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## Advantages/Disadvantages of Various TBC Systems as perceived by the Engine Manufacturer

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### SUMMARY

This paper discusses the relative advantages and disadvantages of Thermal Barrier Coatings systems (TBC's) produced by thermal spraying and electron-beam PVD processing technology from a design point of view. This paper reviews the structure/property relationships for electron-beam physical vapour deposition (EB-PVD) TBC's in contrast to those of plasma sprayed TBC's, particularly with respect to thermal conductivity, erosion resistance and mechanical behaviour. Examples are used to show how, through the development of customised bondcoat systems, the performance of TBC systems can be considerably enhanced, an important incremental step towards the ultimate goal of "designed-in TBC's".

### INTRODUCTION

To improve fuel efficiency and performance the operating temperatures of the turbine section of the aero-engine have been increased significantly over the past twenty years. This temperature rise has been met by the use of materials with increasing temperature capability, the introduction of advanced manufacturing technology producing cast blades with improved cooling effectiveness, and the introduction of directionally solidified and single crystal turbine blade technology

(Figure 1), [Ref.1]. Thermal barrier coatings (TBC's) offer the potential of allowing an increase in operating temperature of 70 to 150°C without any increase in metal operating temperatures or the ability to reduce the mass flow of coolant whilst maintaining the operating temperature of the turbine. Both possibilities are very attractive to the turbine blade designer. In the first case the equivalent of 2-3 generations of turbine alloy development can be achieved with the application of the coating, in the second case improvements in specific fuel consumption of 0.25% can be realised. This saving may not appear significant, but can result in an annual saving of the order of £6M for an airline operating a fleet of 747 or 777 aircraft.

### USE OF ZIRCONIA-BASED TBC'S

By virtue of a low thermal conductivity, TBC's reduce the heat flux into a component allowing a high thermal gradient to be sustained across the thickness of the ceramic (Figure 2). In addition, TBC systems are designed to match as close as is practical the expansion characteristics of the nickel-based component to ensure that the thermal mismatch stresses are minimised. During the early 1970's, due to their relatively high coefficients of thermal expansion and low thermal conductivities [Ref. 2], zirconia partially stabilised with magnesia (20% MgSZ), calcia (20% CaSZ) or yttria (8wt. % PYSZ) were

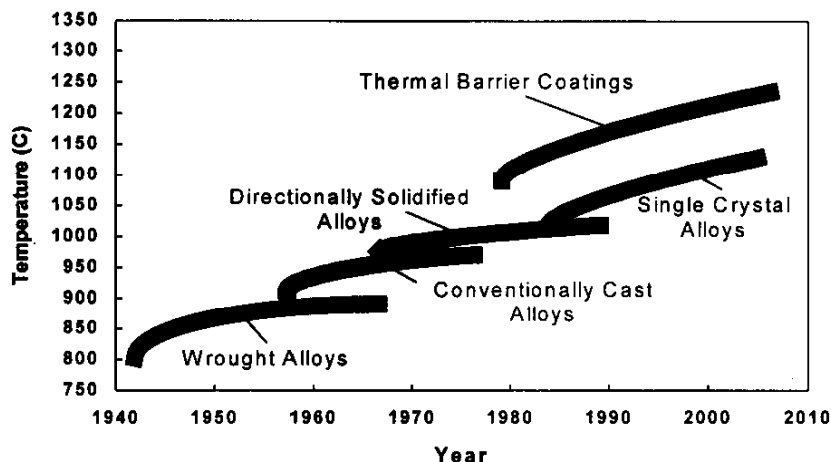


Figure 1 Increase in operational temperature of turbine components made possible by alloy, manufacturing technology and thermal barrier development.

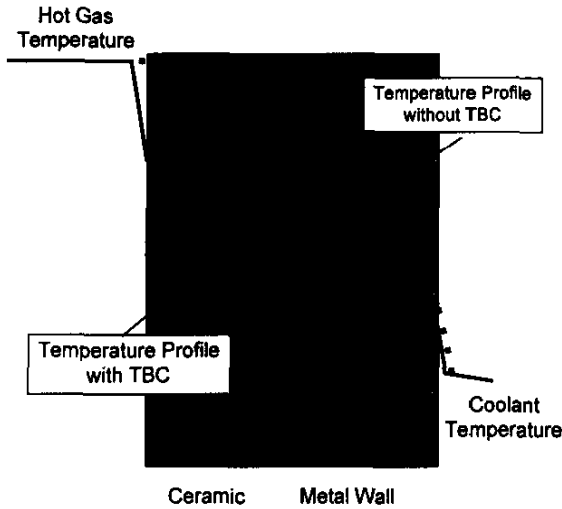


Figure 2 Schematic of the principle of the thermal barrier coating

used for plasma sprayed thermal barrier applications. Early TBC's were manufactured from magnesia or calcia stabilised zirconia, which performed well in service at operating temperatures below c.a. 1000°C. Above this temperature significant diffusion of the magnesium or calcium ions occurs and precipitates of MgO or CaO are formed [Ref. 3] which results in an increase in thermal conductivity (Figure 3) and the monoclinic content of the coating. This rise in the monoclinic content leads to mechanical instability of the coating as a result of the microcracking associated with the martensitic monoclinic/tetragonal phase change on thermal cycling.

This limitation of low operating temperature allied to phase instability was overcome by the introduction of 8% PYSZ in the late 1970's, a material which is relatively stable for elongated periods at temperatures up to 1500°C with no precipitation of Y<sub>2</sub>O<sub>3</sub> from solution; (Figure 4) [Refs. 4,5]. PYSZ TBC's have performed well in service, significantly increasing the life of components. For example, the application of 8% PYSZ TBC to combustion can walls reduces the thermal stresses in the can and can result in component lives in excess of 20,000 hours (Figure 5).

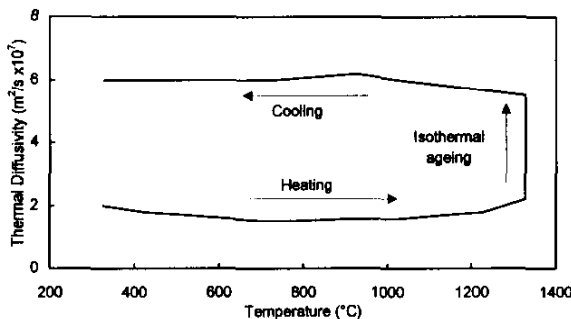


Figure 3 Thermal diffusivity of CaSZ TBC showing thermal instability due to precipitation of CaO out of solution.

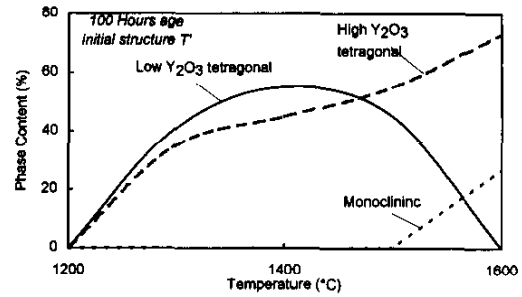


Figure 4 Relative phase compositions of aged 8% PYSZ TBC's. Note the initial coatings were all T' face-centred tetragonal phase.

PLASMA SPRAYED VERSUS PVD TBC'S

Although plasma sprayed TBC's have performed well in service on annular surfaces in the engine, their microstructures do not lend themselves to producing coatings with the necessary strain compliance, erosion resistance or surface finish required for successful application on blade or nozzle guide vane aerofoils. As a result their introduction into the high-pressure turbine has been limited. An example of the structure of a plasma sprayed coating is shown in Figure 6, where the individual platelets formed from the droplets impinging on the surface during the spraying process can clearly be seen. In contrast, more recently electron-beam physical vapour deposition (EB-PVD) has been used to deposit TBC's which, because of their columnar microstructure, exhibit very high levels of strain compliance (Figure 7). The columnar microstructure which forms is due to the atomistic processes, nucleation and growth of the coating from the vapour phase. In addition to their good compliance, EB-PVD TBC systems also offer other benefits over plasma sprayed TBC's in terms of improved adhesion, surface finish and erosion resistance which has led to their application onto turbine aerofoils. The effects of these properties on both coating and engine

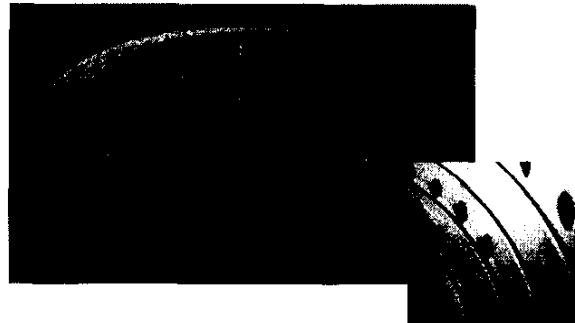


Figure 5 An example of a combustion can with plasma sprayed TBC on the inner can walls.

performance are discussed in the following sections.

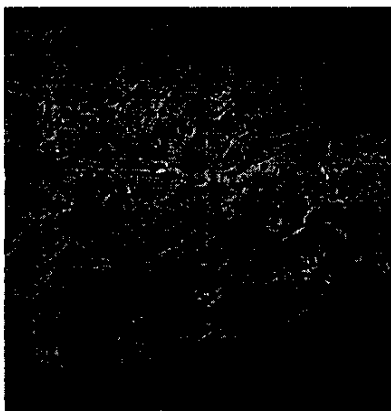


Figure 6 Photomicrograph of a plasma sprayed TBC coating. The network of microcracks (platelet boundaries) are clearly visible together with the porosity associated with these coatings.

### Surface finish

For aerofoil applications, the coefficient of friction ( $C_f$ ) of the surface of the blade is directly related to roughness [Ref. 4] and in turn the  $C_f$  value influences the heat transfer coefficient and efficiency of the turbine [Refs. 6,7,8]. The primary loss coefficient is plotted in Figure 9 for Reynolds numbers between  $0.5-1.5 \times 10^6$  which covers the range for high-pressure turbine aerofoils. As can be seen in Figure 8, the as deposited plasma sprayed TBC will have a significant effect on the performance of the turbine. The plasma sprayed TBC has a typical surface roughness of c.a  $10 \mu\text{m}$  Ra (Figure 9) and a peak to valley height of  $80-100 \mu\text{m}$  which results in an increase in the primary loss coefficient in the turbine of the order of 2% (from 1.5% to 3.5%) [Ref. 7]. In contrast the EB-PVD TBC surface finish is close to that of the metal surface, typically  $1.0 \mu\text{m}$  Ra (Figure 10) with a peak to valley height of  $10 \mu\text{m}$ . These coatings exhibit a primary loss coefficient of the order of 1.5%, and do not appear to increase the loss coefficient over that observed for the uncoated metal surface.

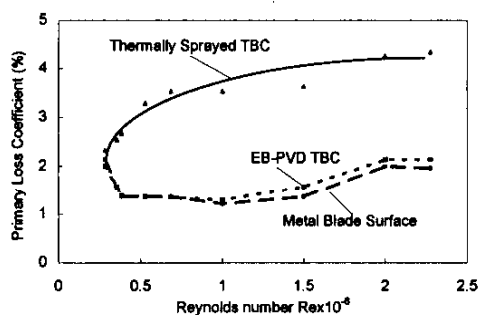


Figure 8 Primary loss coefficient for a high pressure turbine aerofoil showing the effects of different surface roughness of TBC.

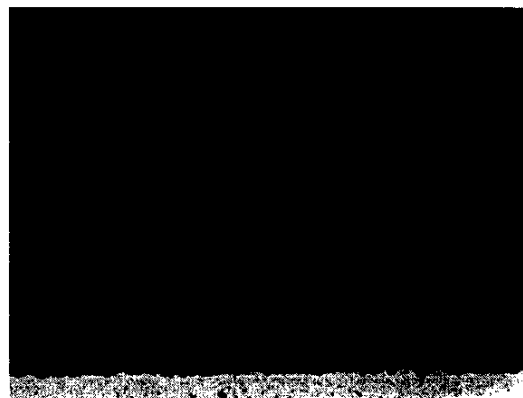


Figure 7 Photomicrograph of EB-PVD TBC showing the columnar microstructure.

Polishing of the thermally sprayed TBC results in a surface finish of  $2-3 \mu\text{m}$ , however as will be discussed later, erosion of the coating in service will increase the surface roughness of the TBC back to values approaching  $10 \mu\text{m}$ . As a result the designer will favour EB-PVD TBC systems for use on high pressure turbine blade and nozzle guide vane aerofoils for the aerogas turbine engine.



Figure 9 Scanning electron micrograph of the surface of a plasma sprayed TBC showing the high surface roughness and undulating nature of the surface.

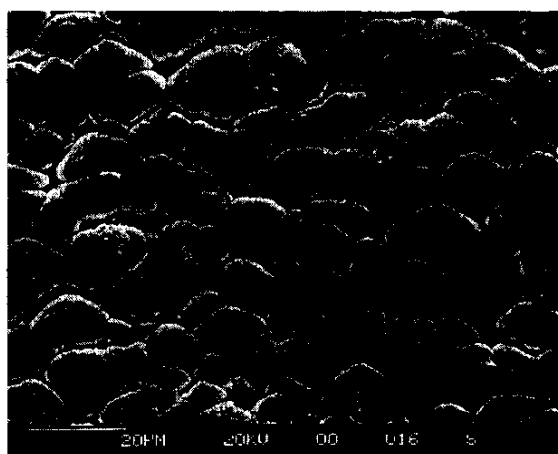


Figure 10 Scanning electron micrograph of the surface of an EB-PVD coating showing the pyramidal end form of the columns and low surface roughness.

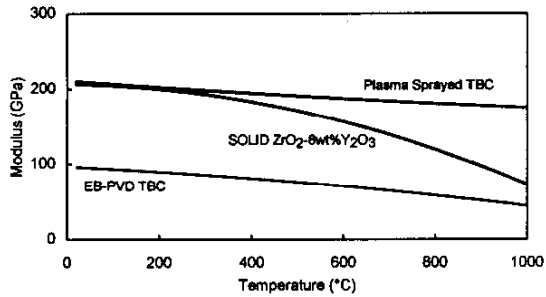


Figure 11 Young's moduli of solid sintered 8% PYSZ, plasma sprayed and EB-PVD 8% PYSZ TBC systems measured by dynamic techniques.

For TBC applications in large turbine components (particularly in the power generation industry) the relative roughness of the plasma sprayed TBC compared to the blade chord dimensions becomes more favourable and the effects of increase friction coefficient become less important. Similarly, the local gas velocities in the combustion zones are lower which can lead to low coefficient of friction losses and use of plasma sprayed TBC systems in such circumstances are not so detrimental to performance.

#### Strain Compliance

Several papers have been published detailing the modulus of TBC systems measured by various techniques including compressive and tensile tests [Ref. 9], dynamic vibration and ultrasonic velocity measurements tests [Refs. 10,11] and the values generated vary depending on the techniques used. More specifically the values vary dependent on the displacements the test method imposes during measurement.

In this paper the moduli of bulk sintered 8% PYSZ material and EB-PVD 8% PYSZ TBC were measured by a laser ultrasonic method [Ref. 11] and compared to those values measured by a resonant technique for plasma sprayed 8% PYSZ [Ref. 9]. In both methods the calculation of modulus is based on the measurement of a compression surface and shear elastic waves in the coating material. Figure 11 summaries the Young's moduli of solid sintered 8% PYSZ, plasma sprayed and EB-PVD 8% PYSZ TBC's. The modulus of the plasma sprayed TBC systems is similar to that of the sintered material, with a room temperature value of 200 GPa reducing to 160 GPa at 1000°C. The EB-PVD TBC in comparison exhibits a Young's modulus approximately half of that of the bulk material, ranging from 100 GPa at room temperature down to 40 GPa at 1100°C. Care has to be taken to remember that this is the modulus of the coating when the columns of the PVD coating are in contact and they are capable of transferring a compressive elastic wave through the structure. When

measurements are made with the laser ultrasonic method at high temperatures the signal is very highly attenuated by the coating indicating that the column boundaries are playing a significant role. It is expected that when the coating is in tension and the column boundaries open up, the composite tensile modulus of the EB-PVD coating and column boundaries will reduce significantly more than the compressive values.

The relatively high modulus associated with the plasma sprayed TBC can lead to high thermal strains in the coating, especially around tight radii of curvature which are found around the leading edges of high-pressure turbine aerofoils. As an example Figure 12 compares the microstructures of a plasma and an EB-PVD TBC which have undergone thermal cyclic testing. In the case of the plasma sprayed coating, there has been significant cracking within the ceramic leading to gross failure of the TBC system, whereas the EB-PVD system has suffered little mechanical damage within the ceramic layer.

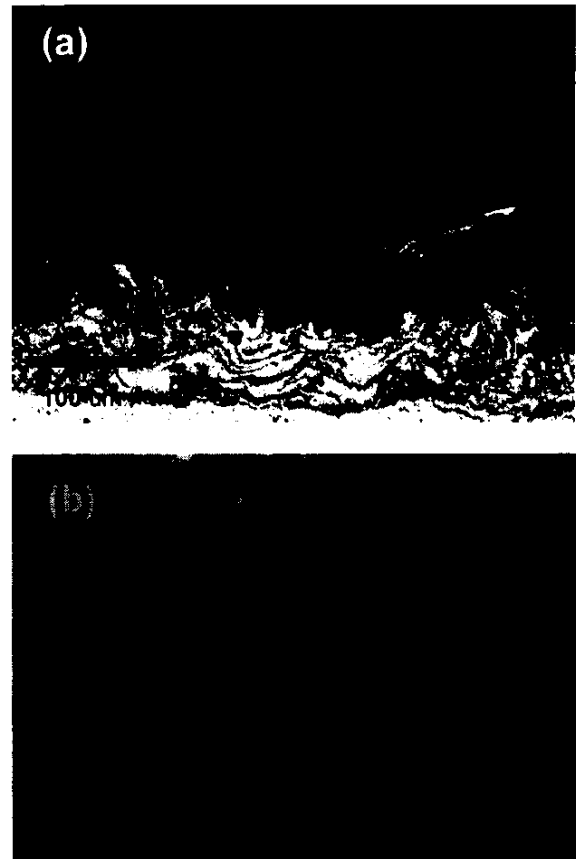


Figure 12 Photomicrographs of (a) plasma sprayed and (b) EB-PVD, TBC's showing the thermal strain damage in the plasma sprayed TBC following burner rig testing.

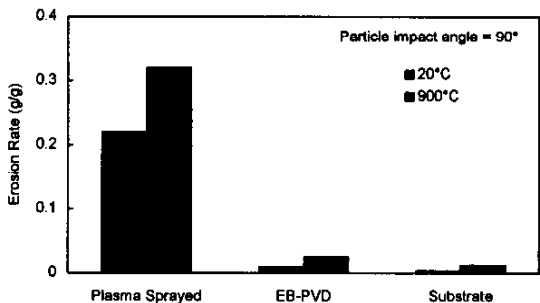


Figure 13 Erosion resistance of plasma sprayed and EB-PVD TBC's, compared to that of a metallic substrate.

Again, like surface finish, the EB-PVD TBC systems are more attractive to the designer where the coating is subjected to high thermal and mechanical loads during engine operation. The conditions encountered around the aerofoil surface in the high-pressure turbine represent such an environment and it is not surprising that EB-PVD is the principal choice in this region.

**Erosion resistance**

The erosion resistance of TBC coatings has been measured using high-temperature erosion facilities. Early studies [Ref. 12] showed that the erosion resistance of EB-PVD TBC's was approximately 8-10 times that of the plasma sprayed TBC system. Further erosion studies at temperatures up to 910°C [Ref. 11,13] using Al<sub>2</sub>O<sub>3</sub> erodant at velocities up to 230 m/s, showed that the erosion resistance of EB-PVD at both 20 and 910°C were approximately 7 times that of plasma sprayed TBC's at 90° impingement (Figure 13). Erosion tests at room temperature also showed that the angle of incidence of the particle also had a notable effect on the erosion rate. For the plasma sprayed TBC systems the erosion rate decrease with the angle of incidence with the rate at 30° impingement being one third of that at 90° (Figure 14) [Ref. 13].



Figure 15 Generation of cracks in the near surface region of the EB-PVD TBC systems during erosion testing. The reasons for this erosion behaviour and the

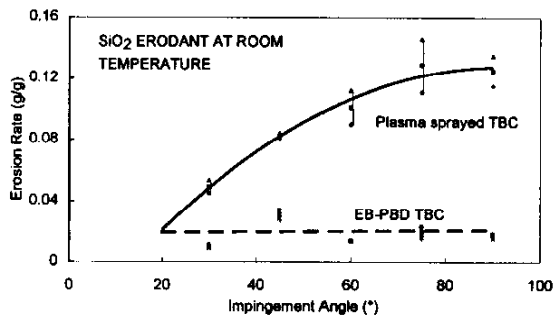


Figure 14 Room temperature erosion rate of plasma and EB-PVD TBC systems as a function of impingement angle.

mechanisms of erosion are well understood [Ref. 13]. At low and intermediate temperatures, the erosion of plasma sprayed TBC systems involves the removal of coating material in the form of the mechanically bonded platelets. This requires relatively low amounts of energy as the coating already contains a high number of microcracks, and particle boundaries, therefore the erodant has to do little work on the systems to generate small amounts of new crack surface to remove the platelet. As relatively large masses are removed with little mass of erodant, the mass erosion rate is high. In contrast, the erosion of EB-PVD TBC's requires the generation of a new crack surface across individual columns which needs a relatively high amount of energy compared with the plasma sprayed coating (Figure 15). When this fracture has occurred, the amount of material which is released is relatively small in comparison to the platelets in a plasma sprayed deposit and, as a consequence, the erosion rate is low. In addition, because the cracking damage in the EB-PVD TBC due to small erodant particles is limited to the near surface regions, the surface finish of the coating is not adversely affected by the erosion process. This is not the case for plasma sprayed TBC's which have been polished, where erosion of the coating causes the surface finish to revert quite quickly to the as deposited values, leading to significant performance penalties as discussed earlier (Figure 16) [Ref. 12].

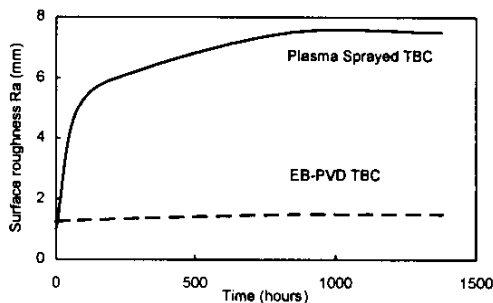


Figure 16 Effects of erosion on the surface finish of EB-PVD and plasma sprayed TBC's.

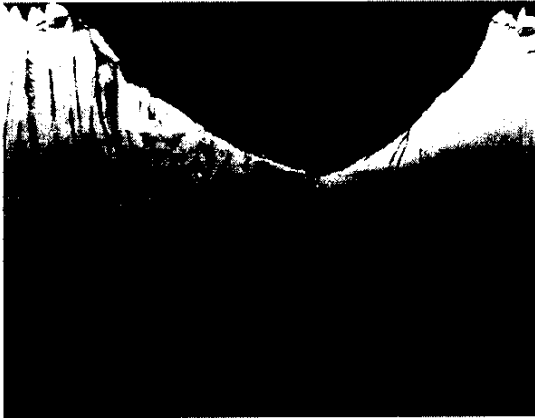


Figure 17 Example of large particle damage at high temperature showing the degree of plasticity shown by the 8% PYSZ coating.

At high temperatures there is certainly evidence within EB-PVD TBC's that significant plasticity can occur especially when large particles, foreign object damage (FOD), impinge onto the surface (Figure 17). This FOD mechanism of coating damage has been seen in development engines where the impact damage matches that produced in the high-temperature erosion rig used for laboratory assessment.

In summary, for low angle impingement, such as exists on the annular surfaces of the combustion can and nozzle guide vane platforms, or where gas velocities (and subsequently particle velocities) are low, plasma sprayed TBC systems can perform as adequately as PVD. However where the gas velocities are high and the impingement angle moves closer to 90°, EB-PVD TBC systems offer significant advantages over plasma sprayed TBC's.

#### Coating adhesion

Traditionally the adhesion of plasma sprayed coatings has been assessed by the use of bend testing, lap shear testing and pull-off testing amongst other techniques [Ref. 14]. For plasma sprayed TBC's of 0.25 mm thickness, as deposited adhesion strengths are in the range 20-40 MPa with the strength decreasing as the coating thickness increases. As deposited EB-PVD TBC systems exhibit adhesive strengths higher than the glue and generally no useful data is generated from pull-off testing these systems. To aid in the development of improved bondcoat systems, a method of assessment of adhesion had to be developed which could differentiate between the various forms of aluminide and MCrAlY EB-PVD TBC systems. This requirement led to the development of the transverse scratch adhesion test [Ref. 15].

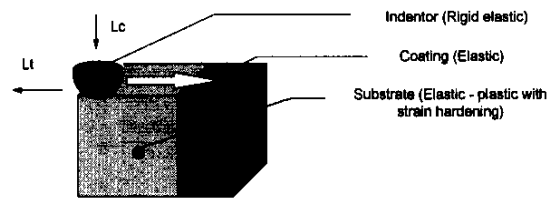


Figure 18 Schematic of the transverse scratch-adhesion test

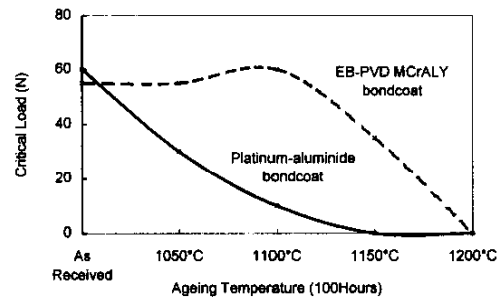


Figure 19 Scratch test adhesion values for EB-PVD TBC's systems on directionally solidified MarM002 alloy.

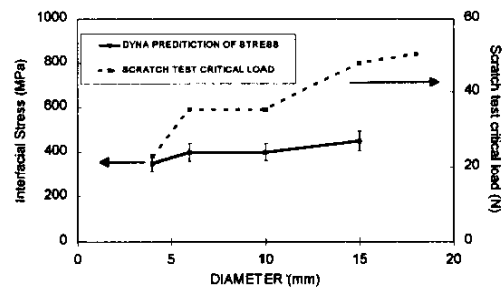


Figure 20 The effect of radius of curvature on scratch test value and the resolved interfacial strength.

Briefly this test involves indenting the substrate of a coated sample which is metallographically prepared in a mount, and moving the indenter from the substrate through the interface region and the coating to the mount material (Figure 18). This process is repeated several times at various indentation loads, the crack length at the interface of the bondcoat and ceramic layers being plotted as a function of load and extrapolated to a no-cracking critical load. This load is then used directly to rank coating systems or can be converted via finite element modelling to an interface strength in MPa [Ref. 15]. Figure 19 shows the scratch-test data for two EB-PVD TBC systems, one with an EB-PVD MCrAlY bondcoat the other with a platinum-aluminide bondcoat. As can be seen from the figure the test has enabled differences in the ageing performance of the interface region to be studied, even at adhesive strengths far in excess of those measurable by the pull-off test (typically equivalent to 5N load on the scratch test). The modelled adhesive strength for the as deposited coating systems was 400 MPa (Figure 20).

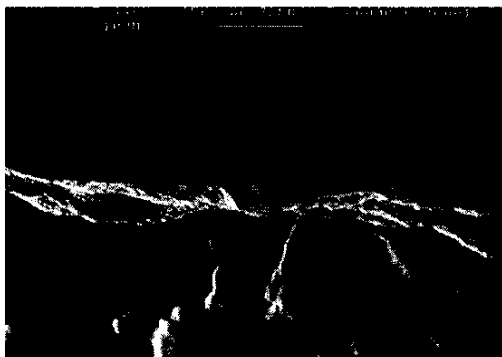


Figure 21 Transport of Hf through grain boundaries in the platinum-aluminide (top) to form HfO<sub>2</sub> pegs (bottom) at the interface with the Al<sub>2</sub>O<sub>3</sub> thermally grown oxide scale.

### Thermal Conductivity

Where as the EB-PVD TBC system offers significant benefits over plasma sprayed TBC's for aerofoil application in the areas of compliance, surface finish, erosion and adhesion, the thermal conductivity of EB-PVD TBC's are higher than their plasma sprayed counterparts. A typical plasma sprayed TBC will have a thermal conductivity of 0.7-0.9 W/m.K [Ref. 4] whilst a 0.25 mm thick PVD coating exhibits a thermal conductivity of 1.6 W/m.K [Ref. 16]. Again, these property differences are related to the microstructure of the systems, in the case of the plasma sprayed TBC the platelet boundaries (air gaps) offer a significant resistance to heat flow whilst the EB-PVD TBC column boundaries lay parallel to the principal heat flux direction and have little effect on the conductivity [Ref 17]. Further more, due to the structure of the EB-PVD coating, the thermal conductivity varies as a function of the thickness of the coating. This variation is related to the high thermal resistance of the coating near the interface region where the coating has a high density of column boundaries due to the nucleation and competitive growth nature of the PVD process [Ref. 17]

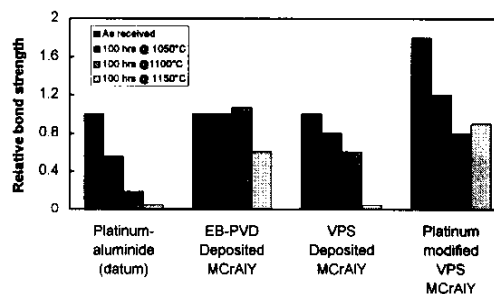


Figure 22 Relative bond strengths of PVD TBC systems on MarM002 substrates (datum = platinum -aluminide bondcoat)

### BOND COAT DEVELOPMENT

The first bondcoat systems for EB-PVD TBC's were based on the environmental protection coatings that were in use, for example MCrAlY coatings produced by EB-PVD. During the early development phase of bondcoat technology, it became apparent that the substrate played an important role in the adhesion of the ceramic, especially with regard to the diffusion of alloying elements from the substrate through the bondcoat to the near interface region with the oxide [Ref. 18]. This led to a development programme where the rules for the design of a bondcoat were formulated from a detailed understanding of the mechanisms of interface degradation and ceramic spallation. For example, in the case of a platinum-aluminide bondcoat applied to MarM002 the degradation mode was identified as:

- Short circuit diffusion of matrix elements along prior  $\beta$ -phase ((NiPt)Al) grain boundaries forming hafnia pegs.
- With continued exposure growth of these hafnia pegs occurs, these being surrounded by a shell of  $\alpha$ -alumina, and finally,
- Void formation and coalescence which causes a plane of weakness at the thermally grown oxide (TGO) bondcoat interface which results in ceramic spallation (see Figure 21) [Ref. 18].

The progressive reduction in the adhesive strength of the platinum-aluminide EB-PVD TBC systems being previously shown in Figure 19.

Further research showed that even within the MCrAlY family of bondcoats of the same composition, significant variation in the adhesive strengths of the ceramic could result from differences in the processing techniques (Figure 22) [Ref. 19]. The differences in the adhesion behaviour of the EB-PVD and vacuum plasma sprayed (VPS) MCrAlY bondcoats are due to the role of yttrium and the cleanliness of the bondcoat manufacturing processes. In the case of the EB-PVD bondcoat, the yttrium is available as Y in an uncombined form (yttrium nickel intermetallic) which is mobile and can be taken up

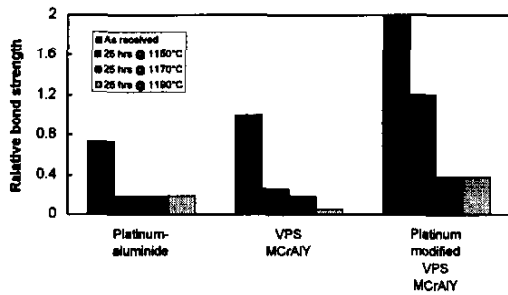


Figure 23 Relative bond strengths of PVD TBC systems on CMSX-4 substrates (datum = platinum -aluminide bondcoat on MarM002)

by the growing oxide. In the case of the VPS coating, the yttrium is present as  $Y_2O_3$  and although dispersed throughout the coating, cannot migrate and is not available to be incorporated into the coating or to tie-up tramp elements coming through from the substrate.

When single crystal substrates were evaluated the cyclic lives were lower than the same coating systems on MarM002 and showed lower adhesion values (Figure 23) [Ref. 19]. One important contributing factor to these differences in TBC adhesion relates to the lower carbon levels in the single crystal alloys. Carbon, present in directionally solidified and conventionally cast alloys as a grain boundary strengthener, combines with alloying elements like titanium and tantalum to form grain boundary precipitates. With the low levels of carbon in single crystal alloys there is little to combine with the titanium and other alloying additions to stop them diffusing through to the interface with the thermally grown oxide. Such elements disrupt the growth of  $\alpha$ -alumina and markedly reduce TBC adherence.

To counteract this problem with single crystal alloys a bondcoat system was developed to stop the diffusion of these damaging elements from the substrate [Ref. 20]. This comprises of an MCrAlY bondcoat with a thin layer of platinum diffused into it prior to the deposition of the ceramic layer. This layer is effective in blocking the diffusion of the damaging elements from the substrate and as a result has increased not only the adhesion but also has improved significantly the temperature capability of the system (Figures 22 and 23).

#### CONCLUDING REMARKS

This paper has reviewed the advantages and disadvantages of both plasma sprayed and EB-PVD TBC systems and their applications in the modern gas turbine engine. Although in terms of erosion resistance and strain compliance the EB-PVD TBC systems has significant advantages over plasma sprayed TBC's, in many applications in the gas turbine engine, such as the

combustion can and nozzle guide vane platforms, plasma sprayed TBC performs adequately. These applications for plasma sprayed TBC's will continue and because of their relatively low cost compared to EB-PVD TBC's, their application to these types of components in the future seems to be assured.

Where EB-PVD technology undoubtedly wins over plasma sprayed TBC's is on the aerofoils of the modern aero-gas turbine, where a good surface finish is paramount and excellent strain compliance and adhesion are required. In these areas EB-PVD offers significant benefits over plasma spraying which more than justifies the higher manufacturing costs.

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