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New low K coatings for gas turbine components

How newly developed low thermal conductivity coatings can allow higher blade temperatures and therefore more power from the turbine

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Compared to 20 or more years ago when heavy industrial gas turbine engines were mostly used intermittently as peak load machines, today's engines are increasingly used to generate continuous base load power. The continued effort to reduce manufacturing costs and increase efficiencies has helped the advancement of the gas turbine as one of the main sources for power generation. They have several advantages, one of which is the relatively short cycle start time compared to a steam turbine or coal fired gas turbine. Another is the delivery time which at 1 to 2 years is short compared to the several years for construction of a new power plant and the long approval and development process for nuclear power plants. At a time of ever-increasing global demand for energy such a short delivery time is a distinct advantage.

Gas turbines are operated either in single cycle or combined cycle mode (gas turbine plus steam turbine powered by the waste heat from the turbine exhaust), and produce power 24/7 when used as base load machines. Modern CCGTs can operate at an efficiency of up to 60 %, a significant advance on the 52 % achievable in 1992.

While higher inlet temperatures increase the output and efficiency of the turbine and translate into lower operating costs, the challenge for the turbine engine manufacturers is to reduce the cooling air usage, which in turn helps in the control and lowering of emissions. In today's industrial environments, gas turbine engines operate with inlet temperatures approaching 2600°F (1427°C), which translates to more demanding requirements for hot section materials, advanced cooling, and coatings. During the last 13 years, turbine inlet temperatures have increased by more than 100°C. Higher operating temperatures also translate into the need for higher temperature alloys and associated technologies, such as improved internal and external cooling, and a high temperature oxidation resistant thermal barrier coating system.

Modern role of coatings

Investment cast nickel-base superalloys are the standard alloys for hot gas path components such as blades and vanes. These alloys have been derived from the development of turbine blades and vanes for aircraft engines where they are used in both commercial aviation and military aircraft. Directionally solidified and single crystal nickel-base superalloys have been developed for investment castings of high pressure turbine parts and scaled up to the part size of an industrial gas turbine. Casting technologies have advanced to a level appropriate to the larger size and weight of the industrial hot section components.

In the past, demand for higher temperatures was limited by the ability of most advanced nickel and cobalt based super-alloy turbine blades and vanes to maintain their mechanical strength when exposed to the hot operating environment. However, today's coating technologies and cooling air schemes protect the turbine engine hot section components and extend their life under severe operating conditions. Without coatings and cooling air, the hot gas path components' durability and lifetime would be only a fraction of that of the coated parts.

Coatings not only protect hot gas path components from oxidation, corrosion and the extreme temperatures of the turbine engine – they also offer limited protection from impact damage by foreign objects. Coating technology and coating thickness are the primary factors for the lifetime prediction of the turbine operation.

As gas turbine engines have evolved, developments also have been made to improve coating systems, to increase oxidation and corrosion resistance and ceramic coatings for the thermal protection in order to accommodate the temperature increases. In the beginning of the 1980s, first stage turbine blades and vanes were protected with a diffusion coating. By the end of the 1980s, the low pressure plasma sprayed metallic overlay coating became the standard coating for the first stages. Four years later, blades and vanes required an internal coating in addition to the external coating. By the mid-1990s the thermal barrier coating – an advanced coating system – was applied to first stage turbine blades and vanes for greater protection.

Improved cooling

Improved cooling of hot section components and cooling air consumption was another consideration, as engine designs evolved to increase output and as coatings also evolved. Thirty years ago the earlier turbine blades and vanes had a relatively simple core and cooling hole through the trailing edge, compared to today's designs. The downstream stages were usually solid airfoils. This changed with the increase of the turbine inlet temperature. Even the second and third stages of the engine became hollow with a core design and cooling holes either through the trailing edge or along the airfoil. For the first stages the core got more complex with impingement cooling, turbulator ribs, pedestals and cast in trailing edge slots or holes. Further increase of the turbine inlet temperature required film cooling of the leading edge, pressure and suction side of the airfoil and the vanes also needed film cooling on the inner and outer platform.

Figure 1. Robot applying a thermal barrier coating by air plasma spray

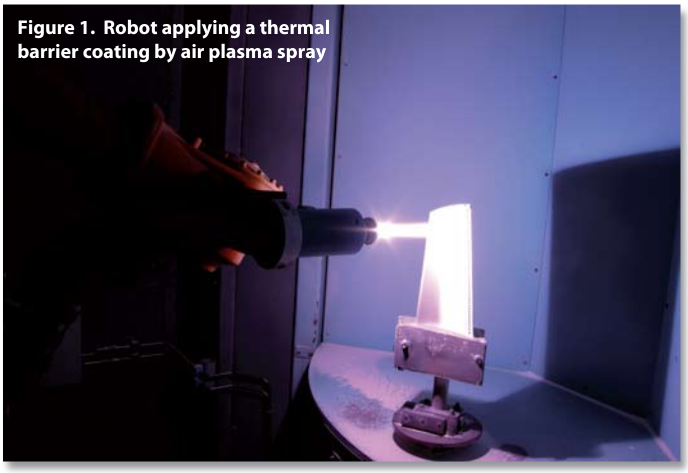
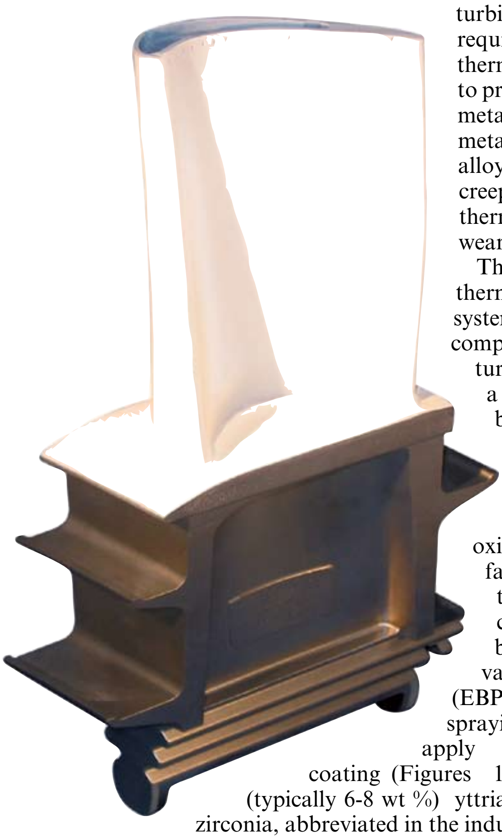


Figure 2. Turbine blade immediately before coating

Figure 3. Turbine blade after coating



The increasingly higher turbine temperatures required the use of thermal barrier coatings to protect the underlying metallic bond coat or metal blade or vane base alloy from overheating, creep, oxidation, thermal fatigue, erosion wear and hot corrosion.

The current typical thermal barrier coating system on the superalloy components in a gas turbine engine consists a MCrAlY overlay bond coating or Pt/Al diffusion bond coating that is accompanied by thermally grown oxides (TGO) which facilitate the adhesion to the ceramic top coating. Electron beam physical vapour deposition (EBPVD) or air plasma spraying (APS) are used to apply the top ceramic coating (Figures 1-3) that is 7 wt % (typically 6-8 wt %) yttria partially stabilised zirconia, abbreviated in the industry as 7YSZ.

Benefits of low K coating

When operating temperatures become higher and higher in advanced gas turbine engines, especially when over 2400 °F, the conventional 7YSZ thermal barrier coating shows rapid deterioration due to its insufficient thermal protection, as well as its own sintering that reduces the thermal barrier coating's compliance, and from additional stresses resulting from volume changes due to phase transformation at these higher temperatures.

To address this, new thermal barrier coatings have been developed to provide lower thermal conductivity to more effectively insulate the thermal transfer to the components, as well as provide a coated component with longer service life based on increased coating durability.

Chromalloy explored several unique applications for the use of advanced thermal barrier coatings to enhance the performance of existing part designs by providing extended life and reduced cost to customers. Over the years the company's continued investment in research and development of coating technologies – beginning with its formation in 1951 through its later development of the EBPVD with ceramic materials, vacuum plasma, diffused precious metal/aluminide coatings, and vision-guided interactive laser welding and drilling for most advanced turbine engine components – have kept Chromalloy well to the forefront of this field.

New patented coatings

To address the most current challenges to gas turbine operators in terms of new coatings to allow the higher temperatures, Chromalloy recently patented two thermal barrier coatings – low K coatings – that have a lower thermal conductivity and enhanced performance in cyclic oxidation, sintering resistance, erosion resistance and phase stability. The primary chemistry of the low K thermal barrier coating is neodymium rare earth oxide doped in zirconia matrix (Nd-Zr). The low K coating is applied by either the EBPVD or by the air plasma spray process, depending on the part size and coating locations.

Low K is applied by EBPVD as a single layer Nd-Zr or multi-layer of Nd-Zr and 7YSZ. Figure 4 shows the microstructure with typical EBPVD columnar structure that gives the thermal barrier coating the compliance to withstand the stresses caused by the mismatch in thermal expansion between the ceramic coating and the metallic part and the underlying metallic bond coating, as well as thermally-grown oxides growth during engine service. The EBPVD low K thermal barrier coating has about half the thermal conductivity and more than twice the cyclic oxidation lifetime of the standard EBPVD 7YSZ. The low K coating is also applied by air plasma spray of Nd-Zr and 7YSZ, as a multi-layer coating. Figure 5 shows the layered air plasma spray microstructure. The air plasma spray low K thermal barrier coating has slightly over half the thermal conductivity and nearly 50% better cyclic oxidation lifetime than the APS 7YSZ.

The attributes of the new low K coatings mean turbine engines can perform at improved efficiency levels because low K coatings with higher thermal insulation capability allow an increased operating temperature without overheating the metallic parts, and also reduce the requirements for air cooling the part. The resulting benefits to turbine operators include a reduction of thermal conductivity by 50%, which in turn allows the thermal barrier coating thickness to be reduced by approximately one half for the same degree of thermal insulation. The reduction in thickness lowers the cost of the coating. And decreasing the thickness also lowers the weight of the gas turbine component, which can provide a significant reduction in the weight of the engine disk that holds the components. In addition, the low K coating extends the life of the engine components, another source of cost savings to the operator.

Given the two ways to increase turbine engine efficiency – one being to increase the gas temperature and the other to decrease the heat loss caused by the essential air cooling – the low K coating in both cases ensures parts' survival at the increased temperature environment based on its high thermal insulation. In addition, the purpose of cooling is to decrease the bond coat and substrate temperature. The low K provides the same result without high cooling, indicating lower heat loss. High heat provided by high gas temperature and low heat loss caused by cooling will result in increased efficiency – a benefit to gas turbine operators reliant on power systems' ability to produce optimum output. MPS

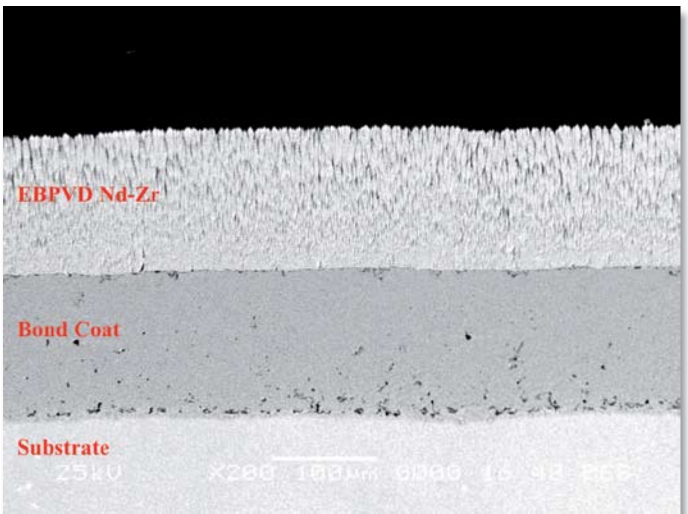


Figure 4. Electron beam physical vapour deposited low-K thermal barrier coating showing a columnar microstructure

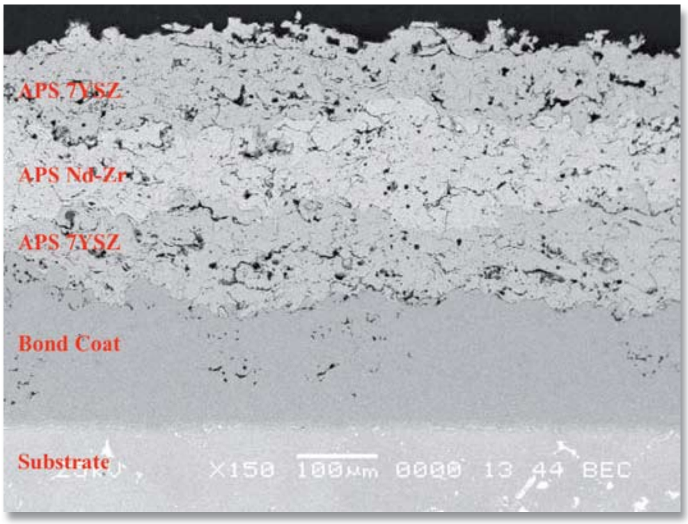


Figure 5. Air plasma sprayed low-K thermal barrier coating showing multiple compositions and a layered microstructure