Challenges in Developing New Coatings to Improve Performance

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Coatings are used for enhancing the performance of many aerospace components. Coatings are necessary because the properties required on the surface of a component are different from those in the bulk. In this paper, the focus is on coatings that enable improvements in the performance of critical high temperature components in aircraft engines and in space vehicles. The majority of aircraft engines are based on gas turbines. The efficiency of a gas turbine is higher at higher operating temperatures. The maximum allowed temperature is restricted by the materials used for the construction of the engine. Large increase in the turbine inlet temperature has been achieved over the last six decades as new alloys were continuously developed.

Nickel base superalloys form a class of metallic materials which retain adequate strength at temperatures up to ~1050°C. A large number of metallurgical advances were made in developing these alloys. The most critical component in a gas turbine, which is the high pressure turbine, is made from a superalloy with the highest temperature capability. This is achieved by making each turbine blade as a single crystal, with precipitates of an intermetallic compound γ' dispersed throughout its volume to impart high temperature strength. The superalloys have been optimized for creep resistance, which is the measure of high temperature strength. However, their lifetime can be extended by coating them with a thermally insulating ceramic coating called 'thermal barrier coating' (TBC).

Current TBC's for aircraft engines consist of ZrO_2 with ~7 wt% $YO_{1.5}$ (7YSZ) The primary requirements of a TBC material are low thermal conductivity, thermal expansion coefficient matching that of the superalloy, thermochemical compatibility with the TGO, phase stability at operating temperature, resistance to sintering, resistance to attack by molten dust (CMAS) or molten salts (sulfate-vanadate), high fracture toughness, and low elastic modulus. Candidate materials for future TBC's mainly include ZrO_2 stabilized with rare earth oxides, as well as rare earth zirconates with pyrochlore structure (RE_2Zr_2O7). These materials exhibit lower thermal conductivity than 7YSZ.

The TBC, also known as the top coat, is in direct contact with the thermally grown oxide (TGO, usually α-Al_2O_3) which forms on the bond coat during exposure to high temperatures. The TGO protects the underlying metallic component from catastrophic oxidation. All metallic alloys, except for noble metals, are prone to oxidation because oxides are thermodynamically more stable than metals. Oxidation is of greater concern at high temperatures than at room temperature. The successful high temperature alloys develop a uniform, impervious oxide scale on their surfaces. Such an oxide film slows down further oxidation significantly as the transport of oxygen from the atmosphere through the oxide scale up to the underlying metal is very slow. Similarly, the outward transport of the metal atoms through the oxide scale is also very slow. It is desirable to decrease the rate of oxidation as much as possible to increase the lifetime of a high temperature component. Special metallic coatings are used for this purpose, whose compositions are optimized for oxidation resistance rather than creep strength. Currently these coatings, called bond coats (BC's), are invariably used in conjunction with 'thermal barrier coatings' (TBC's). The bond coat is deposited on to the superalloy prior to TBC deposition.

Air plasma spraying (APS) is the preferred technique for depositing TBC's on stationary components. For critical components experiencing frequent thermal cycling, electron beam physical vapour deposition (EBPVD) is preferred. This is because of the better strain compliance of EBPVD coatings. This is desirable for minimizing thermal stresses. Dense vertically cracked APS coatings have been developed to enhance the strain compliance while retaining the lower thermal conductivity characteristic of the APS microstructure. New deposition techniques such as directed vapour deposition (DVD), solution precursor plasma spraying (SPPS) and plasma enhanced chemical vapour depositions have (PECVD) been developed for TBC's. Research is in progress to evaluate the benefits of these processes before they can be adopted in the industry.

Bond coat materials used for critical applications in aircraft engines are primarily of two types, Pt-modified NiAl and MCrAlY (M = Ni, Co, Fe). The (Ni, Pt)Al is usually processed by electroplating of Pt, followed by aluminizing. The Ni required for BC formation diffuses outward from the superalloy. This gives rise to the interdiffusion zone (IDZ), which may consist of embrittling intermetallic phases. Research is in progress to develop overlay bond coats and diffusion barriers to limit the formation of the IDZ and the deleterious intermetallic phases.

The MCrAlY alloys used most often are based on the NiCoCrAlY combination. Argon shrouded plasma sprayed is the preferred processing routes for aircraft engine blades of single crystal superalloys. Refractory metals such as W and Re may be present in these BC's. During service, as the TGO grows, mixed oxides like yttrium aluminium garnet (YAG, $Y_3Al_5O_{12}$) may form in the form of 'pegs'. The formation of spinel type mixed oxides in the early stages of TGO growth may also occur. These are considered detrimental to the durability of the TBC system.

The thermal barrier system is evolving at all levels, the superalloy, the bond coat and the top coat. Instead of independently developing these materials, a systems approach is being increasingly adopted, wherein all the layers of the system are developed together.

Many aerospace applications are at higher temperatures than gas turbines, for example the leading edges of re-entry vehicles and engine components for hypersonic planes. These demanding applications require ultra-high temperature ceramic components. One of the most promising set of materials is silicon based non-oxide ceramics, including their composites. Examples would be $SiC\text{-}SiC_f$ composites, and composites of SiC with borides such as ZrB_2. These ceramics are prone to oxidation but possess better high temperature strength than oxide ceramics. The silicon based UHTC materials develop a silicon dioxide (silica) scale that is protective under static dry conditions. However, in the presence of high velocity gases laden with water vapour the silica scale is volatilized in the form of silicic acid, $Si(OH)_4$. This leads to recession, i.e. steady loss of material from the surface. Protective coatings called 'environmental barrier coatings' (EBC's) are being developed to prevent recession, especially for components in combustion environments, such as encountered in aerospace engines. These coatings are based on silicates such as mullite, rare-earth silicates and glass-ceramics (barium-strontium alumino-silicate). These materials are resistant to water vapor attack, though not completely immune to it. The challenges in developing these materials pertain to deposition of impervious coatings, selection of a material with thermochemical and thermomechanical compatibility with the underlying UHTC. There is also a requirement of thermal barrier coatings for deposition on the UHTC's as well. Conventional TBC materials are not adequate for this purpose. The search for new coating concepts and materials forms an exciting research opportunity.

The high performance aerospace materials, especially for critical high temperature applications, have evolved into multi-functional layered systems. Each layer is a different material that has a specific function. These materials are often with disparate compositions and chemical bonding. The development of new materials and the processing of these systems forms a great challenge for materials scientists with exciting research opportunities.