HIGH TEMPERATURE COATINGS FOR INDUSTRIAL GAS TURBINE USERS

by

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ABSTRACT

High temperature coatings are used for protecting the high temperature turbine components from environmental attack due to oxidation and hot corrosion. These coatings have developed from simple aluminide coatings to complex overlay and duplex coatings. Over the past 15 years thermal barrier coatings, which lower the temperature of the metal, have become increasingly used in industrial gas turbines.

This tutorial reviews all these coatings, how they provide protection, how they are applied, and their degradation. Included is a discussion of high temperature oxidation and hot corrosion. Also discussed is recoating and expected future developments of these coatings.

INTRODUCTION

High temperature gas turbine coatings have developed from simple aluminide coatings designed to provide enhanced oxidation protection for jet engine turbine blades in the 1960s, to complex, multilayer coatings that reduce the temperature of the turbine blades. High temperature coatings continue to advance as we learn more about them, and as we develop new coatings and new methods of applying them.

The two principal types of high temperature coatings are oxidation and corrosion resistant coatings, and thermal barrier coatings. Oxidation and corrosion resistant coatings are used to provide protection from environmental attack due to high temperature oxidation and hot corrosion. They consist primarily of aluminide and overlay coatings. Thermal barrier coatings (TBCs) are used to reduce the temperature of the component, as well as to provide some resistance to oxidation and corrosion.

The objective of this tutorial is to provide an overview of high temperature coatings technology for the gas turbine user. Included in this overview are the different types of coatings, what makes them work, how they are made, how they degrade, recoating, and environmental attack. Also presented is a brief look at future development trends in coating technology.

HOW COATINGS WORK

Oxidation and Corrosion Resistant Coatings

Oxidation and corrosion resistant coatings work by forming a thin oxide barrier on the surface, as shown in Figure 1. This barrier separates the base metal and coating from the reactive gases. This barrier is extremely thin, on the order of 0.0001 inch (100 micro-inches, or 2 microns). Without this barrier, the reactive gases would oxidize and corrode both the base metal, as well as the coating itself. This oxide barrier is typically alumina, Al_2O_3, although chromia, Cr_2O_3, will also provide protection at lower temperatures.

Hot Gas (O_2, S, K, Na, ...)

Protective Oxide Scale →

Al_2O_3
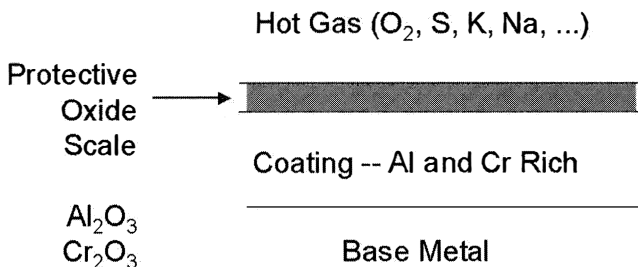Cr_2O_3

Coating -- Al and Cr Rich

Base Metal

Figure 1. High Temperature Coatings Protect the Base Metal by Forming a Protective Oxide. (While aluminum and alumina are more common, chromium and chromia are also used, often in combination with aluminum and alumina.)

The role of the coating is to form this oxide barrier. Ideally, this barrier is perfectly adherent to the substrate, has no imperfections, and grows very slowly after first forming. Since one cannot achieve ideal oxide barriers, the coating must be able to reform the oxide barrier should some of it become damaged due to cracking, spallation, etc. The role of the coating is to act as a reservoir of the oxide forming elements, which are primarily aluminum and chromium. Thus, these coatings contain as much aluminum and chromium as possible. (Chromium assists in the formation of the alumina oxide barrier.)

Thermal Barrier Coatings

TBCs work by adding a thin insulative ceramic layer to the surface of the blade. This layer is from 0.003 inch to 0.020 inch (0.762 mm to 5.08 mm) thick. With some of the more recently developed TBCs, this layer is much thicker. The limit to the layer thickness is the spallation of the ceramic with increasing thickness. The thicker the ceramic layer, the greater the temperature reduction of the blade that can be achieved.

This ceramic insulative layer causes a temperature drop across it, as shown in Figure 2. By introducing a temperature drop at the surface of the blade, the temperature of the blade itself can be lowered. Lower blade temperatures result in longer life. Of note is that the blade must be cooled. That is, there must be a heatsink in order for the TBC to function. Without such a heatsink, both the TBC and the blade will eventually reach the same, constant temperature.
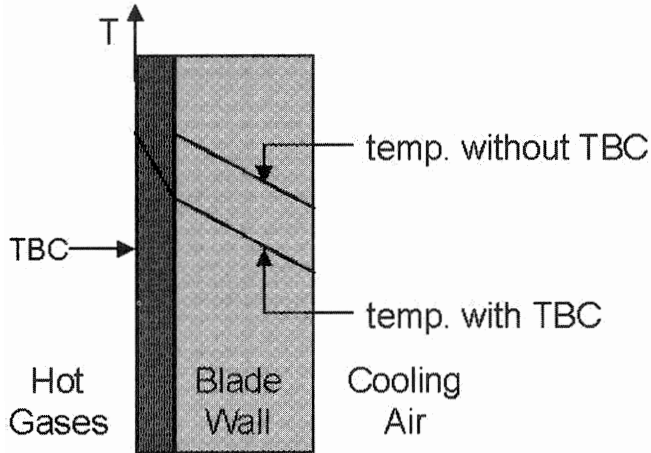

Figure 2. Thermal Barrier Coatings Reduce the Temperature in the Base Metal by Adding a Layer of Insulation at the Surface of the Base Metal.

COAT NG TYPES FOR ENVIRONMENTAL ATTACK

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. (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-base 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 3.
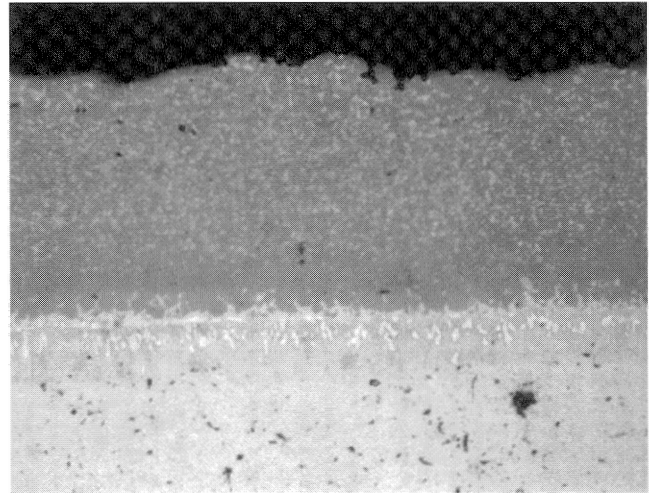

Figure 3. Micrograph of Nickel-Aluminide Coating, 800×.

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.

There are two types of platinum-aluminide coatings—two-phase and one-phase. Two-phase coatings, which are widely used, consist of a layer of platinum-aluminide particles, $PtAl_2$ (and other chemistries), on the surface and a nickel-aluminide plus platinum layer, (Ni, Pt) Al, underneath. One-phase coatings, which are a recent development, have only the nickel-aluminide plus platinum layer. These coatings have better resistance to cracking than the two-phase coatings, and can have better resistance to environmental attack. Micrographs of these coating types are shown in Figure 4.
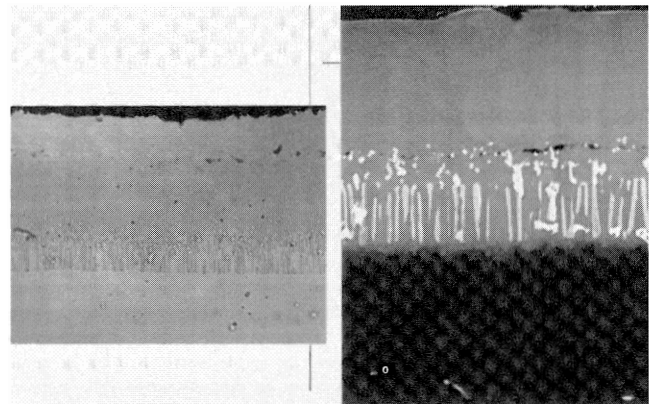

Figure 4. Micrographs of Platinum-Aluminide Coatings. (A two-phase coating is on the left and a one-phase coating is on the right.) (Courtesy of Howmet)

Chrome diffusion coatings are applied by a pack cementation process similar to aluminide coatings. The coating thickness is limited to the 1 mil 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 5.
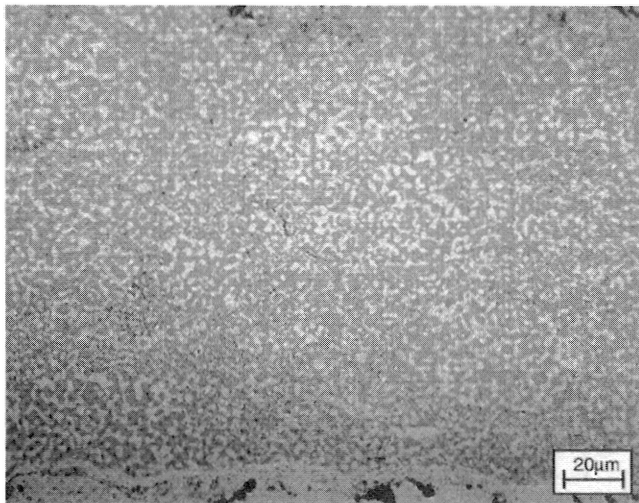

Figure 5. Microstructure of an Overlay Coating Made by HVOF. (Courtesy of Howmet)

There is 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, Ni_3Al, 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 (Hecht, 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.

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 a duplex coating is shown in Figure 6.
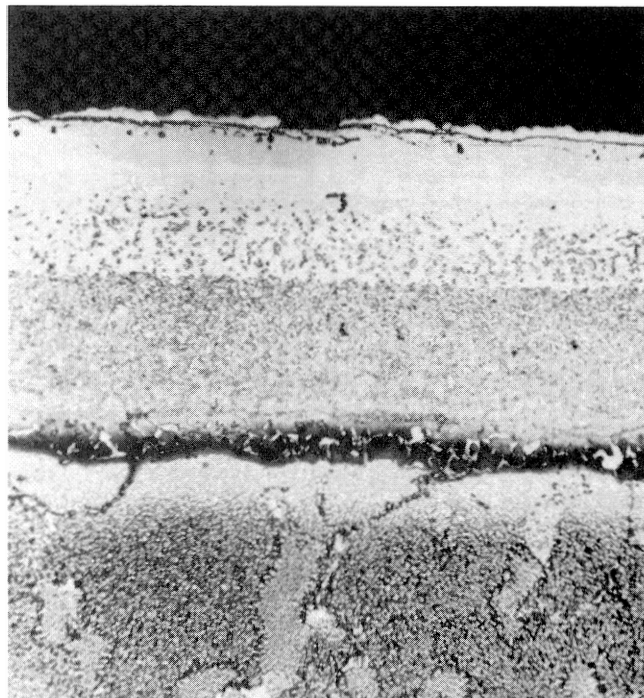

Figure 6. Micrograph of an Overlay Coating, GT-29+. (Bernstein and Allen, 1992)

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% yttria, Y_2O_3, 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 mils to 15 mils thick, and the overlay bond coat is usually 3 mils 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 also be made by electron beam physical vapor deposition (EBPVD), which 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 7. An EBPVD TBC is shown in Figure 8.

Another type of ceramic layer has been recently developed, called a segmented TBC, and is shown in Figure 9. It has cracks through the thickness of the ceramic, which are perpendicular to the substrate surface. These cracks provide increased resistance to spallation, similar to EBPVD ceramic layers. The segmented TBC is made by a proprietary, plasma spray process, and very thick ceramic layers can be made.

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
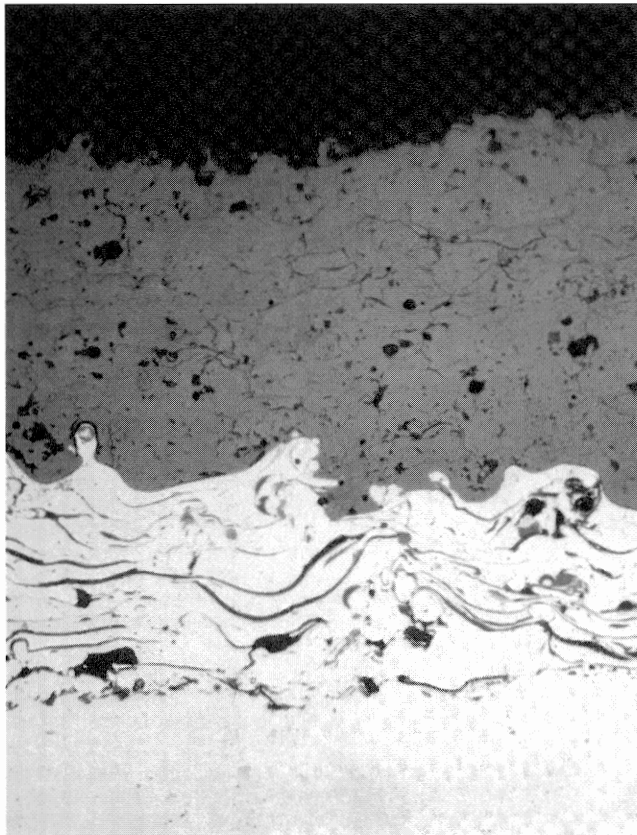
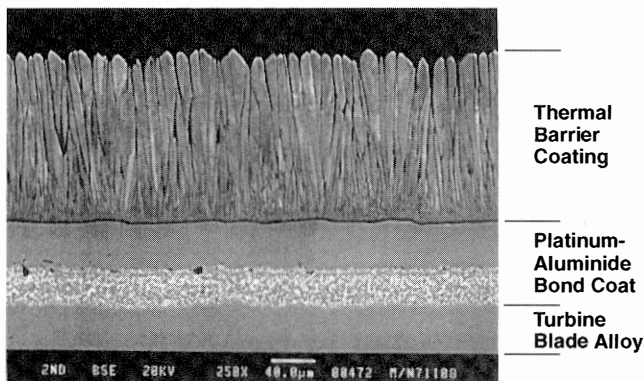*Figure 7. Plasma Sprayed Thermal Barrier Coating, 250×.*

Figure 8. EBPVD Thermal Barrier Coating on Top of a Platinum-Aluminide Bond Coat. (Courtesy of Howmet)
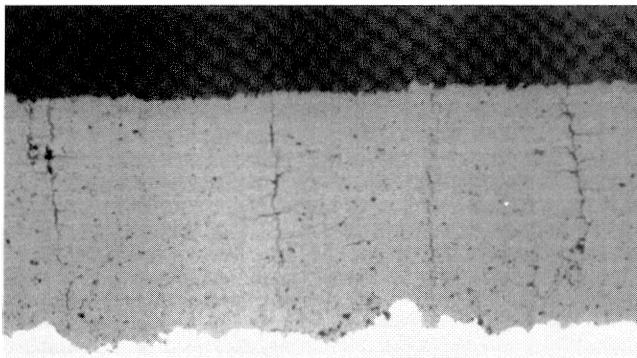

Figure 9. Segmented Thermal Barrier Coating. (Courtesy of Praxair)

provided that the metal component is air cooled. (The air cooling provides a heatsink.) 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 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.

APPLICATION METHODS

Aluminide Coatings

Aluminide 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 sometimes called diffusion aluminide 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.

Pack cementation is the oldest, and still the most widely used, process for making aluminide coatings. Components are packed in metal powders in sealed retorts, as shown in Figure 10. These are then heated inside a furnace to specific temperature-time profiles. Pack cementation has been reviewed by Mévrel, et al. (1986).
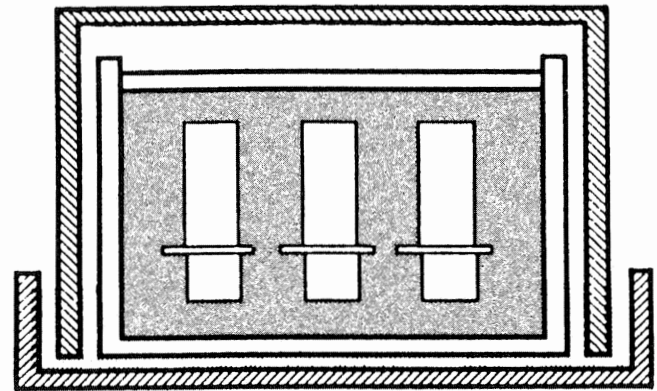

Figure 10. Schematic of the Pack Aluminizing Process. (Smith and Boone, 1990)

Pack cementation processes include aluminizing, chromizing, and siliconizing. In the aluminizing process, a source of Al reacts with a chemical activator on heating to form a gaseous compound (e.g., pure Al with NaF to form AlF). This gas acts as the transfer medium that carries aluminum to the component surface. The gas decomposes at the substrate surface depositing Al and releasing the halogen activator (F). The coating forms at temperatures ranging from 1600°F to 2100°F over a period of several hours.

This process can also be used to produce chromium-modified aluminide coatings. The addition of Cr is known to improve the hot corrosion resistance of nickel-base alloys. Cr can be codeposited

with Al in a single-step process, or a duplex process can be used to form the Cr-modified aluminide. The component is first chromized using either a packed cementation or a gas phase process, which is then followed by a standard aluminizing treatment. The final distribution of the Cr in the coating will depend on whether a low-activity or high-activity aluminizing process is employed.

For a platinum-aluminide coating, a thin (typically 0.3 mil) layer of platinum is first deposited onto the substrate by a plating process. The platinum is then diffused into the substrate by a heat treatment. Finally, the part is aluminized to form the Pt-aluminide coating.

Conventional pack cementation processes are unable to effectively coat internal surfaces such as cooling holes. The coating thickness on these internal surfaces is usually less than on the surface due to limited access by the carrier gas. Access can be improved by pulsing the carrier gas (Restall and Hayman, 1984), or by use of a vapor phase coating process. A process has been developed in which the part to be coated is separated from the pack, and the gas diffuses to the part as shown in Figure 11. This process can coat internal surfaces. Another method of coating both the internal and external surfaces involves generating the coating gases in a reactor separate from the vessel the parts are in (Smith and Boone, 1990). The coating gases are pumped around the outside and through the inside of the parts by two different distribution networks, as shown in Figure 12. Finally, internal passages can be coated by filling them with the powder used in the pack (actually a variation of this powder) (Rose, 1989). This powder process is widely used commercially. Care must be exercised to ensure that all the powder is removed from the passages after coating.
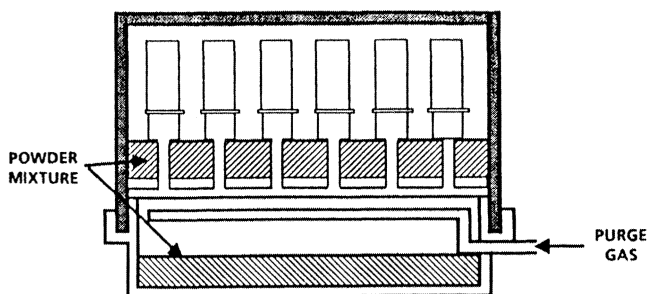

Figure 11. Schematic of the Vapor Phase Aluminizing Process. (Smith and Boone, 1990)
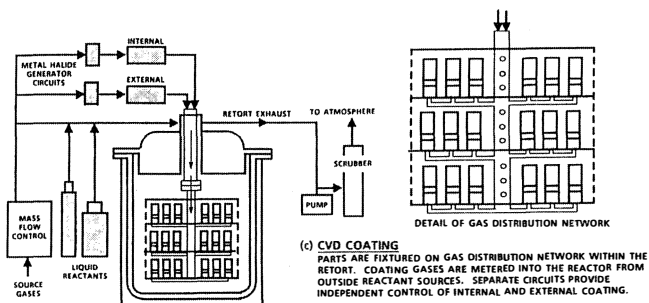

Figure 12. Schematic of a "CVD" Aluminizing Process. (Smith and Boone, 1990)

Slurry processes can also be used to deposit the aluminum. The slurry can also contain other alloying elements for the coating. The slurry is usually sprayed on the component similar to spray paint. The component is then given a low temperature heat treatment that burns off the binder in the slurry, and fuses the slurry to the surface. Then the part is given a high temperature heat treatment to form the coating.

Chemical Vapor Deposition

Chemical vapor deposition, CVD, is an older process that can be used to form both aluminide and overlay coatings. During CVD, a coating is formed by chemical reaction between a gaseous phase and a heated substrate. Packed cementation involves CVD, but CVD is a much more versatile process, and coatings range from diffusion to overlay type, depending on the chemistry. The process can be used to apply metallic, intermetallic, and refractory coatings of almost any composition. The principles of CVD have been described by Viguié (1974).

OVERLAY COATINGS

Overlay coatings can be applied by chemical vapor deposition (CVD), physical vapor deposition (PVD), high velocity oxygen/flame (HVOF), or plasma spray. Plasma spray is the most widely used process today.

Physical Vapor Deposition

Physical vapor deposition (PVD) is a coating process in which the atoms of the coating material are evaporated and then deposited onto the surface of the part (Boone, 1986). The process must be done in a vacuum chamber. Coating materials can be pure metals, metallic alloys, or ceramics. Most materials can be coated by the PVD process.

Electron beams are usually used to vaporize the coating material, in which case the process is called "electron beam, physical vapor deposition," or EBPVD. A schematic of the EBPVD process is shown in Figure 13. The electron beams are focused by magnets on the ingot of the coating material, causing it to melt. Due to the vacuum environment, a vapor cloud of the coating material forms over the molten ingot pool. This vapor rises and deposits on the part to be coated. The evaporated atoms move in a straight line from the molten ingot to the part. Complete coating coverage is obtained by rotating and tilting the part in the vapor cloud.
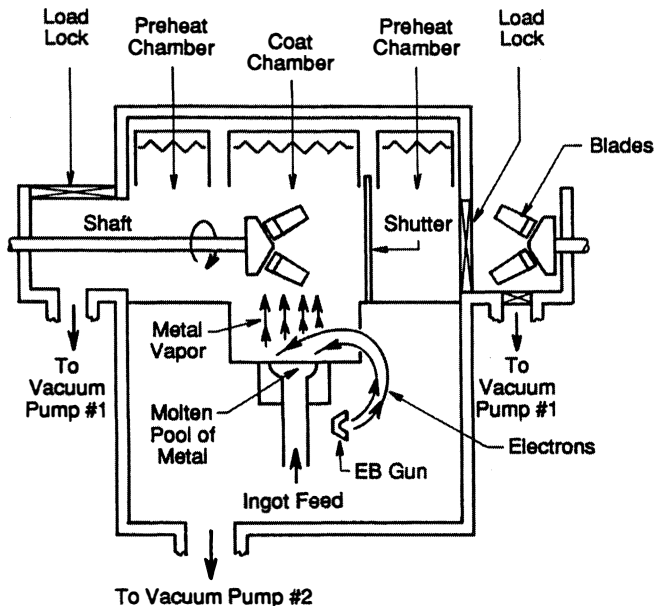

Figure 13. Schematic of an Electron Beam, Physical Vapor Deposition (EBPVD) Process. (Kalman and Lee, 1983)

Diffusion normally occurs during the PVD process at the substrate-coating interface. This diffusion forms a metallurgical bond of the coating with the substrate. However, post-deposition diffusion treatments are commonly performed to improve the bond and the coating. Glass bead peening is also frequently used to close areas of unbonded columnar grain structure to produce a fully dense structure.

The PVD process is a line-of-sight process, so internal and recessed surfaces cannot be coated. A good vacuum is required to prevent oxidation of the reactive vapor cloud and the substrate surface, since oxide layers can result in a nonadherent coating.

Because of the large part size of industrial gas turbine components and limited chamber size of PVD coaters, the cost of PVD coatings for industrial gas turbine parts can be quite high. These costs may decrease as larger PVD coaters become commercial.

Plasma Spraying

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. There are several books and reviews on plasma spraying (Gerdeman and Hecht, 1972; Gross, et al., 1968; Fisher, 1972; Gill and Tucker, 1986; Herman, 1988).

The plasma is generated from a high current arc with inert gases and powder particles, which is then accelerated toward the part, as shown in Figure 14. The particles strike the substrate surface at a high velocity. (Prior to spraying, the substrate surface is roughened by an abrasive process, such as grit blasting.) The particles cool very quickly on the roughened surface. The coating is attached to the substrate by the mechanical interlocking of the coating and the surface irregularities. In addition, chemical bonds can form, and post spraying heat treatments can be used for further interdiffusion of the coating and substrate.
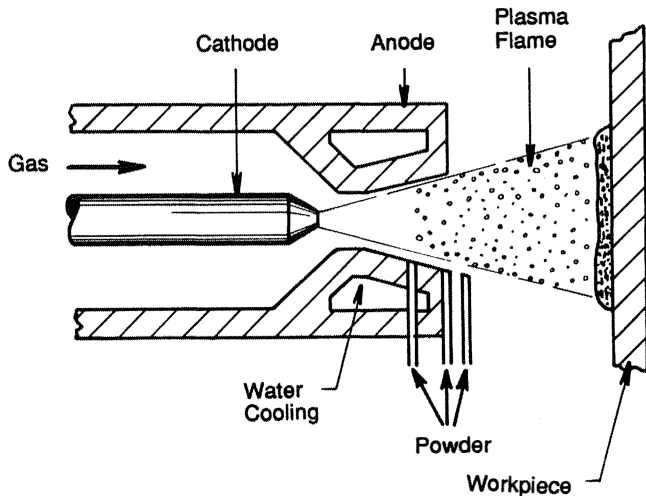

Figure 14. Schematic of a Plasma Gun. (Gill and Tucker, 1986)

Particles continue to be deposited at a high rate, such as a million particles per second. Each particle forms into the irregularities of the previous particles and the coating is built up. These solidified particles are called splats and cool very quickly. Voids form in the coating due to gas that is trapped by the plasma spray, and oxides are deposited due to particles that are oxidized. Sometimes particles are not heated enough and become embedded in the coating as spherical particles.

A post-coating heat treatment is often carried out to ensure coating-substrate bonding through interdiffusion and to homogenize the structure of the coating. This is normally performed at 1800°F to 2000°F in a vacuum or inert atmosphere for periods of one to 10 hours.

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). A schematic of the air plasma spray and LPPS processes is shown in Figure 15. 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).
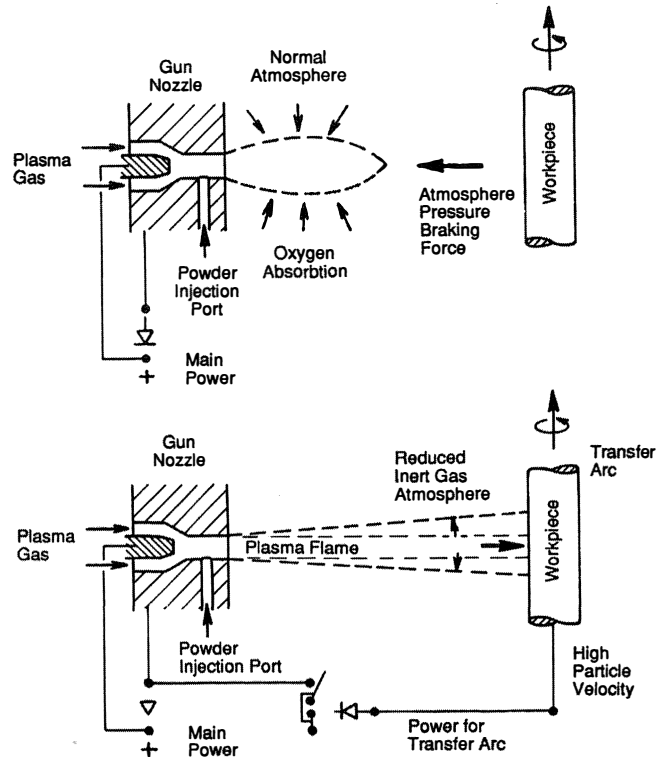

Figure 15. Schematic of Air Plasma Spray and LPPS Processes. (Nicoll, 1984)

When the plasma spraying is done in air or in an inert gas, the particles cool and slow down as they leave the plasma jet and collide with the gas molecules. If air is used, oxidation of the particles occurs. Inert gas greatly reduces, but does not completely eliminate, this oxidation.

HVOF

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. (Plasma spray produces a hotter flame than HVOF, but has a lower particle velocity. The higher particle velocity of HVOF produces a denser coating, which improves the properties of the coating.) HVOF is in commercial use for wear resistant coatings, which are made from ceramic powders. It is in developmental use for high temperature coatings.

The HVOF coating also has much less oxidation of the particles than air plasma spray. Thus, HVOF coatings can be produced that are far superior to air plasma sprayed coatings, despite the HVOF process being done in an air environment.

HVOF is being considered as an alternative to LPPS because of its lower cost. While LPPS coatings are still of higher quality than HVOF coatings, the quality of HVOF coatings may be sufficient for many applications.

Electro-Deposition

Electro-deposition refers to processes in which the coating material is deposited on the surface by an electrical process. The coating material is a positively charged powder in the bath. After deposition, the coating material is then heat treated to form the coating.

One of the earliest electro-deposition processes is the Allison electrophoretic process (AEP), which is still in use. In this process, an aluminum rich material is deposited on the surface. This powder is then heat treated at temperatures similar to those used in pack aluminization. The aluminum rich powder reacts with the surface to form the aluminide coating.

A later development is the deposition of overlay powders using a nickel or cobalt matrix as a binder. The binder is provided from a consumable electrode, as in electroplating. Micrographs of the coating both before and after heat treatment are shown in Figure 16. Essentially, the same coating is produced as in a plasma spray process. The advantages of the electro-deposition process are that it is not a line-of-sight process and, as such, can coat blind areas. It also avoids the imperfections that are present in plasma spray, and does not require the coating to be applied in a vacuum chamber.
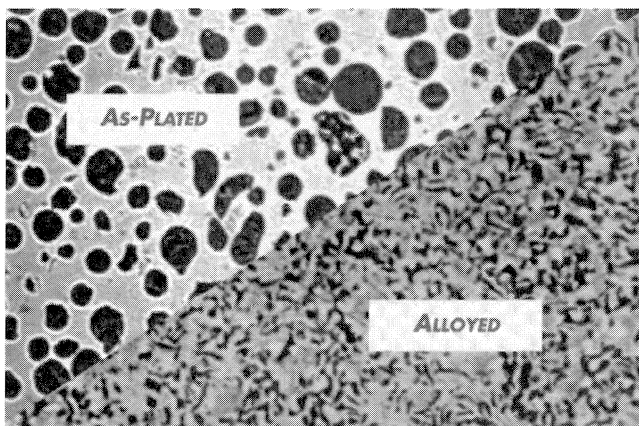

Figure 16. Micrographs of an Electro-Deposited Overlay Coating Both Before and After Heat Treatment. (Courtesy of Praxair)

ENVIRONMENTAL ATTACK AND COATING DEGRADATION

There are two basic forms of high temperature attack—high temperature oxidation and hot corrosion. Hot corrosion can be subdivided into two types—high temperature hot corrosion (Type I) and low temperature hot corrosion (Type II). The approximate temperature regimes over which these forms of attack occur, and their severity, are shown in Figure 17.
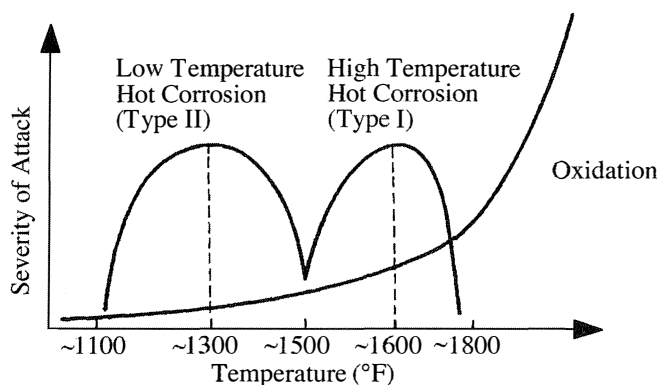

Figure 17. Approximate Regimes of High Temperature Environmental Attack. (Committee on Coatings for High-Temperature Structural Materials, 1996)

Oxidation

High temperature oxidation is the oxidation of the metal and its alloying elements. It results in the formation of an external oxide scale that may or may not be protective. A protective scale grows slowly (due to a slow rate of diffusion through the scale) and is adherent to the metal substrate. For nonprotective scales, an internally oxidized region occurs beneath the metal surface. Micrographs of external and internal oxidation are shown in Figure 18. High temperature oxidation accelerates with higher temperatures.
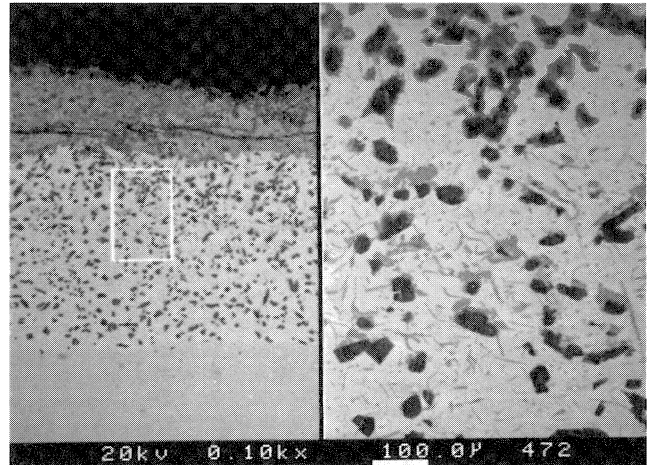

Figure 18. Micrographs of External and Internal Oxidation. (Courtesy of Solar)

Hot Corrosion

There are two types of hot corrosion, high temperature hot corrosion and low temperature hot corrosion. High temperature hot corrosion, also called Type I hot corrosion, occurs at metal temperatures between 1500°F and 1750°F when sulfur is present along with potassium or sodium. It is most severe at temperatures between 1600°F and 1700°F. High temperature hot corrosion is caused by the formation of alkali metal salts, such as sodium sulfate (Na_2SO_4) and potassium sulfate (K_2SO_4), which melt and form a liquid on the surface. This molten salt attacks the oxide scale, destroying the protection normally afforded by the scale. Once the oxide scale is breached, sulfidation and oxidation of the metal occur. High temperature hot corrosion results in the rapid destruction of the metal surface. A micrograph of high temperature hot corrosion is shown in Figure 19.

Low temperature hot corrosion, also called Type II hot corrosion, occurs at temperatures between 1100°F to 1500°F with a maximum rate of attack between 1250°F to 1350°F. It is caused by the mixture of alkali sulfates with alloy metal sulfates, such as $CoSO_4$ or $NiSO_4$, and requires a significant partial pressure of SO_3. This sulfate mixture destroys the oxide scale and its protective ability. Low temperature hot corrosion results in pitting of the metal surface, a porous layered scale, little base metal depletion, and few internal sulfides. A micrograph of low temperature hot corrosion is shown in Figure 20. The rate of pitting can be as great as the rate of attack by high temperature hot corrosion.

Coating Degradation

High temperature coatings are sacrificial in nature. They are designed to be consumed during the operation of the engine and then replaced during the refurbishment of the component. High temperature coatings provide their protection by forming a thin oxide layer, either aluminum oxide or chromium oxide, which acts as a barrier between the environment and the substrate. (The
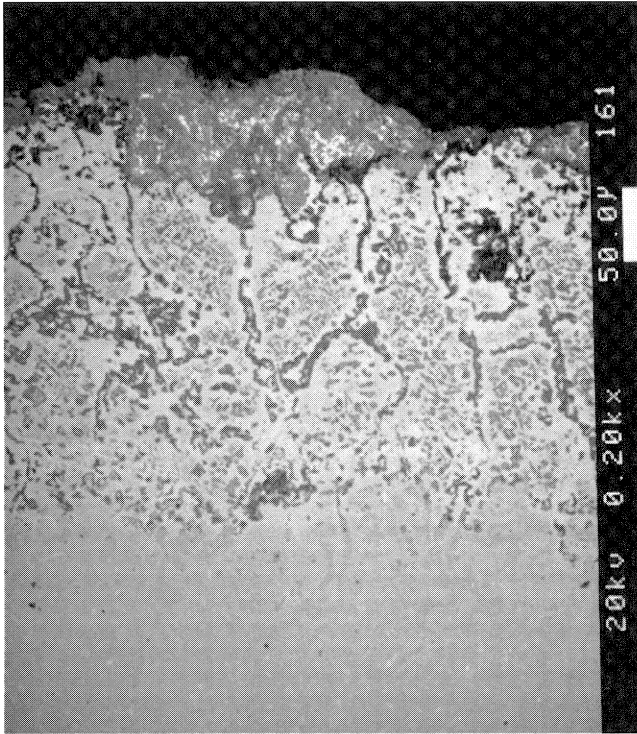
Figure 19. Micrograph of High Temperature Hot Corrosion (Type I) of FSX-414 Coated With RT-44. (Courtesy of Solar)
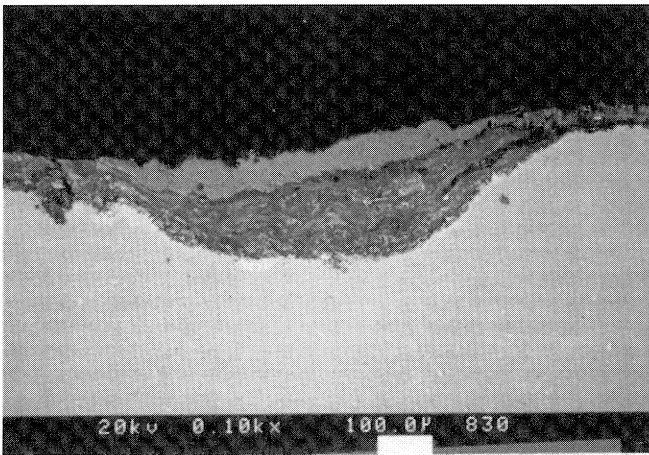

Figure 20. Micrograph of Low Temperature Hot Corrosion (Type II) of MarM 421. (Courtesy of Solar)

substrate is the base metal and the coating.) This thin oxide is removed during engine operation by spallation and/or erosion. The coating then supplies sufficient aluminum or chromium to reform this protective oxide layer. The coating is simply a reservoir of the elements that form the protective oxide layer. When this reservoir is depleted by the successive loss and reformation of the oxide layer, then the coating can no longer protect the substrate underneath it. The coating is then attacked by oxidation and/or hot corrosion. After attacking the coating, this environmental attack continues through the coating and into the base metal.

The important aspect to note about coating degradation is that it is controlled by the chemistry of the coating, and not by the thickness of the coating. While the thickness can be an important variable, and cannot be overlooked, it is the aluminum and chromium content of the coating that determines when the coating can no longer provide adequate protection to the component.

The prediction of coating degradation, as well as base metal attack, is not well developed. Most original equipment manufacturers (OEMs) rely upon empirical methods. These methods are based upon laboratory testing that is heavily supported by engine experience (Strangman, 1990). Methods are being developed for predicting coating degradation by high temperature oxidation (Chan, et al., 1998), which is more amenable to prediction than is hot corrosion. Prediction of coating degradation by hot corrosion is complicated by the difficulty of determining what the corrodants are and their rate of deposition upon the surface.

Coatings can also degrade by cracking if the imposed tensile strains become too great. Most coatings undergo a ductile-to-brittle transition with temperature, as shown in Figure 21. Below a certain temperature, the coatings show very little ductility, but above this temperature, their ductility increases rapidly with increasing temperature. Components must be designed and operated such that the tensile strain in the coating does not exceed the strain to cause cracking in the coating. As shown in Figure 22, this cracking is most likely during the shutdown of the engine, when the surface of the component goes into tension. The most severe situation occurs during an emergency shutdown (or trip).
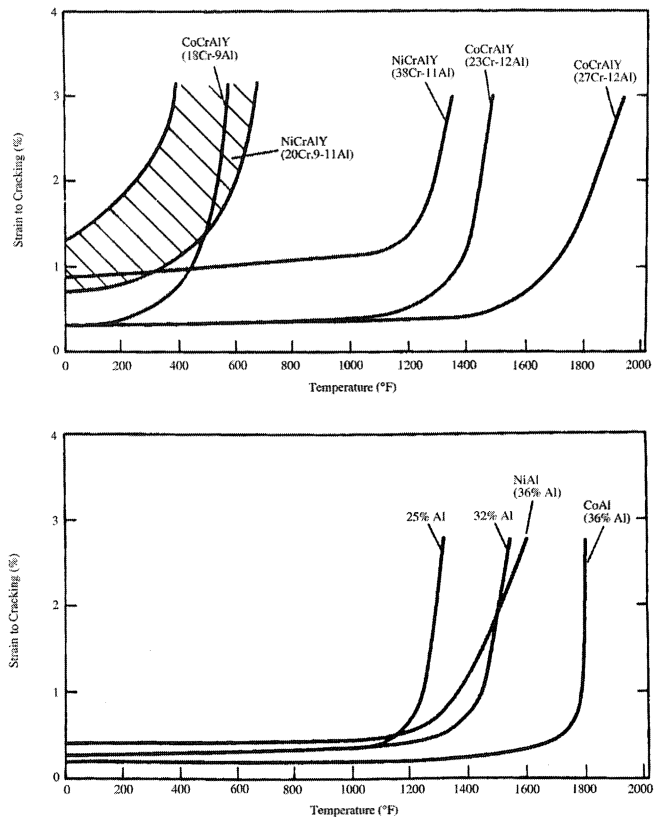

Figure 21. Coating Transition From Ductile to Brittle as a Function of Temperature. (Bernstein and Allen, 1992)

RECOATING

Recoating restores the surface protection to the base metal when the coating has either been breached or its protective ability exhausted. Recoating is widely done. The process of recoating is the same as that for a new coating, except that the old coating has to be removed, and any surface damage, or attack, removed as well. If a fresh metal surface is not obtained, then the life of the coating may be less than that of the original coating.

There is no limit to the number of times that a metal can be recoated, although most manufacturers recommend only one recoating cycle. This recommendation is based upon the removal
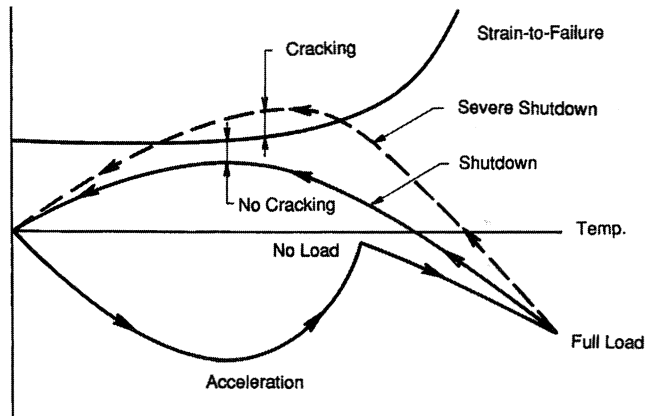
Figure 22. Schematic of the Strain and Temperature at the Leading Edge of a Blade Showing the Effect of Different Starts and Stops. (Bernstein and Allen, 1992)

of surface metal that occurs as part of removing the coating. When the thickness of the metal becomes too thin, especially adjacent to interior cooling surfaces, the component can no longer be repaired or recoated.

FUTURE DEVELOPMENTS IN COATINGS

Diffusion and Overlay Coatings

Future developments in coating technology for diffusion and overlay coatings will be driven by economics and reliability. Existing coatings are largely adequate for today's operation, which is mostly with natural gas fuels. Operation on distillates and other liquid fuels remains important for areas not served by natural gas pipelines, and hot corrosion problems persist with these fuels. However, many of these hot corrosion issues are addressed by fuel handling and quality issues, as opposed to the development of new coatings. Coatings can be expected to provide only limited protection in situations of aggressive hot corrosion.

Economic developments are directed to less expensive coatings. Since the primary cost of coatings is the application of the coating material, efforts will be focused upon application methods that are less expensive. The most promising method is the use of HVOF for overlay coatings. Other methods will continue to be refined so as to reduce costs, which will be mainly directed to reducing the number and cost of the processing steps, including secondary operations.

Reliability developments are directed to the inspectability of coatings, both when made and in the field, and the life prediction of coatings. There will also be an increased academic understanding of coatings as gas turbines become more important for baseload power generation.

Thermal Barrier Coatings

Thermal barrier coatings (TBCs) will continue to be a very active area of development. Since these coatings offer one of the few opportunities to increase the performance of gas turbines by permitting higher firing temperatures, significant efforts for both aircraft and industrial engines are occurring. The key to achieving this higher performance is the reliability of the coating and the ability to accurately determine the life of the coating. (If one is going to rely upon the TBC to increase engine temperatures, then one must have confidence in the durability of this coating.)

Other developmental thrusts for TBCs are better insulation by using thicker coatings and developing materials having lower heat transfer through the coating. Economics will continue to be important, but more expensive coatings will be justified by the performance gains they will afford. There is also a large effort directed to obtaining an improved academic understanding of these coatings, which should result in better TBCs.

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