

MATERIALS ISSUES FOR USERS OF GAS TURBINES

by

Henry L. Bernstein

Gas Turbine Materials Associates

San Antonio, Texas



Henry L. Bernstein is the President of Gas Turbine Materials Associates, providing technical services to the gas turbine community in the materials area. He is an expert on gas turbine materials, and high-temperature coatings and the durability of the hot section components. Dr. Bernstein is a Fellow of ASME, and Chairman of the Manufacturing Materials and Metallurgy Committee of IGTI.

Previously, Dr. Bernstein was with Southwest Research Institute, as Assistant Director of the EPRI Materials Center for Combustion Turbines. While there, he developed the EPRI Life Management System, the EPRI Coatings Guidebook, and the computer programs REMLIF[®] and ABC. He was also the Project Manager for programs on the RB211, Centaur, and Frame 6 and 7 engines including GTD-111.

Dr. Bernstein earned his Ph.D. at the University of Cincinnati, an M.S. at the University of Illinois at Champaign-Urbana, and a B.S. at the Ohio State University.

ABSTRACT

Material issues are of paramount importance for the reliable and cost effective operation of gas turbine engines. Because of the high turbine temperatures, the materials degrade over time, which requires their repair or replacement. Rapid degradation or the inability to repair these complex materials result in excessively high operating costs.

This paper concentrates upon the hot section components, because this is where the majority of turbine distress occurs. Superalloys, both nickel based and cobalt based, and high temperature coatings are discussed from a user's perspective. The degradation of the hot section components—combustor hardware, blades, and vanes—is described. This degradation includes that due to creep, thermal mechanical fatigue, high temperature oxidation, and hot corrosion. Approaches to determining the remaining life of these components is discussed, including the data that the user must supply. A computer program for determining the remaining life of the first stage blades and vanes is presented. Finally, the repair and rejuvenation of the materials and components are described, including heat treatment, welding, brazing, and recoating.

INTRODUCTION

Material issues are of paramount importance for the reliable and cost effective operation of gas turbine engines. Because of the high turbine temperatures, the materials degrade over time. This degradation must be reversed during overhaul, either by the repair or replacement of the component. It has been estimated that hot section component costs comprise from 50 percent to 70 percent of the maintenance costs for gas turbine operation. Furthermore, the timing of the overhaul of the engine is governed by durability of the hot section components, and the majority of engine failures are caused by failure of the hot section components.

By contrast with the hot section components, other material issues in industrial gas turbines are of less importance. While still important when they occur, the durability of compressors, casings, shafts, and disks (or wheels) is sufficiently great that material issues are less frequent. Thus, the focus of this tutorial will be on the hot section components.

Several excellent books about gas turbine materials are available. Two widely used books are *The Superalloys* (Sims and Hagel, 1972) and *Superalloys II* (Sims, et al., 1987). While the second book is intended to succeed the first book, there is still valuable material in the first book that was not included in the second. Another excellent book is a collection of articles entitled, *Superalloys Source Book* (Donachie, 1984). A detailed discussion of high temperature coatings can be found in several articles (Committee on Coatings for High-Temperature Structural Materials, 1996; Bernstein and Allen, 1993; Bernstein, 1991).

Objective

The objective of this tutorial is to acquaint gas turbine users with the various materials, components, and degradation mechanisms that occur in industrial gas turbines. The repair of these components and materials is discussed, as is the prediction of their lifetimes. It is not possible to treat each of these subjects in the detail that they deserve in a tutorial paper. Such a treatment is the subject of at least one book, if not several. Instead, the objective is to provide a framework and understanding that the readers can build upon as they learn more about materials and encounter different material issues in the operation of their gas turbines. Such an understanding is especially important for the types of materials and coatings. If one can grasp the basic principals behind these materials, then one can sort through the myriad number of different materials and their variations that exist in the marketplace.

The readers should bear in mind that high temperature materials is an area that we are continually learning more about, encountering situations that have not occurred before, developing new materials, and applying older materials in new ways and in more demanding applications. As such, it can be both an exciting area, and one of great frustration, especially when one is seeking solutions to specific problems. Confusion in the materials area occurs partly because we have incomplete knowledge, and partly because of the desire to provide simple explanations to complex phenomena.

HOT SECTION COMPONENTS

In this section, the major hot section components are briefly reviewed, including the principal modes of degradation and the various terminology used to describe them. Also, included is a description of the various terms and definitions of the temperatures in the gas turbine.

As in many technical (and nontechnical) areas, there is no single terminology to describe the components of the gas turbine. Most of the different terms in use are described in this section, along with the nomenclature that will be used in this tutorial. In addition, nicknames are often used in place of formal names, especially for more cumbersome terms. Examples of these nicknames are "rat ears" for the floating seal stops and "bullhorn brackets" for the transition piece support brackets.

Combustion Hardware

The combustion hardware consists of the area in which the fuel is burned and the adjacent area where the hot gases are guided into the turbine. The area in which the gases are burned is called the combustion liner or the combustion basket (liners and baskets for short). The area that guides the hot gases has a variety of names. Common names are transitions and transition pieces for United States manufacturers and hot gas casings for European manufacturers. A schematic of a combustion liner is shown in Figure 1, and a transition piece is shown in Figure 2.

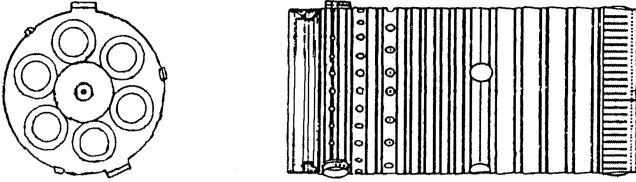


Figure 1. Combustion Liner with Six Fuel Nozzles. The Fuel Nozzles Are in the Left End, and the Combustion Gases Exit the Right End.

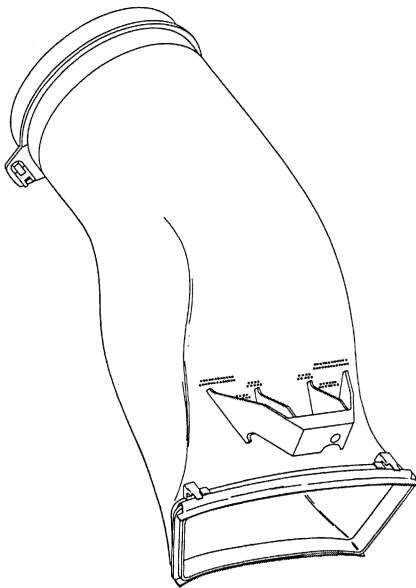


Figure 2. Transition Piece. The Combustion Liner Fits in the Top, and the First Stage Vanes at the Bottom.

Nozzles and Vanes

The stationary airfoils in the turbine section are typically called either vanes or nozzles. Vane is a more generic term and will be used in this tutorial. The term nozzle describes the function of the vanes to accelerate the flow of the hot gases. The term stationary blades is used by some European manufacturers. A schematic of some vanes is shown in Figure 3.

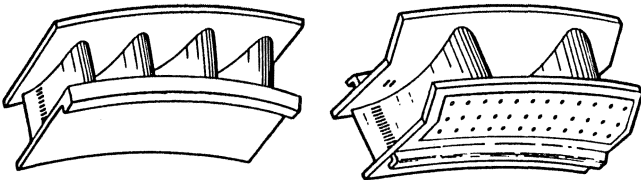


Figure 3. Vanes or Nozzles.

Blades and Buckets

The rotating airfoils in the turbine section are typically called either blades or buckets. Blade is a more generic term and will be used in this tutorial. The term bucket is analogous to the function of buckets on water wheels. The term moving blades is used by some European manufacturers. A schematic of an industrial blade is shown in Figure 4, and that of an aeroderivative blade is shown in Figure 5.

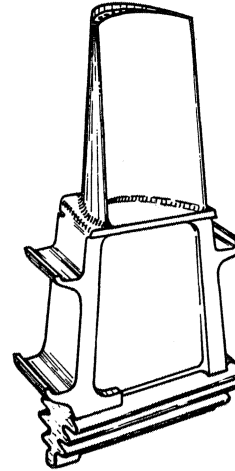


Figure 4. Heavy Duty Industrial Blade or Bucket.

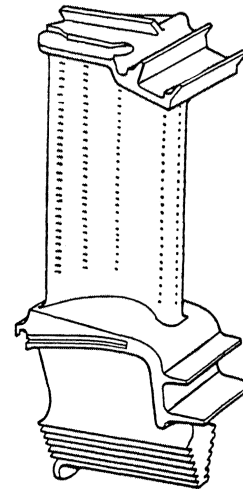


Figure 5. Aeroderivative Blade or Bucket.

Stages

Turbines are composed of a series of blades and vanes. Each set of blades and vanes is called a stage, or a row, as in 1st Stage or Row 1. In aeroderivative engines, there may be two shafts instead of a single shaft. In these engines, the blades and vanes closest to the combustor are often called the high pressure (HP) blades and vanes. The HP blades are on the high pressure shaft (or spool). The blades and vanes further away are called the low pressure (LP) blades and vanes. The LP blades are on the low pressure shaft (or spool).

Temperatures

There is a fair amount of confusion in the terminology for gas turbine temperatures. The same term may mean two different things, depending upon the speaker or type of gas turbine. When in doubt, it is best to obtain a clear definition of the term used.

The most common temperatures used in industrial gas turbines are compressor inlet temperature, compressor discharge temperature, firing temperature, and exhaust temperature. The definitions of these terms, as well as other terms, are given in Table 1.

Table 1. Definition of Temperatures.

Name	Definition
Total Temperature	The temperature of the air at zero velocity. This temperature is also called the stagnation temperature. The kinetic energy of the moving air is converted into a higher temperature.
Static Temperature	The temperature of the moving air as measured by a stationary, or static, observer
Relative Temperature	The total temperature relative to the rotor. Since the rotor is moving, the total temperature relative to it is lower than it is relative to the stator.
Ambient Temperature	The temperature of the air outside the air intake
Compressor Inlet Temperature	The temperature of the air as it enters the compressor. Since the velocity is low, the static and total temperatures are approximately the same.
Compressor Discharge Temperature	The total temperature of the air as it leaves the compressor
Burner Discharge (or Outlet) Temperature	The total temperature of the air as it enters the first stage vanes
Combustor Discharge Temperature	Same as the burner discharge temperature
Firing Temperature	The total temperature of the air as it enters the first stage blades
Turbine Inlet Temperature (TIT)	Either the firing temperature or the burner discharge temperature, depending upon who is speaking. Need to obtain a definition of TIT.
Rotor Inlet Temperature (RIT)	Same as the firing temperature
Exhaust Temperature	The total temperature in the exhaust of the turbine, typically measured away from the last stage of blades.
Temperature After Turbine (TAT)	Same as the exhaust temperature
Blade Path Temperature	The total temperature measured just after the last stage of blades

SUPERALLOYS

The hot section components are primarily constructed of superalloys, both nickel based and cobalt based. Iron based superalloys are still in use in older engines, and sometimes for colder components on newer engines. They may also be used for disks (or wheels). However, this tutorial will not address these iron based superalloys because of both their limited use for gas turbine blading, and a lower frequency of material issues associated with these alloys.

Superalloys derive their name for two reasons. First, they contain so many different alloying elements, they can be truly said to be a "super" alloy. Second, they have such good mechanical properties at high temperatures (and at low temperatures as well) that one could describe them as "super."

Cobalt Based Superalloys

Cobalt based superalloys are primarily used for vanes because of their good weldability, and resistance to hot corrosion. Because they cannot be made as strong as nickel based superalloys, they are not commonly used for blades.

Cobalt based superalloys are composed of cobalt alloyed primarily with chromium, tungsten, carbon, and nickel. Chromium provides protection against hot corrosion and oxidation. Tungsten strengthens the metal by solid solution hardening. Carbon forms carbides with chromium. These carbides are the primary means of strengthening the alloy. Nickel maintains the cobalt atoms in an FCC crystal structure. (Note: FCC refers to a face centered cubic crystal structure. The normal crystal structure for cobalt is HCP hexagonal close packed (HCP), but the HCP structure is not as ductile as the FCC structure.) The alloys X-40, X-45 and FSX-414 are based upon this group of alloying elements. The microstructure of FSX-414 is shown in Figure 6.

In addition to the alloying elements above, titanium, zirconium, columbium, and/or tantalum are sometimes also added to cobalt

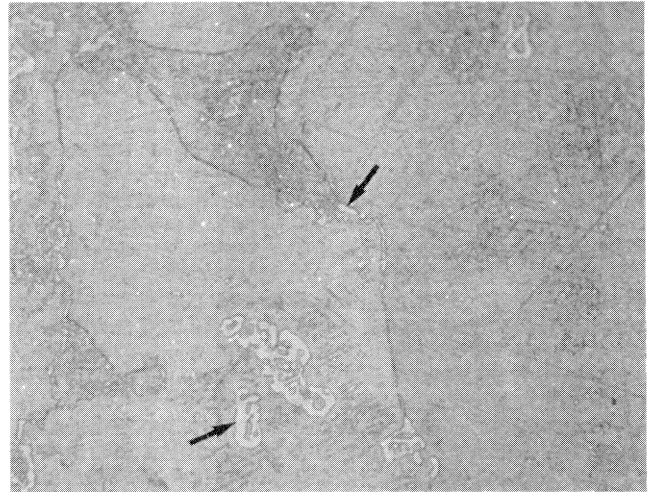


Figure 6. Microstructure of a Cobalt Based Superalloy, FSX-414. Arrows Show the Larger Carbides, 500 \times .

based superalloys, such as in MarM-509 and ECY-768. These elements form additional carbides, further strengthening the metal.

Nickel Based Superalloys

Most of the gas turbine alloy development has been with the nickel based alloy system because of the ability to achieve greater strength with this system. These alloys form gamma-prime second phase particles during heat treatment, which impart very high strengths to the alloy. Gamma-prime has the general composition of X_3Z , where X is primarily Ni, and Z is primarily Al and Ti. (Gamma-prime is generally written as $Ni_3(Al,Ti)$. Ta and Cb can substitute for Al and Ti, and Co can substitute for Ni. Therefore, a more accurate formula would be $(Ni, Co)_3(Al, Ti, Ta, Cb)$.)

Nickel based superalloys can be classified into solid solution alloys, and gamma-prime (or precipitation hardened) alloys. The solid solution alloys, which can be either cast or wrought, contain few elements that form gamma-prime particles. Instead, they are solid solution strengthened by refractory elements, such as tungsten and molybdenum, and by the formation of carbides. They also contain chromium for protection from hot corrosion and oxidation, and cobalt for microstructural stability. Because these alloys are not precipitation hardened, they are readily weldable. Common examples of these alloys are Hastelloy X, Nimonic 263, IN-617, and Haynes 230. The microstructure of IN-617 is shown in Figure 7.

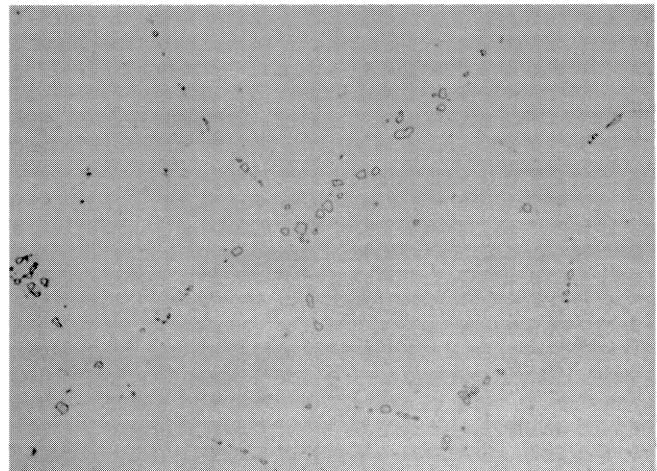


Figure 7. Microstructure of IN-617, 500 \times .

The gamma-prime (or precipitation hardenable) alloys can be either cast or wrought. The cast forms are more common because of the economies of casting complex shapes, the ability to maintain very high mechanical properties by vacuum casting, and the difficulties encountered when forging metals having excellent mechanical properties at high temperatures. In addition to the formation of gamma-prime particles, which is the principal strengthening mechanism, these alloys also incorporate strengthening by solid solution hardening and carbide formation.

The gamma-prime superalloys are composed of many alloying elements. Chromium is used for resistance to environmental attack. Aluminum and tantalum assist in the resistance to environmental attack. Cobalt is used to stabilize the microstructure. Aluminum, titanium, tantalum, and columbium are elements that form gamma-prime. Refractory elements, such as tungsten, molybdenum, tantalum, and columbium are used for solid solution hardening. (Note: Chromium and cobalt also contribute to solid solution hardening.) These same elements, along with chromium, form carbides with the carbon that is added to the alloy. These carbides primarily strengthen the grain boundaries. In addition to these major elements, there are several elements added in minute quantities (sometimes called fairy dust) that strengthen the grain boundaries. These elements include boron, hafnium, and zirconium. The microstructure of a common gamma-prime alloy, IN-738, is shown at two different magnifications in Figures 8 and 9.

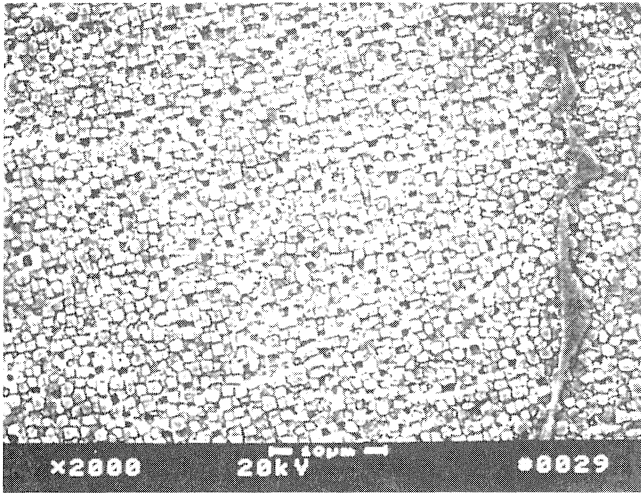


Figure 8. Microstructure of IN-738, 2,000 \times .

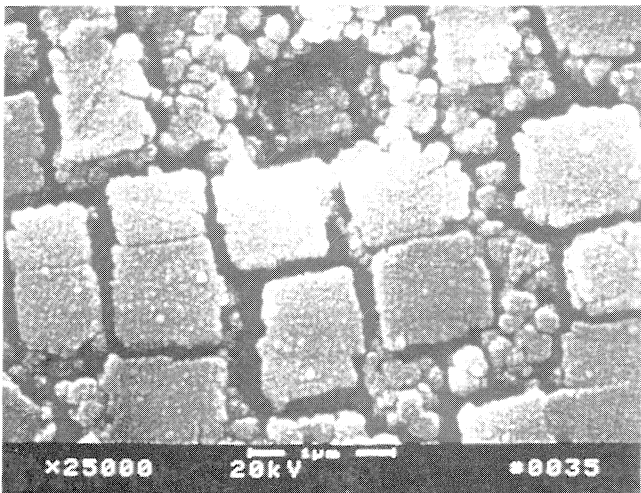


Figure 9. Microstructure of IN-738, 25,000 \times .

Gamma-prime (or precipitation hardenable) alloys can be cast in three forms—conventionally cast, directionally solidified, and single crystal. A conventionally cast form is where there are multiple grains having no preferred orientation, and is the type of casting provided unless one of the other two forms is specifically identified. Conventionally cast alloys (sometimes abbreviated as CC) are sometimes called equiaxed alloys, which means that the dimensions of the grains are equal in all directions, or axes. (Equiaxed is a misnomer because the grains at the surface are typically much longer in the direction perpendicular to the surface.) Directionally cast alloys (abbreviated as DS) have the grains oriented in one direction. These produce long grains that have a preferred orientation in this long direction. Single crystal alloys (abbreviated as SX or SC) consist of a single grain, or crystal, having a preferred orientation along one direction. For both the DS and SX alloys, the preferred orientation is chosen so as to give the maximum mechanical properties in this orientation (which is the $\langle 001 \rangle$ crystallographic direction).

DS alloys typically are stronger than their counterpart CC alloys. The grain boundaries of DS alloys are aligned with the major stress in the blade (which is along the length of the blade). CC alloys have grain boundaries perpendicular to this major stress. Since grain boundaries are frequently the location for creep and fatigue crack formation, placing them perpendicular to the major stress reduces the strength of the CC alloy as compared to the DS version of the alloy. (This relation will not hold if the crack location is within the grain.) In addition, the DS crystals are oriented in a direction with a lower elastic modulus, which increases the thermal fatigue life of a DS blade.

SX alloys are stronger than both CC and DS alloys. SX alloys have the advantage of no grain boundaries, so that crack initiation must occur within the grain. More importantly, the lack of grain boundaries means that alloying elements required to strengthen the grain boundaries are not needed, which increases the incipient melting temperature of the alloy. (The incipient melting temperature is when melting first begins, which occurs at the grain boundaries.) This higher melting temperature allows the alloy to be heat treated at higher temperatures, so more gamma-prime can be formed. The greater amount of gamma-prime gives the SX alloys higher strength levels.

The strengthening mechanisms for the DS and SX alloys are the same as for the conventionally cast alloys. The chemical composition of the DS alloys may be the same as the conventionally cast alloys. The SX alloys are optimized to take advantage of the lack of grain boundaries, by removing elements, including carbon, whose main purpose is to strengthen the grain boundaries.

Examples of the more commonly used CC alloys for industrial gas turbines are IN-738, GTD-111, MarM-247, and Udimet 520. Each of these alloys can be made in a DS version, such as GTD-111DS and DS MarM-247. The SX alloys are usually different from the CC and DS alloys. Examples of these alloys include CMSX-4, SC-16, R-6, and PWA 1484. SX alloys are beginning to be introduced into large industrial engines, but their introduction has been delayed due to low yield (or high scrap rates), due to difficulties in casting large size components as a single crystal.

COATINGS

Two basic types of coatings are used on the hot section blading for protection from environmental attack—diffusion coatings and overlay coatings. These coatings are sacrificial because they are attacked instead of the base metal. They are more resistant to high temperature attack than the base metal because they contain large amounts of aluminum and chromium, which form aluminum-oxide and chromium-oxide scales. These scales act as a physical barrier that reduce the rate of high temperature attack to very low values. When these scales are lost due to spallation, erosion, or other damage, a new scale forms from the aluminum and chromium in

the coating. When the aluminum and chromium in the coating have been consumed below a minimum level for protection, then the coating ceases to protect the base metal and the airfoil must be refurbished.

The protective elements in coatings are aluminum and chromium because they form the protective oxide scale. Nickel and/or cobalt form the matrix of the coatings. Other elements used in coatings, but in smaller quantities, are silicon, platinum, rhodium, palladium, yttrium, hafnium, and tantalum. Silicon improves the hot corrosion resistance. The other elements improve both the oxidation and hot corrosion resistance of the coating.

Yttrium and hafnium improve the adherence of the oxide scale to the substrate by reducing the amount of the oxide that spalls off during a thermal cycle. (*Note:* Platinum, rhodium, and palladium also reduce oxide spalling, due to reasons that are not understood.) These elements are sometimes called “active elements” because of their affinity for oxygen. It has been shown that these elements form sulfides with sulfur in the coating. If unreacted, this sulfur migrates to the oxide-coating interface, weakening this interface and increasing the amount of oxide spalling.

Diffusion Coatings

Diffusion coatings are nickel-aluminide, NiAl, and cobalt-aluminide, CoAl. NiAl forms on nickel based superalloys and CoAl forms on cobalt based superalloys. Diffusion chrome coatings are also used. A micrograph of a nickel-aluminide coating is shown in Figure 10.

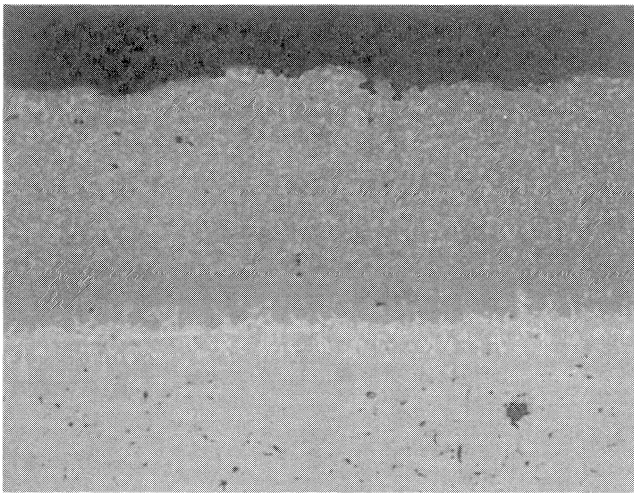


Figure 10. Micrograph of Aluminide Coating, 800 \times .

Diffusion coatings are formed by depositing a layer of aluminum on the metal surface and heating the component in a furnace. During this heat treatment, the aluminum and metal atoms migrate, or diffuse, into each other, which is the reason these coatings are called diffusion coatings. This processing can be performed by pack cementation processes, chemical vapor deposition (CVD) processes, slurry processes, or other processes—all of which involve different methods of depositing the aluminum on the surface. Internal passages can be coated by filling them with an aluminum-rich powder, or by flowing an aluminum-rich gas through the passages.

Aluminide coatings for industrial gas turbines are usually modified by the addition of chromium, silicon, platinum, or other noble metals. Chromium and silicon impart resistance to hot corrosion and can improve resistance to high temperature oxidation. Platinum significantly improves the resistance to high temperature oxidation and high temperature hot corrosion.

Chrome diffusion coatings are applied by a pack cementation process similar to aluminide coatings. The coating thickness is

limited to the 1 to 2 mil range, and the chromium concentration is limited to about 35 percent. These coatings provide resistance to hot corrosion.

Overlay Coatings

Overlay coatings are a layer of a special alloy applied to the metal surface, and are selected for maximum environmental resistance. Overlay coatings can be made thicker than diffusion coatings, which may provide more protection to the base metal. The microstructure of an overlay coating is shown in Figure 11.

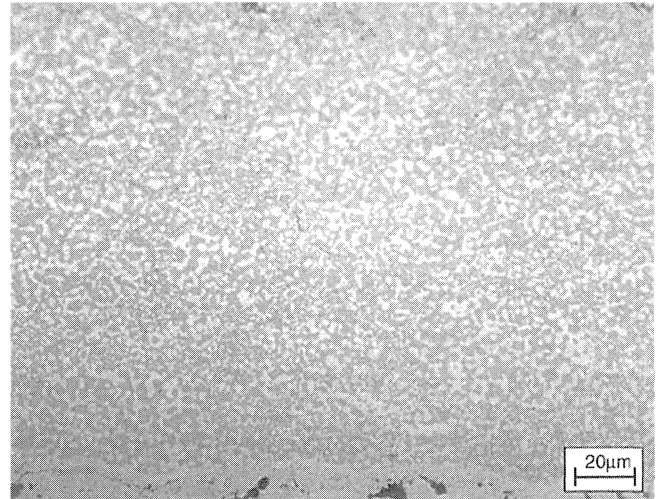


Figure 11. Overlay Coating Made by HVOF. (Courtesy of Howmet)

There are a wide variety of overlay coating compositions. These coatings are usually called MCrAlY (pronounced M crawl-ee) coatings, since chromium, aluminum, and yttrium are almost always present. “M” is either Ni, Co, or a mixture of these elements. The concentrations of the coating elements depend on the intended use of the coating. Other elements such as silicon, hafnium, and tantalum are sometimes added to the coating to improve the performance. The aluminum forms an intermetallic compound with the nickel or cobalt, NiAl, Ni₃Al, or CoAl. Overlay coatings, such as NiCrSi, also can be made without aluminum or yttrium and can protect airfoils up to about 1560°F (Bauer, et al., 1985).

Chromium and aluminum provide the oxidation and hot corrosion resistance of the coating. Their levels are adjusted to provide maximum resistance to one or another form of attack, or are balanced to provide protection from several types of attack. Higher aluminum is used for oxidation protection, and higher chromium is used for protection from low temperature hot corrosion. In order to be fatigue resistant, the aluminum and chromium levels should be kept low because higher levels reduce the ductility of the coating. However, if these levels are too low, there will be inadequate protection from high temperature attack.

The majority of overlay coatings are composed of cobalt, nickel, or a combination of the two. Cobalt is better for hot corrosion, and nickel is better for high temperature oxidation. A mixture of both cobalt and nickel is a compromise for protection from both types of attack. NiCrAlY coatings are more ductile than CoCrAlY coatings, but NiCoCrAlY coatings can be more ductile than either (Hect, et al., 1975). CoCrAlY coatings containing high levels of aluminum are prone to cracking (Linask and Dierberger, 1975).

Overlay coatings are generally applied by plasma spray, although other procedures such as electron beam physical vapor deposition, chemical vapor deposition, and high velocity oxygen flame are available. Frequently, a diffusion anneal treatment is carried out after coating to obtain diffusion between coating and

substrate, which gives good bonding, and homogenizes the as-sprayed microstructure.

Plasma spraying is a process in which a powder of the coating material is heated and accelerated toward the part being coated by a plasma gas stream. Since it is a line-of-sight coating process, it is necessary to rotate and tilt the part and plasma gun during coating. Internal passages, such as cooling holes, cannot be coated by plasma spray.

Plasma spraying can be performed in air at atmospheric pressure (air plasma spraying), in air with an inert shielding gas such as argon (shielded plasma spraying), or in a vacuum chamber. The vacuum processes are called vacuum plasma spraying (VPS) or low pressure plasma spraying (LPPS). The LPPS process decreases contamination of the powder and base metal from oxidation, and, therefore, substantially improves coating quality. The process also produces high density coatings with virtually no unmelted particles, and it allows the substrate to be heated without oxidizing. Shielded plasma spray can produce excellent coatings, but requires special procedures and equipment to be used (Taylor, et al., 1985).

A new method of spraying coatings, called high velocity oxygen fuel (HVOF), has been developed. In this method, the powder is both heated and propelled by a high velocity flame onto the substrate. The high velocity allows denser coatings to be made than can be achieved by conventional plasma spray processes. HVOF is in commercial use for wear resistant coatings, which are made from ceramic powders. It is in developmental use for high temperature coatings.

Duplex Coatings

Duplex coatings are a combination of overlay and diffusion aluminide coatings. The overlay coating is applied first. Then a diffusion aluminide coating is applied on top of the overlay coating to provide increased protection by substantially increasing the aluminum content of the outer layer. However, this increased aluminum level makes these coatings more prone to cracking of this outer layer. A micrograph of an overlay coating is shown in Figure 12.



Figure 12. Micrograph of a Duplex Coating, GT-29+. (Bernstein and Allen, 1993)

Thermal Barrier Coatings

Thermal barrier coatings (TBCs) are ceramic coatings applied over metal substrates to insulate them from high temperatures. They consist of zirconium oxide, ZrO_2 , stabilized by about 8 wt percent yttria, Y_{23} , or magnesia, MgO . They are applied over a bond coat that is usually an MCrAlY overlay coating, but can be a diffusion coating. The ceramic layer is typically 5 to 15 mils thick, and the overlay bond coat is usually 3 to 8 mils thick.

The bond coat improves the adhesion of the ceramic top coat by reducing the oxide buildup underneath the ceramic. (The ceramic is porous to oxygen, and will spall off when the oxide formed on the bond coat is sufficiently thick.) The bond coat is applied in the same manner as for overlay coatings.

The ceramic layer is normally plasma sprayed in an air environment. This layer can be made by electron beam physical vapor deposition (EBPVD) and is used on aircraft engines. The ceramic layer made by EBPVD is columnar grained and is more resistant to spalling than the plasma sprayed TBC (Sheffler and Gupta, 1988). EBPVD TBCs are more expensive than air plasma sprayed TBCs. A plasma sprayed TBC is shown in Figure 13. An EBPVD TBC is shown in Figure 14.

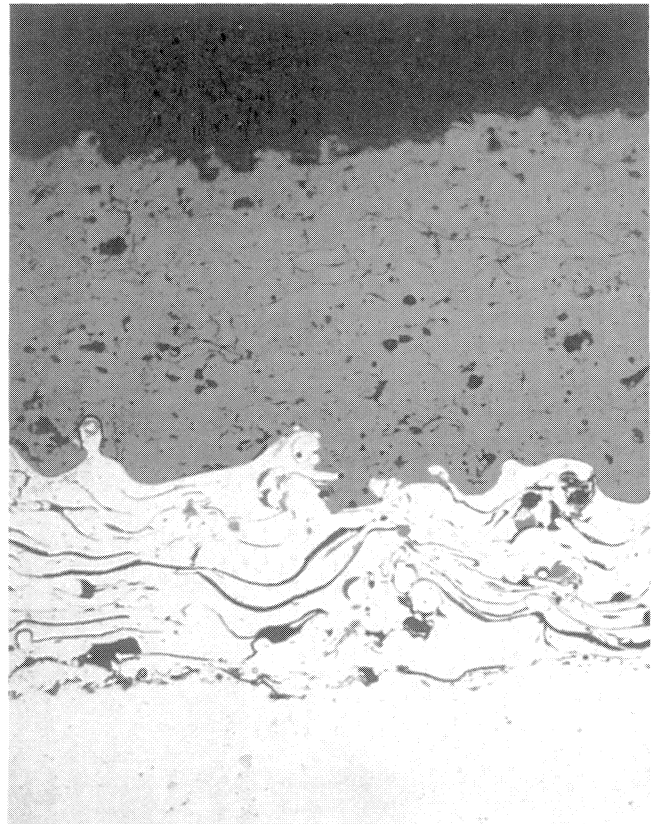


Figure 13. Plasma Sprayed Thermal Barrier Coating, 250x.

The TBC protects the metal by acting as an insulator between the metal and the hot gases. The thermal conductivity of the ceramic is one to two orders of magnitude lower than the metal. Although thin, the TBC can significantly reduce the metal temperature, provided that the metal component is air cooled. (The air cooling provides a heat sink.) Furthermore, the ceramic has a higher reflectivity than the metal. This means that more of the radiative heat is reflected away, which is important for combustion hardware.

During startup and shutdown, the TBC improves the thermal fatigue life by reducing the magnitude of the temperature transients the metal is exposed to. A 10 mil thick TBC on airfoils in

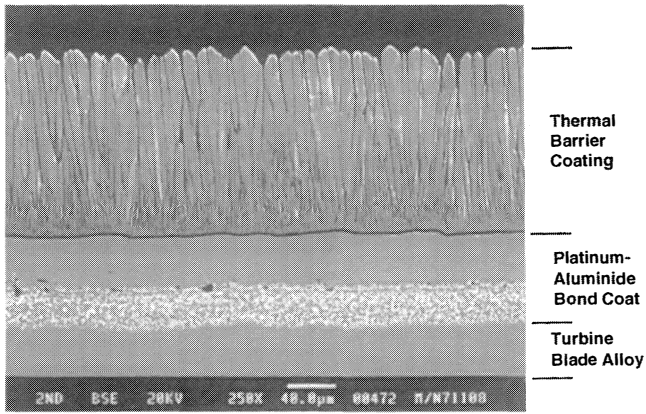


Figure 14. EB-PVD Thermal Barrier Coating on Top of a Platinum-Aluminide Bond Coat. (Courtesy of Howmet)

experimental aircraft engines has achieved a 300°F reduction of metal temperature (Brindley and Miller, 1989). During steady state operation, the TBC lowers the temperature of the underlying metal, thereby improving its durability. It also reduces the severity of hot spots.

The principal failure mechanism of thermal barrier coatings is the spallation of the ceramic layer. Spallation is caused by the synergistic interaction of bond coat oxidation and thermal cycling. The oxidation occurs at the interface between the bond coat and the ceramic. As more oxide forms at this interface, the ceramic layer is more likely to spall.

DEGRADATION OF HOT SECTION COMPONENTS

The hot section components degrade by a number of different mechanisms. The most common mechanisms encountered in service are cracking, environmental attack, creep, wear, and metallurgical embrittlement. Cracking is normally due to thermal mechanical fatigue and/or creep, and can be assisted by environmental attack and metallurgical embrittlement. Environmental attack is caused by oxidation and hot corrosion, and results in the loss of the surface profile. Environmental attack can lead to cracking of the metal in combination with fatigue and creep. (Coating degradation, which is a very important degradation mode, is considered as a form of environmental attack, since this degradation is caused by this attack.) Creep is the gradual distorting or elongation of the component, and can lead to cracking and/or wear. Metallurgical embrittlement is the loss of mechanical properties because of metallurgical changes within the metal. Wear processes, especially for combustor hardware, are important for surfaces in contact with each other.

High cycle fatigue is not considered a material degradation mechanism, although it certainly can lead to cracking and failure of the components. Instead, it is usually treated as a design issue, since both the cause and the solution to high cycle fatigue cracking is the vibrational response of the component, or the exciting forces that cause the vibration.

Creep

Creep is caused by the steady operating stress on the blades, vanes, and combustion hardware in conjunction with the high temperatures that these components operate at. During creep, the metal elongates due to the tensile stresses acting on it. This elongation can result in tip rub of blades, loss of dimensions on vanes, and bulges in combustion hardware. (On cooled blades, tip rub can close off exit holes for the cooling air, resulting in loss of cooling air flow and overheating of the blades.) Excessive creep strains will lead to cracking, and, at worse, fracture of the component.

Minimizing creep and preventing fracture by creep are some of the primary objectives during component design. Due to the

conservative design practices typically used in industrial gas turbines, creep fractures are rare, but they do occur. When failures are due to a generic design deficiency, it is typically because the temperatures of the component are higher than predicted by the designers. In this case, the solution requires design or material modifications. When creep fractures occur due to operation, they are usually caused by excessive operating temperatures or the blockage of the cooling air channels.

Prediction of creep life, or the amount of creep life consumed, is difficult to perform by operators because they lack the requisite design data for this analysis, and because the calculation of the metal temperatures is quite difficult, even for the OEM. In the absence of creep cracking, there may be no means of measuring the amount of creep strain that has occurred.

Determination of the remaining creep life by testing metal samples from the component suffer from a number of methodological difficulties, including a potential change in creep mechanism between the test conditions and the operating conditions. Data from stress rupture tests on service-exposed buckets, new buckets, and cast specimens for IN-738LC have been collected (Bernstein, 1990) and are shown in the graph in Figure 15. The horizontal axis is the Larson-Miller parameter (LMP), which is equal to $T \times [20 + \log t]$. (Note: T is in absolute temperature, either °R or °K, and t is time, usually in hours. Factors other than 20 can be used, but 20 has been found to be adequate in most instances. There are other time-temperature parameters similar to LMP, but none have been shown to be consistently better than any other.) It can be seen that at low stresses, there is no loss in stress rupture life, but at higher stresses, there is a loss in life. The reason for this discrepancy is most likely due to the different metallurgical deformation mechanisms operating at the two stress levels, as described by Koul and Castillo (1988) and McLean and Peck (1984). Thus, determining remaining life from stress rupture tests at high stresses can lead to conclusions inconsistent with those reached from tests at low stresses. At best, these tests tell one how the material compares to the original material, and if the material is in a very brittle condition.

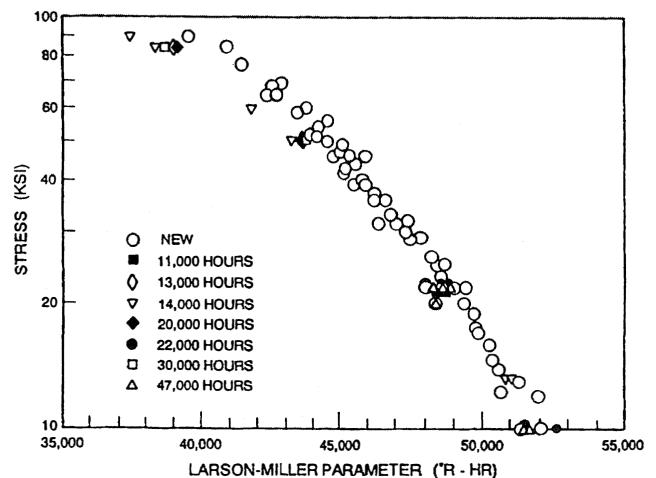


Figure 15. Stress Rupture Life of IN-738 Expressed in Terms of the Larson-Miller Parameter. Results Are Shown for New and Aged Material and for New and Service Run Blades. (Bernstein, 1990)

Thermal Mechanical Fatigue

Thermal mechanical fatigue (TMF) occurs during the start-stop cycle of the engine. It is sometimes called thermal fatigue, or low cycle fatigue (LCF), although LCF usually describes constant temperature conditions. TMF derives its name because both the temperature and the mechanical load is cycled simultaneously.

