White hot technology – a turbine revolution

HP turbine blade with EBPVD thermal barrier coating

Better thermal barrier coatings are needed for high pressure turbine components to meet ever more exacting performance demands, says Rodney Wing

The high pressure turbine section of a modern gas turbine engine operates in a very aggressive environment. Following combustion, highly oxidising gases enter the turbine at a temperature more than 200ºC above the melting point of the superalloy turbine blade. In the new generation of civil aircraft, turbine entry temperature (TET) on take-off will exceed 1800K. The only reason turbine components survive under these conditions is due to the massive amount of cooling air blown through them, maintaining actual metal temperature below the superalloy melting point.

The continuing demand for increased power and improved specific fuel consumption in modern aero gas turbine engines has resulted in a progressive increase in TET over the last 20 to 30 years. This trend is expected to continue into the forseeable future, as even more powerful large aero-engines are developed. These increases in TETs, with the associated increases in turbine component operating temperatures, have been made possible in the past largely due to the continuing development of nickel base superalloys with higher temperature capability, and improvements in component air cooling technology. However, as TETs in aero gas turbines continue to increase, this requirement will not be able to be realised through improved cooling technology or higher temperature capability superalloy materials.

Another route that enables turbine components to operate at higher TETs is to insulate the metal surface from the hot combustion gas, reducing actual metal temperature. This is an attractive proposition and was the basis for the development of thermal barrier coatings some 25 years ago. The first thermal barrier coating systems tested in aero gas turbines were deposited by air plasma spraying (APS), but proved unreliable on aerofoils and nowadays are only used on nozzle guide vane platforms and in combustors. The current state-of-the-art thermal barrier coatings use electron beam physical vapour deposition (EBPVD), and are favoured for use in gas turbine engines due to their increased strain tolerance, improved erosion resistance and better surface finish.

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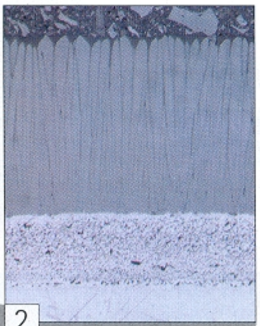
Air plasma sprayed thermal barrier coating showing porous, lamellar ceramic top layer



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EBPVD thermal barrier coating showing columnar ceramic top layer

Coatings on blade aerofoils in today's aero-engines are normally deposited to a ceramic layer thickness of 125-200 microns and reduction in component metal temperature of the order of 60-100°C can be achieved using current blade cooling design. This increased component temperature capability is significant in that it equates to something like 20-30 years of superalloy development.

EBPVD thermal barrier coatings have been applied to turbine blades and nozzle guide vane aerofoils in production aero-engines for the past 15 years, essentially to overcome 'hot spot' problems, and have demonstrated excellent reliability in service. With increasing confidence in this technology, aero-engine manufacturers are now incorporating thermal barrier coatings into new engine design to take full advantage of the increased temperature capability. However, it is essential that a very good understanding of the 'science' of thermal barrier coating systems is reached, as failure of the coating could have a significant effect on component life.

Thermal barrier coatings currently in use in gas turbine engines are 8 wt% yttria/zirconia ceramics. This composition has a high melting point, low thermal conductivity and a relatively high coefficient of thermal expansion, and is ideal for use as a thermal barrier coating on nickel base superalloy materials.

EBPVD and APS are the methods currently used in production to deposit ceramic thermal barrier layers, but the deposition characteristics of the two processes are markedly different, and result in important differences in the coatings produced, figures 1 and 2.

APS ceramic coatings are deposited in sequential layers to achieve the desired thickness, and lines of weakness occur parallel to the surface. EBPVD coatings are very different in that the ceramic layer is

Superalloys

PC

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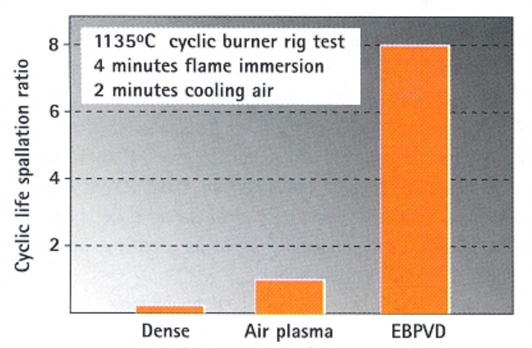

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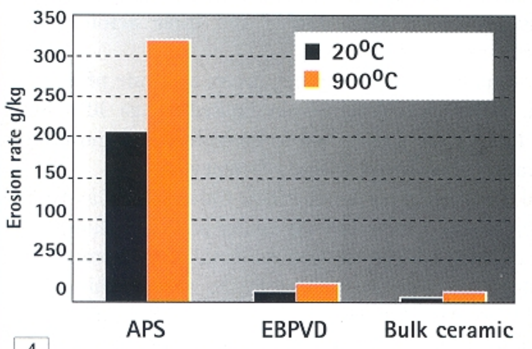
Thermal cycle rig testing at 1135°C of different ceramic microstructures



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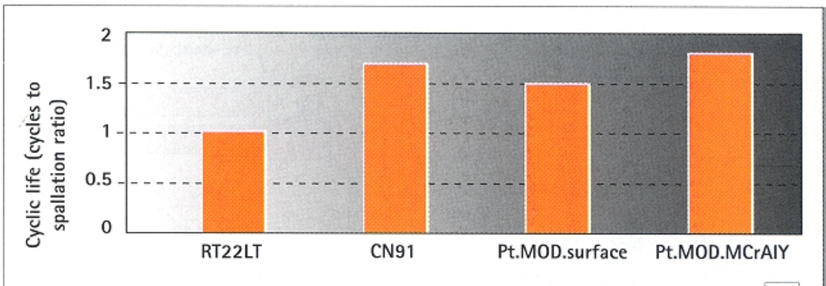
Erosion resistance of different ceramic microstructures at 20°C and 900°C

grown from a 'ceramic cloud' and the thickness of the deposit increases with increasing time in the coater. Growth occurs as columnar grains that grow upwards from the component surface – individual grains are strongly bonded at their base but are weakly bonded to each other, allowing thermal stresses to be easily accommodated.

The differences between APS and EBPVD coating structures determine how these coating systems behave in aero-engine operation. Significant benefit in both thermal cycle life and erosion resistance is shown by EBPVD ceramic layers, with an improvement of about an order of magnitude for each property, figures 3 and 4.

In addition to the ceramic layer, thermal barrier coating systems incorporate an intermediate metallic bond coat layer between the ceramic and the superalloy. Bond coats can palliate expansion mismatch between the ceramic and the superalloy and also provide hot corrosion/oxidation protection, but their major role is to provide a means of adherence for the ceramic layer.

Bond coats used with APS thermal barrier coatings have a rough surface that acts as a mechanical key for the ceramic layer. With EBPVD thermal barrier coatings adherence to the metallic bond coat is provided by a layer of alumina less than 1 micron thick, which is developed at the bond coat/ceramic layer interface during the initial stages of the EBPVD coating process. The 8 wt% yttria/zirconia ceramic layer is subsequently deposited onto the alumina. Chemical bonding occurs between the bond coat, the alumina and the ceramic layer, and the alumina acts as a 'glue', joining the ceramic to the underlying metallic bond coat.



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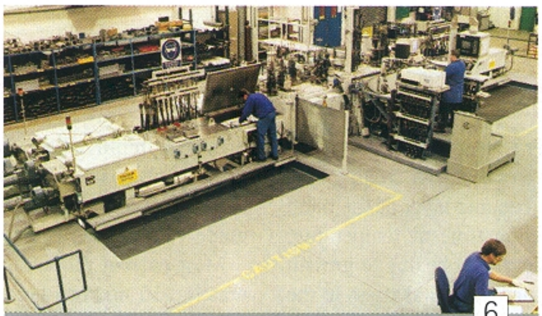
Thermal cycle rig test at 1135°C. EBPVD thermal barrier coating systems on CMSX-4, new bond coats – CN91 platinum aluminide, platinum modified surface and platinum modified MCrAlY



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Production EBPVD coater at Chromalloy United Kingdom Ltd

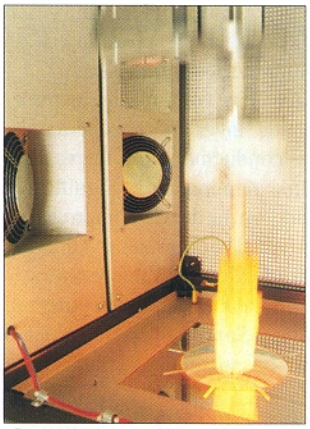
MCrAlY overlays, aluminide and platinum aluminide diffusion coatings (which were originally developed for hot corrosion/oxidation protection of turbine components) were selected as the initial bond coats for EBPVD ceramic layers. Thermal barrier coating systems of this type have proved reliable in service and many millions of flying hours have been accrued in production engines.

However, these bond coat/ceramic layer systems are 'first generation' thermal barrier coatings and improved systems need to be developed to meet higher TET and increased lifetime requirements in new gas turbine engines. EBPVD ceramic layers with reduced thermal conductivity and improved temperature capability, and bond coats with greater resistance to ceramic spalla-

Chromalloy United Kingdom Ltd's continuing research into improved thermal barrier coatings is supported by a thermal test rig supplied by specialist furnace manufacturer Carbolite.

Designed to evaluate the performance of new bond-coat/ceramic layers, the equipment provides long-term thermal cycling at temperatures up to 1200°C. Samples are subjected to the test procedure until spallation of the coating or other failure occurs.

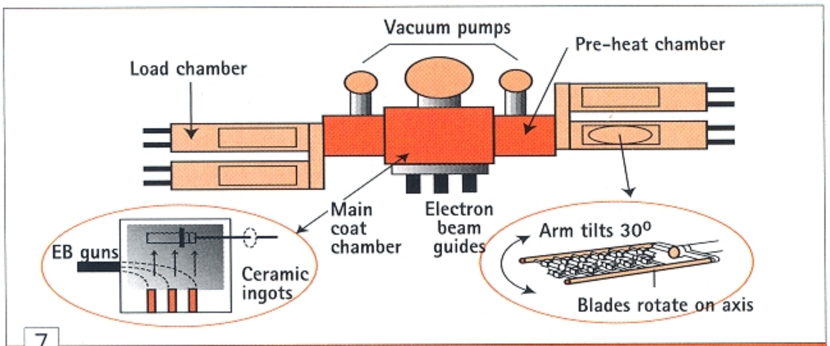
The furnace consists of a 900mm long vertical tube, 100mm in diameter, with an electrically operated hearth beneath, to hold the samples. Test samples consist of superalloy buttons, typically 20mm in diameter, with the thermal barrier coating on one side. Groups of three buttons are welded to backing strips to form 'traffic light' test pieces and six such assemblies are usually tested at one time.



Carbolite's special vertical tube furnace tests thermal barrier coatings at Chromalloy United Kingdom Ltd

When the thermal cycle is started, the actuator lifts the samples into the hot zone and the furnace is heated to 1135°C. After one hour at temperature the samples are lowered into a quench area where they are cooled down to 80°C using electric fans. They are then automatically raised back into the hot zone, and the cycle starts again.

Every day the samples are taken to the laboratory for detailed inspection of the thermal barrier coatings. Up to 20 cycles can be completed every 24 hours. Apart from the daily inspections, test programmes often continue automatically for several hundred hours until failure of the coating occurs.



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Schematic of Chromalloy United Kingdom Ltd EBPVD coater

tion, will be needed in order to meet these objectives.

It is known that EBPVD thermal barrier coating systems fail by spallation of the ceramic layer at the bond coat/alumina interface following time at temperature exposure. This failure is considered to be due to growth of the alumina 'glue', which increases total stress in the ceramic system, and diffusion of bond coat and/or superalloy elements to the alumina interface, causing weakening of the interface bond strength. Improvement in bond coat technology is needed so that degradation of the alumina 'glue' can be retarded.

Chromalloy Gas Turbine Corporation has pursued improved EBPVD thermal barrier coating systems through joint development programmes with a number of major gas turbine engine manufacturers, and as a result a series of new bond coats has already been developed and patented.

These bond coats are based on improvements that can be achieved by using precious metals, mainly platinum, to maintain the purity, (which equates to the strength) of the thermally grown alumina 'glue' during time at temperature exposure. Typical life improvements obtained in thermal cycle rig testing compared to RT22LT, a first generation platinum aluminide bond coat, are shown in figure 5.

As TETs continue to increase improvements to the ceramic layer will also be required, with reduced thermal conductivity and increased fusion temperature the prime requirements. Significant research is currently going on to develop improved ceramic materials, with particular effort being applied to the compositional modification of the existing 8wt% yttria/zirconia system and to the development of new ceramic compositions. Some reduction in thermal conductivity may also be possible by modifying the columnar growth structure of the EBPVD deposited ceramic layer, and this is also under investigation.

The flipside to these efforts is that since the behaviour of the existing 8 wt% yttria/zirconia ceramic layer is widely understood in aero-engine applications, any change to the ceramic composition, even if there appear to be benefits of reduced thermal conductivity and/or increased fusion temperature, will have to be thoroughly investigated to ensure that other coating properties have not been compromised.

As well as the nature of the coating itself, the machines used for the coating process are themselves evolving. The first production coaters capable of depositing EBPVD ceramic layers became operational some 20 years ago. Since then the design of the equipment has improved significantly and current coaters, located mainly in the USA, are capable of coating complex shapes through sophisticated component movement. Although the process is essentially line of sight, 'double' and 'triple' aerofoil nozzle guide vane segments can be coated successfully.

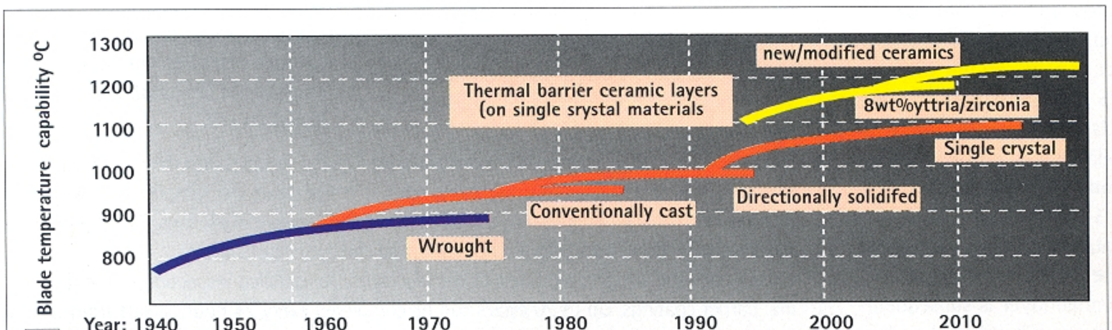
Most current production coaters will deposit ceramic layers at a rate of approximately 250 microns per hour. Early coater designs were limited to just 30 hours of continuous operation, before the ceramic ingots had to be replenished and ceramic deposits removed from the coating chamber to restore efficiency.

With an increasing demand for thermal barrier coatings, Chromalloy Gas Turbine Corporation made the decision to site a new EBPVD coater at Chromalloy United Kingdom Ltd. The design of existing US coaters was reviewed and improvements, using state-of-the-art technology, were incorporated into the new machine. These include increased work throughput from longer campaign cycles, the ability to coat larger components, less maintainance time, and advanced computer control and data logging systems.

The new coater was commissioned in 1994, figures 6 and 7, and deposition of thermal barrier coatings onto production components began several months later. Since then more than a hundred thousand components (turbine blades and nozzle guide vanes from both industrial and aero-gas turbine engines) have been satisfactorily coated. The Chromalloy United Kingdom Ltd EBPVD coater is being further developed to increase deposition rate and reduce coating cost. Making even advanced processes as cost competitive as possible is important if customers are to be able to fully utilise the technology.

The evolution of the gas turbine engine has relied in large part on the development of improved materials, and this is especially true in the field of high pressure turbines. Temperature capability increases in this area have been possible thanks to improvements in nickel based superalloy materials but, with the development of high rhenium content single crystal materials, this technology is now reaching its end.

Until turbine components can be reliably manufactured wholly from ceramic materials, thermal barrier coatings with reduced thermal conductivity and increased temperature capability are the only way of meeting the demands of increasing TETs in gas turbine engines. It is expected that ceramic coating technology will be developed in a similar way to that of superalloy materials, figure 8. With a growing need for aircraft to be more efficient and environmentally friendly, thermal barrier coatings are essential to future gas turbine engine development.



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Turbine blade temperature capability

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