apply the MCrAlY coating which leads to increased production costs.

Examples for the application Thermal Barrier Coating Systems on some commercial turbine airfoils are given in table3.

*Table3*: Application of Thermal Barrier Coating Systems on turbine airfoils

| Bond coat | VPS MCrAlY | APS MCrAlY ( aluminized) | Aluminide | PtAl | EB PVD MCrAlY |
|---|---|---|---|---|---|
| Topcoat | APS TBC | APS TBC | EB PVD TBC | EB PVD TBC | EB PVD TBC |
| Example GE | CF6-50 Vane 2 | CF6-80 Vane 2 | CFM56-7 Vane 1 | CF6-80 Blade 1 | not applied |
| Example PW | V2500 Vane 1 | not applied | not applied | not applied | PW2000 Blade 1 |

The given overview has shown that depending on the design and the operating conditions of the engines different possibilities for the protection of turbine airfoils exist. In the next paragraph two examples will be presented, where the different coatings are applied:

1.) A static vane from the second stage of the High Pressure Turbine (HPT) of a commercial engine, where conventional Plasma sprayed and aluminide coatings are applied.
2.) A rotating blade from the first stage of the High Pressure Turbine (HPT) of a commercial engine, coated with advanced PtAl and EB PVD TBC coatings

## Conventional Coatings applied on a Stage 2 HPT Vane

In *figure2* a picture of a typical stage 2 HPT Vane is shown.

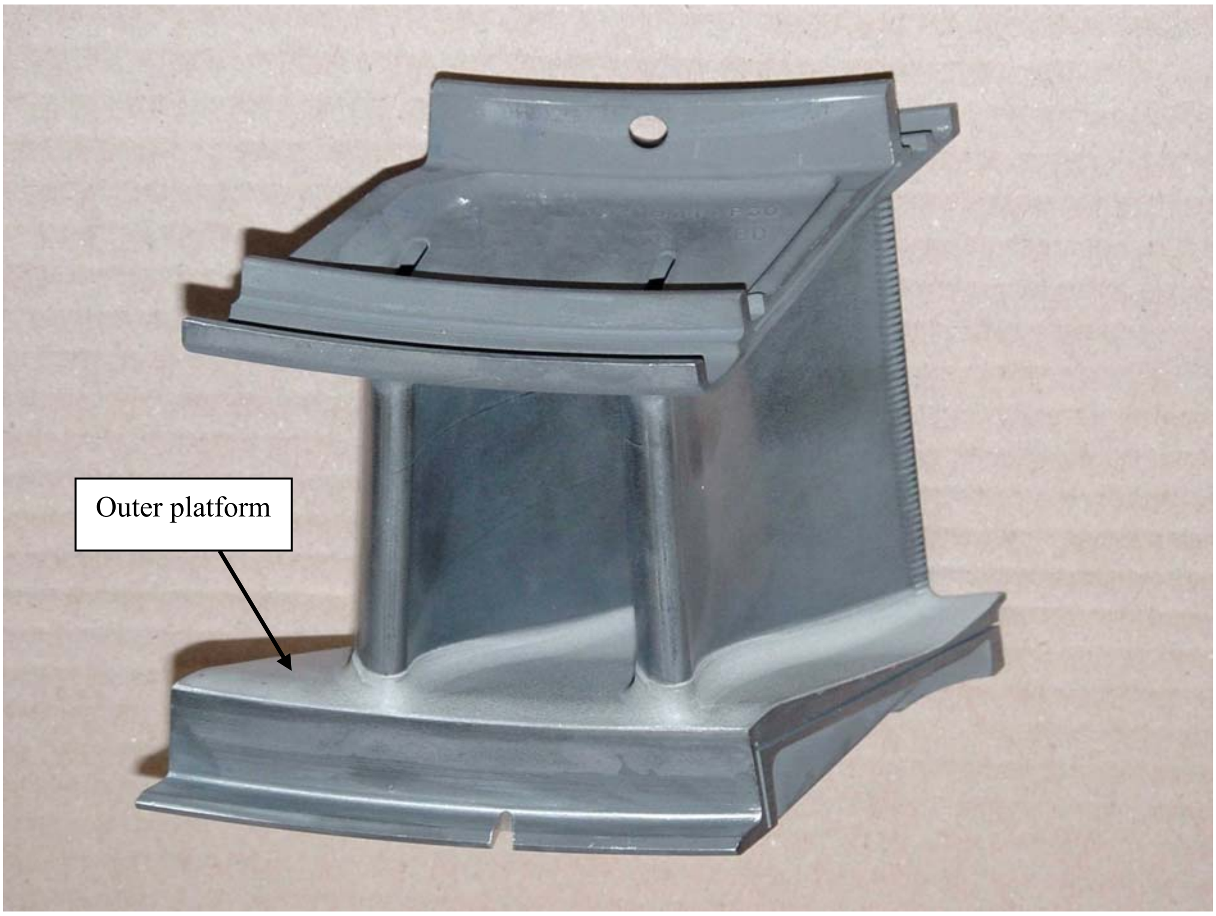

*Figure2*: Picture of a stage 2 HPT Vane

The principles applied here are:

1.) Use of a polycrystalline cast base material
2.) An oxidation protective aluminide coating on the airfoils
3.) A TBC system consisting of a VPS MCrAlY bond coat on the outer platform and an APS TBC made of Yttria Stabilized Zirconia

A typical manufacturing sequence is as follows

- Mechanical processing (grinding, drilling etc.)
- Cleaning
- Grit blasting of the platform to create a rough interface
- Aluminising of the whole part
- VPS Spraying of MCrAlY Bond coat on the platform
- Diffusion Heat treatment
- APS Spraying of Yttria Stabilized Zirconia TBC on the bond coat
- Surface finish

The morphology of the coating on the platform is shown in *figure3*.

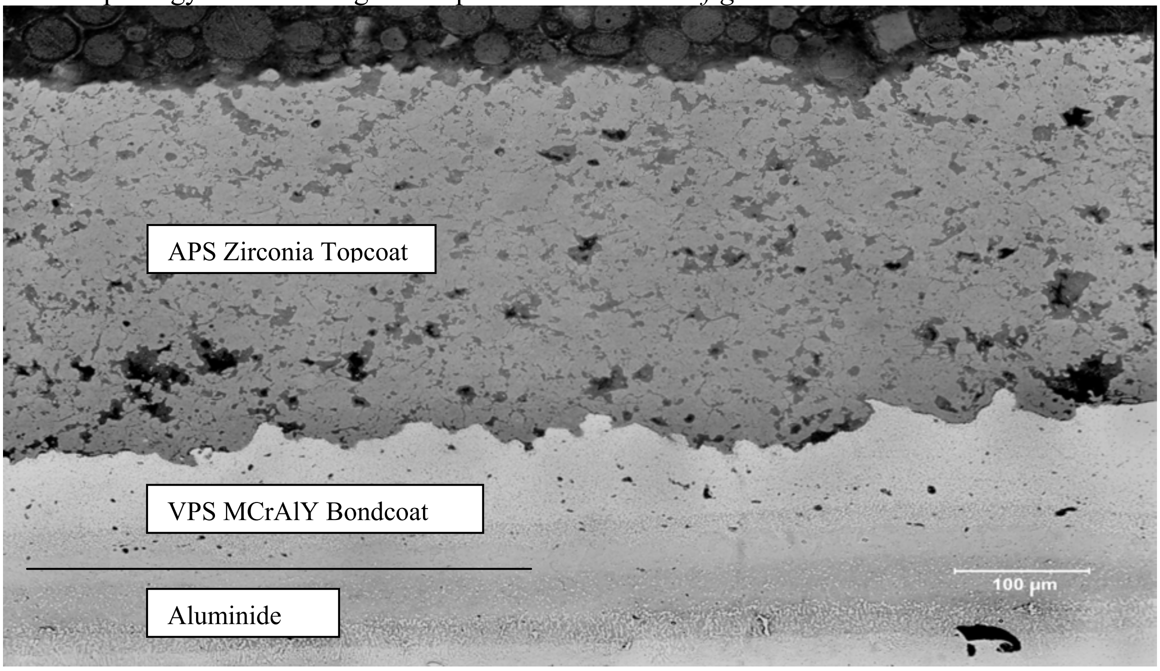

*Figure3*: Coating morphology of the aluminide and TBC system on the platform

The coating nearest to the substrate is the aluminide which has the function to protect the non TBC coated areas against oxidation. The coating thickness for an aluminide is normally in the range between 50 and 100 µm. On top of the aluminide one can see the MCrAlY bond coat which gives on the one hand an additional oxidation protection and on the other hand serves as interface for the TBC. Typical thicknesses of plasma sprayed bond coats range from 50 – 200 µm. Due to the application of the bond coat by Vacuum Plasma Spray the bond coat is very dense with only few pores. As topcoat serves the grey porous Yttria Stabilized Zirconia. The adhesion of the zirconia results mainly from mechanical adhesion, therefore the surface of the underlying bond coat has to be rough. Typical thicknesses of such plasma sprayed TBC's are in the range between 250 and 400 µm.

### Repair aspects of the Stage 2 HPT Vane

The MCrAlY-bond coat/TBC coating system is very well adapted to the operation conditions of the part. *Figure 4* shows a part in incoming condition for repair. Typical times between overhaul are for this type of part in the range between 10000-20000 hours and 2000-4000 Cycles depending on operating conditions. One cycle consists of one take-off and one landing. As can be seen in *figure4* the Thermal Barrier Coating shows only very little spallation at the edges. The main reasons for the repair of the part are cracks of the base material which are caused by thermo-mechanical stresses. For the braze repair of those cracks it is required to strip the coating, because a braze repair can only be performed on the clean base metal. A typical repair sequence is as follows:

- Cleaning
- Inspection
- Removal of TBC by abrasive blasting or high pressure water jet stripping
- Removal of Aluminide and MCrAl-coatings by chemical stripping
- Fluoride Ion Cleaning (FIC) to remove oxides in the cracks
- Braze repair of cracks
- Machining and manual re-contouring
- Re-Drilling of cooling holes (if required)
- Aluminising
- VPS MCrAlY bond coat
- APS Top coat
- Surface finish
- Final inspection

*Figure4*: Incoming condition for repair of a stage 2 HPT Vane

As a summary it can be concluded, that the conventional coating system consisting of an aluminide diffusion coating and a plasma sprayed Thermal Barrier Coating system fulfils well the requirements for the stage 2 HPT vane. The coating normally is not the weak element of the part, but has to be removed for the braze repair of thermo-mechanical cracks.

### Advanced Coatings applied on a rotating Stage 1 HPT Blade

As was shown before, a conventional coating system has sufficient lifetime for a stage 2 turbine vane. The first stage of a turbine operates at higher temperatures. Therefore more complex coating systems have to be applied to guarantee the required performance and lifetime. One example for such a part is the HPT stage 1 blade shown in *figure5*.

*Figure5*: Picture of a HPT stage 1 blade

The principles to resist the higher temperatures are

1.) Use of a directionally solidified base material
2.) An oxidation protective PtAl coating as bond coat
3.) A Thermal Barrier Coating (TBC) consisting of Yttria Stabilized Zirconia applied by Electron Beam Vapour Deposition (EB PVD)

A typical manufacturing sequence is as follows

- Mechanical processing (grinding, drilling etc.)
- Cleaning
- Platinum Plating
- Diffusion Heat Treatment
- Aluminising
- EB PVD TBC Application
- Final Heat treatment/Aging
- Surface finish

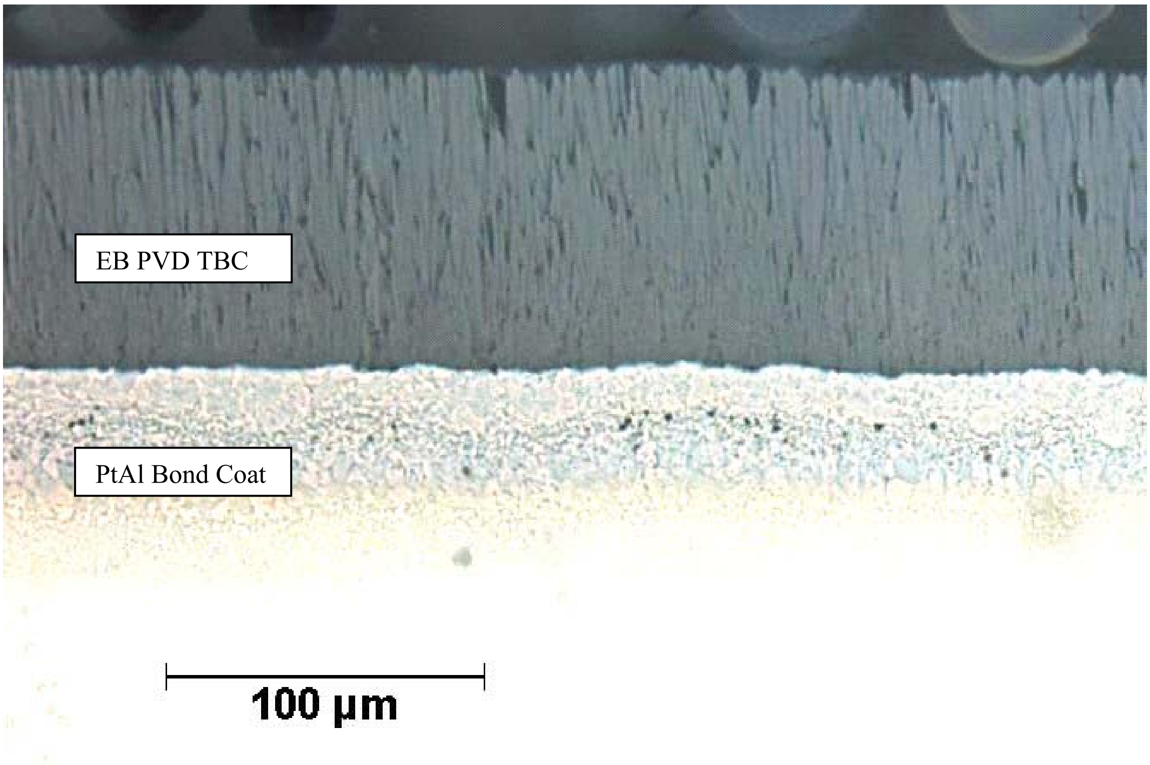

*Figure6*: Coating morphology of the PtAl and EB PVD TBC system on a HPT Stage 1 blade

In figure 6 the morphology of the coating is shown which consists of the PtAl bond coat and the Thermal Barrier Coating. This bond coat contains bright $PtAl_2$-precipitations in a darker NiPtAl-Matrix. The morphology changes during the final heat treatment or during engine operation to a single phase NiPtAl-morphology. Typical thicknesses are in the range between 40 and 80 µm. The surface of the PtAl-bond coat is very smooth compared to the APS plasma sprayed bond coats. This originates from the fact, that the adhesion of the EB PVD TBC is not determined by mechanical adhesion but by a chemical bonding between the zirconia and a thin layer of $Al_2O_3$. This alumina layer is formed on the PtAl during the EB PVD coating process. Typical coating thicknesses for EB PVD TBC's on rotating parts are in the range between 75–150 µm. The top coat has the typical columnar structure known for EB PVD TBC's. This structure is more strain tolerant, than APS plasma sprayed TBC's because of the voids between the columns. However, the EB PVD coating has a higher density in the direction perpendicular to the surface. Therefore the thermal insulation is less than for plasma sprayed coatings. Since Zirconia is an oxygen ion conductor, the normal failure mechanism of EB PVD TBC's is caused by oxidation of the underlying bond coat. When the PtAl oxidizes, $Al_2O_3$ is formed at the interface. As a ceramic, this oxide has a lower thermal expansion coefficient than the metallic bond coat and the airfoil. After the oxide has reached a thickness of approximately 6-8 µm the expansion mismatch leads to stresses during the operation of the engine, which finally causes the spallation of the TBC. Besides TBC's are susceptible for mechanical impact which can be caused by ingestion of sand or dust. Therefore TBC's are normally applied as a medium to increase the lifetime of the parts but the part will not completely burn or fail, if the TBC is missing.

**Repair aspects of the Stage 1 HPT Blade**

The stage 1 blade is operating at higher temperatures than the stage 2 vane mentioned before. Therefore the coating has to be replaced from time to time due to TBC spallation and bond coat oxidation. *Figure7* shows a part in incoming condition for repair. Typical times between overhaul are in the range between 10000 and 20000 hours, corresponding to 2000 to 4000 cycles.

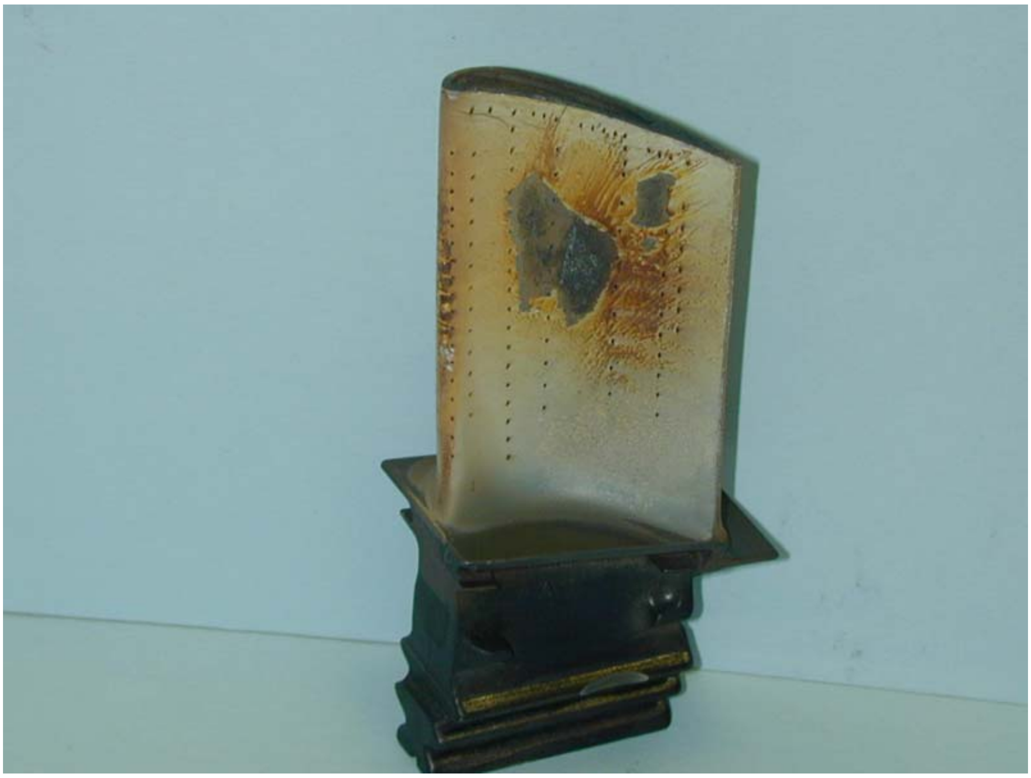

*Figure7*: Incoming condition for repair of a stage 1 HPT blade

As can be seen on *figure7* the blade shows wear on the tip and spallation of TBC coating. Therefore the repair sequence for this part is as follows:

- Cleaning
- Inspection
- Removal of TBC by abrasive blasting or high pressure water jet stripping
- Removal of PtAl-coating by chemical stripping
- Tip restoration by welding
- Machining and manual re-contouring
- Platinum Plating
- Diffusion Heat Treatment
- Aluminising
- EB PVD TBC Application
- Final Heat treatment/Aging
- Surface finish

The number of repairs including coating removal is often limited, because by stripping the PtAl bond coat, the wall thickness of the part is reduced. Newer developments aim to not completely strip the bond coat and to apply the new bond coat with reduced thickness. This offers a possibility to perform a higher number of repairs.

## Conclusions

Modern turbine airfoils have to be protected by oxidation resistant coatings or Thermal Barrier Coating systems. The complexity of the coatings and therefore the production costs strongly depend on the design and the operating conditions of the engines. Some airfoils can be protected by simple aluminides and plasma sprayed Thermal Barrier Coatings. Driven by the demand for higher turbine efficiency and lower operating costs, advanced airfoils have to be protected by advanced coatings as PtAl in combination with EB PVD Thermal Barrier Coatings. MTU Aero Engines is capable to manufacture aluminides, PtAl and all types of plasma sprayed coatings in house and is a partner of the

OEM’s in new parts manufacturing. Since 2001 MTU Aero Engines is also able to produce EB PVD Thermal Barrier Coatings at the Ceramic Coating Center in Chatellerault, France, which is a 50/50 Joint venture between MTU Aero Engines and Snecma Services.

New developments often use single crystals as base material together with an advanced cooling configuration. Coating developments have the goal to improve PtAl coatings by addition of other elements as for example yttrium. Trends in TBC development aim to improve long-term stability and to reduce thermal conductivity, either by new materials or by changing the morphology of the coating by modifying the manufacturing process.