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Technical Note

A Design Perspective on Thermal Barrier Coatings

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This article addresses the challenges for maximizing the benefit of thermal barrier coatings for turbine engine applications. The perspective is from the viewpoint of a customer, a turbine airfoil designer who is continuously challenged to increase the turbine inlet temperature capability for new products while maintaining cooling flow levels or even reducing them. This is a fundamental requirement for achieving increased engine thrust levels. Developing advanced material systems for the turbine flowpath airfoils, such as high-temperature nickel-base superalloys or thermal barrier coatings to insulate the metal airfoils from the hot flowpath environment, is one approach to solve this challenge. The second approach is to increase the cooling performance of the turbine airfoil, which enables increased flowpath temperatures and reduced cooling flow levels.

Thermal barrier coatings have been employed in jet engine applications for almost 30 years. The initial application was on augmentor liners to provide thermal protection during afterburner operation. However, the production use of thermal barrier coatings in the turbine section has only occurred in the past 15 years. The application was limited to stationary parts and only recently incorporated on the rotating turbine blades. This lack of endorsement of thermal barrier coatings resulted from the poor initial durability of these coatings in high heat flux environments. Significant improvements have been made to enhance spallation resistance and erosion resistance, which has resulted in increased reliability of these coatings in turbine applications.

Keywords design issues, thermal barrier coatings

1. Introduction

Gas turbine performance can be improved by increasing the efficiency of the fan, compressor, and turbine components. This approach yields reduced specific fuel consumption of the gas turbine with a moderate increase in engine thrust. Large increases in thrust can be obtained by increasing the turbine inlet temperatures while maintaining or improving component efficiency levels. Figure 1 illustrates the potential improvement that remains in increasing the core horsepower, defined as the horsepower generated per pound of airflow, of a gas turbine engine as a function of the turbine inlet temperature. The solid line represents components with 100% efficiencies; that is, the maximum potential at a given temperature. Symbols on this figure represent the status of current production engines as well as the original Whittle gas turbine demonstrator engine.

There has been a significant improvement in performance largely due to improvements in materials and the introduction of cooling technologies into the turbine. Each of the production engines is near its optimum core horsepower level with the technology level incorporated into that engine. Therefore, each engine symbol represents continual improvements in technology. Note that turbine inlet temperature increases for a fixed technology level can actually cause the core horsepower to be reduced. The cause for this is parasitic loss increases in the turbine due to increased cooling flow requirements for the turbine flow path, specifically the turbine vanes, blades, and blade outer air seals. As can be readily observed, there is significant potential for improving gas turbine power output by increasing turbine temperatures; however, technological improvements in materials, coatings, and cooling will be required to achieve the potential.

Material improvements have been dramatic over the past years. The composition of the alloys used for turbine airfoil materials and their processing methods have allowed increased metal temperature operation, and hence, increased turbine inlet temperatures. As the alloy compositions have been improved, the incipient (or onset) melt temperatures increased and the creep strength, fatigue strength, and oxidation resistance also increased. Increased temperature operation was, therefore,

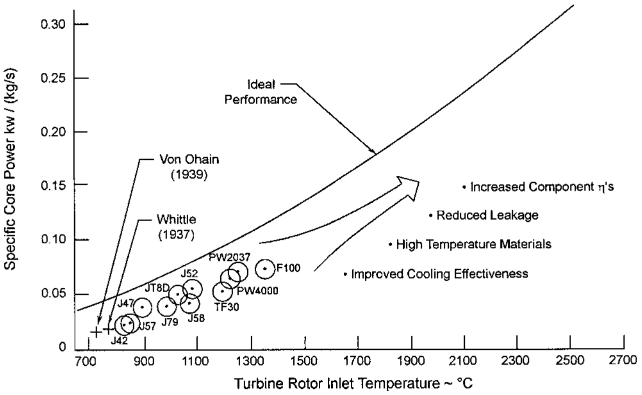

Fig. 1 Increase of core horsepower attained with increased operating temperatures and turbine technologies

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allowed because all of the material characteristics that affect turbine airfoil durability were improved. The material processing improvements resulted in investment cast airfoils produced in equiaxed, directionally solidified, and single-crystal structures. Figure 2 shows the material temperature improvements obtained since 1960. A 100 °C (180 °F) improvement in turbine airfoil materials has been obtained in 25 years. This is a 4 °C (7 °F) improvement per year. To put this into perspective, for a turbine operating at constant operating temperature, the benefit is equivalent to doubling the durability every three and a half years.

Turbine airfoil materials are nickel-base superalloys whose incipient melt temperatures have been increased to 1316 °C (2400 °F). Since 1985, there have been no major breakthroughs in the development of nickel-base superalloys. The fundamental reason is that the incipient melt temperature has slowly approached the melting temperature of the nickel alloys. The melting point of nickel alloys is 1399 °C (2550 °F). There is further room for alloy improvement; however, the complexity of defining the alloy composition has become more difficult. A collaborative effort among the major U.S. gas turbine engine producers is under way to define the ultimate nickel alloy compositions. The goal is to improve the temperature capability another 27 to 42 °C (50 to 75 °F). To obtain increased turbine inlet temperature capability, improved cooling techniques or thermal barrier coatings (TBCs) need to be applied.

Figure 3 illustrates the amount of cooling required in a typical production turbine today. The gas temperature referred to in this figure reflects the maximum inlet temperature to the first-stage turbine vane. This temperature is higher than the average combustor exit temperature because combustor cooling requirements dictate that combustion and dilution processes occur with a minimum length of the burner. This results in a nonuniform turbine inlet temperature. The allowable operating temperature for the metal is about halfway between the maximum gas temperature and the temperature of the cooling flow supplied to the first vane. Also shown in this figure is the relationship of the allowable design metal temperature levels to the incipient melt temperatures. As shown, the allowable metal temperature levels are near the incipient melt point of nickel-base superalloys. In addition, a small increase in operating metal temperatures results in a significant durability decrement, that is, 13 °C (25 °F) produces a two-fold reduction in airfoil durability.

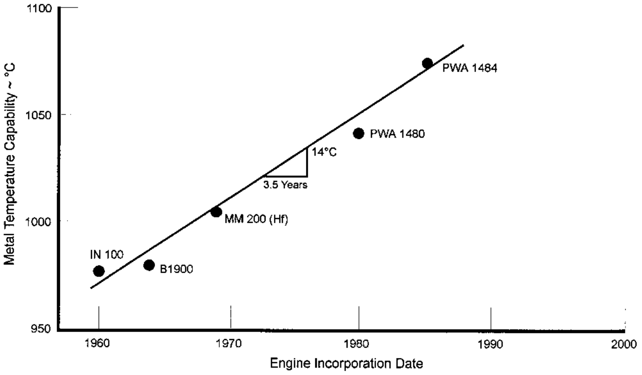


Fig. 2 Turbine blade material temperature improvements

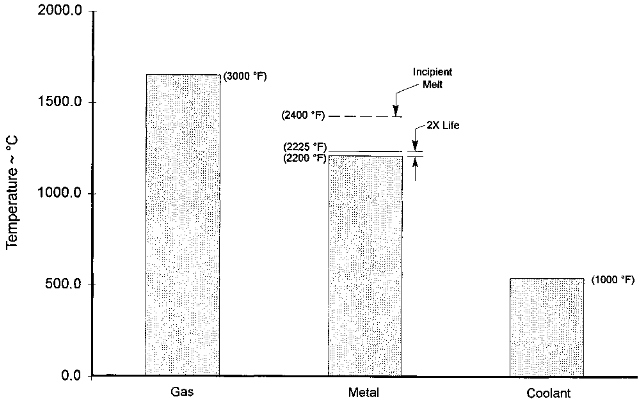


Fig. 3 Typical airfoil cooling requirements for maximum temperature operation

Efficient heat exchangers have been developed to cool turbine airfoils. Initially, simple internal convective cooling designs were employed. Advances in the development of airfoil cooling designs have been achieved by combining high convective cooling efficiencies with film cooling. Figure 4 shows the turbine inlet temperature increases possible with the use of cooled single-crystal turbine blades. An example of this is the F100-PW-220, the cooling configuration shown in Fig. 4, that was proven in accelerated mission testing where more than 10 years of equivalent service was demonstrated. It should be noted that no TBCs were employed in this engine model. However, TBCs were beginning to be introduced into commercial and military products after the F100-PW-220 went into production. Cooling technology improvements will permit higher gas path operating temperatures, similar to the application of TBCs. Over time, small, incremental improvements in materials and cooling design will yield exponential increased gas path temperature capability.

2. Thermal Barrier Coating Design Considerations

2.1 Early Application of Thermal Barrier Coatings

Thermal barrier coatings were initially incorporated on turbine vanes. The benefits of these coatings were documented in back-to-back instrumented engine tests where turbine vanes

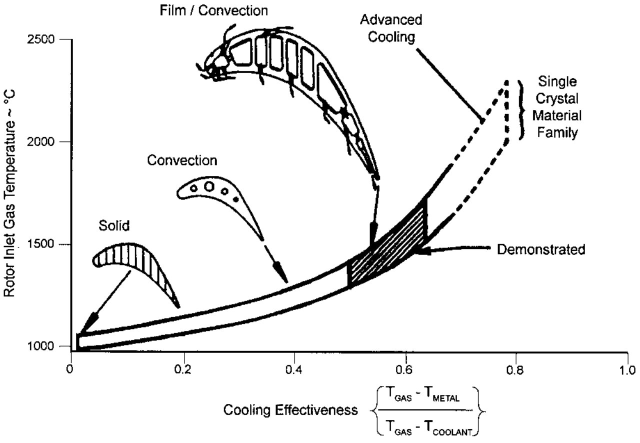


Fig. 4 Dramatic increase in turbine temperature attained with cooling augmented by improved materials

were initially evaluated in an uncoated state. The instrumented vanes were removed from the engine, and TBCs were applied for subsequent testing. Figure 5 shows that the reduction in operating metal temperatures with TBCs is directly proportional to the coating thickness. The thickness was measured by sectioning the airfoils post test, and the data trends were as expected. The insulative benefit was also documented by measuring transient thermal response during a rapid engine acceleration from idle to intermediate power. Figure 6 presents a comparison of the uncoated and coated thermal response during this transient. The coated airfoil thermal response was slower than the uncoated airfoil. This demonstrated that the TBC damped the thermal response of the airfoils to rapid engine acceleration or deceleration transients. The benefit is that the coating reduces the thermal gradients within the metal airfoil. Because the thermal gradients in the metal are smaller, thermally induced stresses and strains will also be smaller, resulting in improved thermal fatigue capability of the substrate material.

Thermal barrier coatings have not been applied to rotating turbine blades primarily due to the increase in load applied to the airfoil, attachment, and disk. Figure 7 dramatically illustrates the forces applied by the rotating blades, excluding their platforms and extended necks. The centrifugal force of a blade without a TBC is on the order of 6364 kg (7 tons). This is roughly equivalent to the weight of a Lockheed F-16 fighter aircraft, and considering that the number of blades on a disk ranges from 50 to 70, poses a very challenging structural design. Thermal barrier coatings and the bond coating applied to the nickel-base superalloy for adherence, result in significant increases in the centrifugal load transferred to the disk. Thermal barrier coatings do not have sufficient capability to support their own load in a rotating turbomachinery application. The load associated with the rotating mass of the coating must therefore be supported by the underlying superalloy structure. The mass of this structure must be increased to maintain acceptable stress levels while supporting the coating dead load. Additionally, attachment and disk masses must also be increased to provide a suitable blade/coating support structure. For rotating turbomachinery applications, it is extremely important to reduce the dead load, which means that thin, low thermal conductivity systems must be developed to maximize the benefit of TBCs.

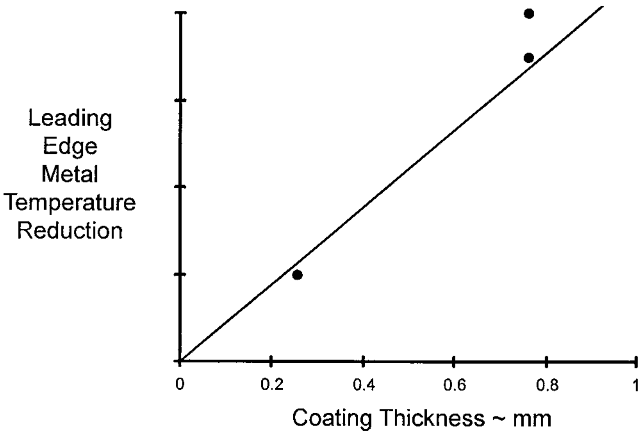


Fig. 5 Documentation of engine data dependency of metal temperature reduction on thermal barrier coating thickness

2.2 Thermal Barrier Coating Benefits

The benefit of TBCs is schematically shown in Fig. 8, where the metal temperature versus the coolant flow rate is represented for an uncoated and a coated airfoil. For a fixed engine cycle, the addition of TBC can be used to improve durability while main-

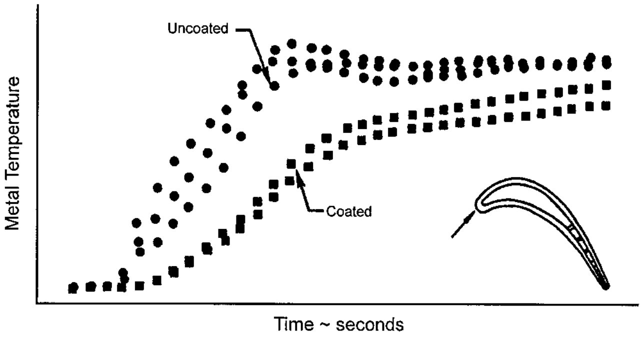


Fig. 6 Transient thermal response damped with thermal barrier coating

Fig. 7 Highly loaded turbine blades

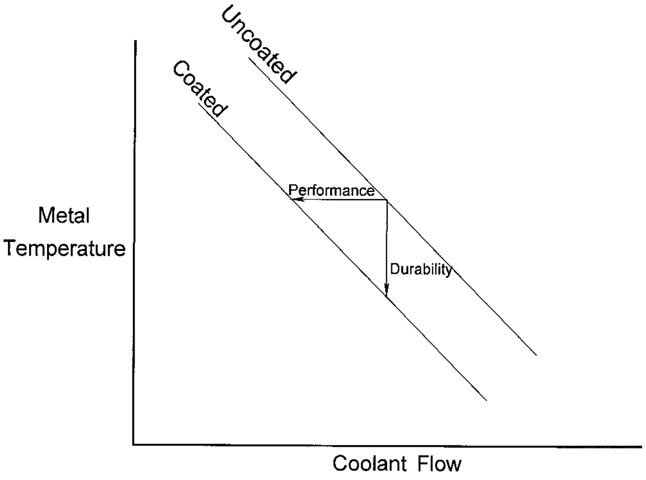


Fig. 8 Thermal barrier coating payoff—reduced airfoil cooling/improved durability

taining constant airfoil cooling rates. In this situation, the airfoil operating metal temperatures are reduced, thus providing increased durability. The other approach is to improve the performance of the engine by increased thrust and reduced specific fuel consumption. In this approach the cooling flow rates to the airfoil are reduced while holding the operating metal temperatures constant. An alternate approach, not shown in this figure, is to maintain cooling flow levels and increase the turbine inlet temperature until the operating metal temperatures are maintained constant. This will provide greater thrust improvement than with the coolant flow reduction approach. The temperature reduction potential is dependent on the superalloy wall thickness and the thermal resistance of the TBC as well as the magnitude of heat flux.

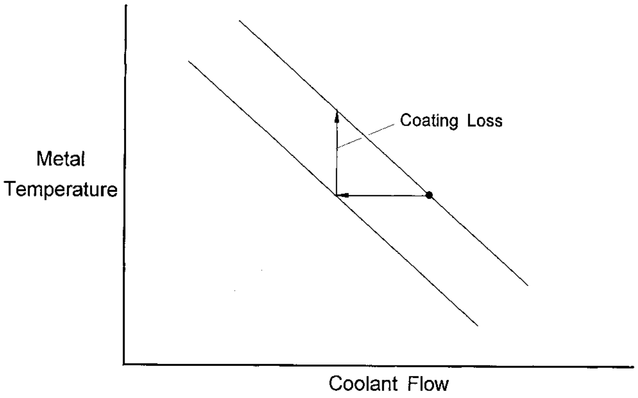


Fig. 9 Thermal barrier coating risk—coating loss reduces life as flow is reduced

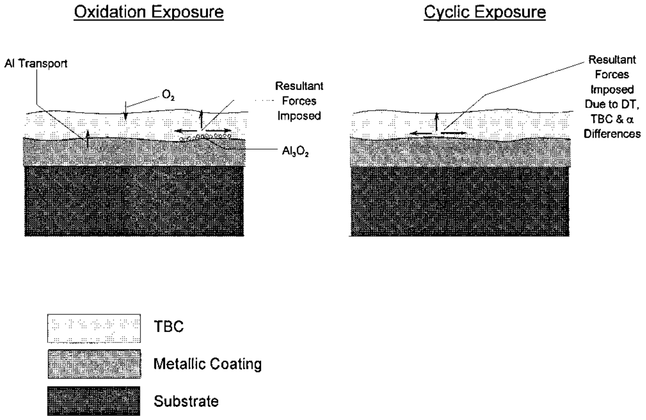


Fig. 10 Similar spallation mechanisms from oxidation and cyclic strain exposure

If TBCs are used for improved engine performance, the integrity of the coating becomes increasingly important because loss of the coatings can result in a reduction of the durability of the airfoil. Figure 9 graphically shows this effect. The loss of coating will result in increased metal temperatures and accelerated loss of durability. Researchers in this field have commonly referred to the need for the development of prime reliant coatings to overcome the accelerated damage of the coatings if spallation were to occur. The issue here is not the development of a prime reliant coating, but rather the development of a design prediction system for determining when coating loss will occur. This enables design and overhaul trades to be made by defining inspection intervals that coincide with the projected coating spallation. This yields the largest performance benefit to the engine system while potentially increasing overhaul costs. Figure 3 shows that the operating metal temperatures are near the incipient melting point of the superalloys. Therefore, if the maximum performance advantage is utilized with TBCs, the metal temperatures could exceed the incipient melting point of the alloy in a failure scenario. This would result in rapid deterioration of the airfoil. A design prediction system could also allow tailoring of the airfoil design to maximize durability for local spallation; however, this approach would require cooling flow to be increased locally to provide a more robust design.

2.3 Thermal Barrier Coating Failure Mechanisms

There are several mechanisms by which TBCs can spall from the turbine airfoil. These are from oxidation, fatigue, and particle

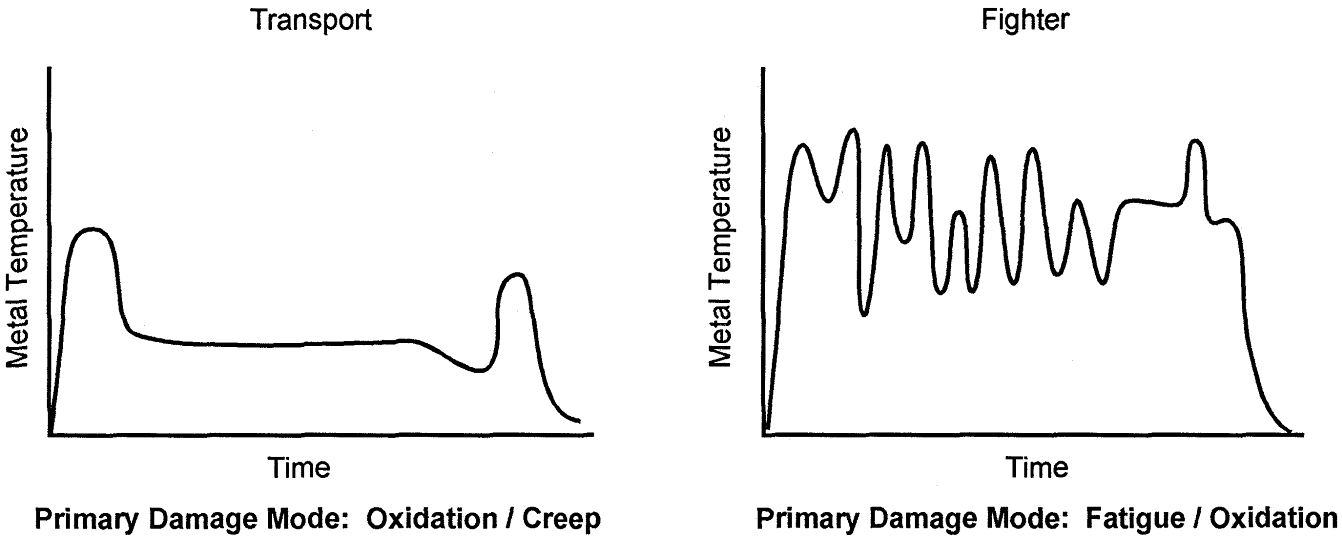
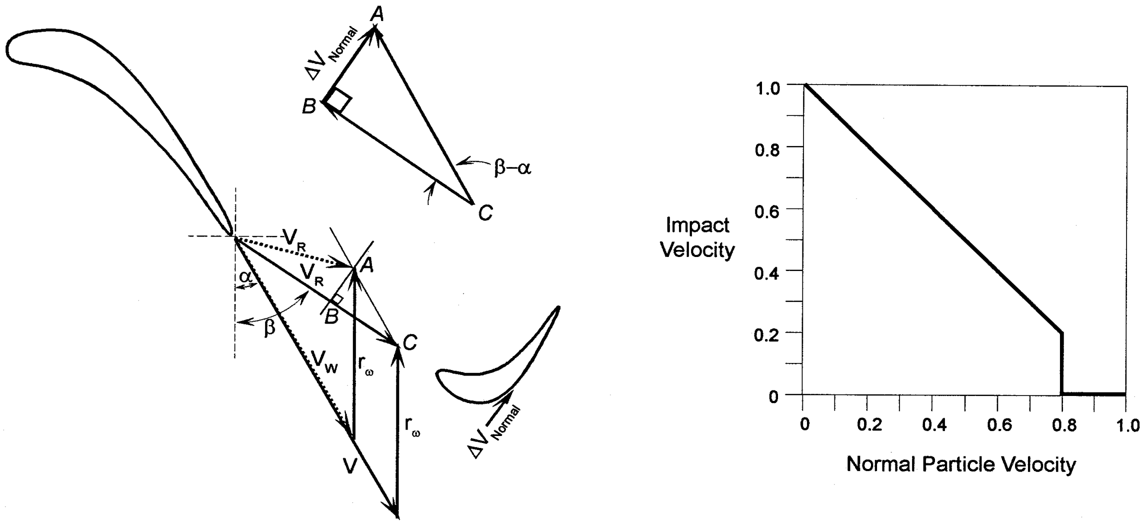


Fig. 11 Different damage modes produced by engine usage

erosion. Figure 10 shows that the applied forces that cause coating spallation are similar for both oxidation and fatigue; that is, the resultant forces at the interface between the TBC and the metallic bond coat are similar in nature, but the mechanisms are different. Thermal barrier coatings in use today are oxygen permeable, and therefore alumina may form with aluminum-bearing bond coats. The alumina scale produces a volumetric expansion above the bond coat, which may cause delamination leading to the spallation of the TBC. Under engine transient loading, cyclic stresses are introduced at the bond interface due to the combination of applied thermal gradients and thermal coefficient of expansion mismatch. The cyclic stresses can also result in coating spallation as demonstrated under laboratory testing sponsored by the National Aeronautics and Space Administration (NASA). It is, therefore, important that both oxidation and cyclic damage be recognized and investigated during the selection and optimization of new TBC systems. Future systems need to have a dual-role capability for transports and military engine products by recognizing the difference in engine usage, as shown in Fig. 11.



V = Gas Velocity
V_W = Particle Velocity
ΔV_{NORMAL} = Impact Velocity
rω = Rotational Velocity

Fig. 12 Particle erosion most prevalent on blade suction side thermal barrier coating

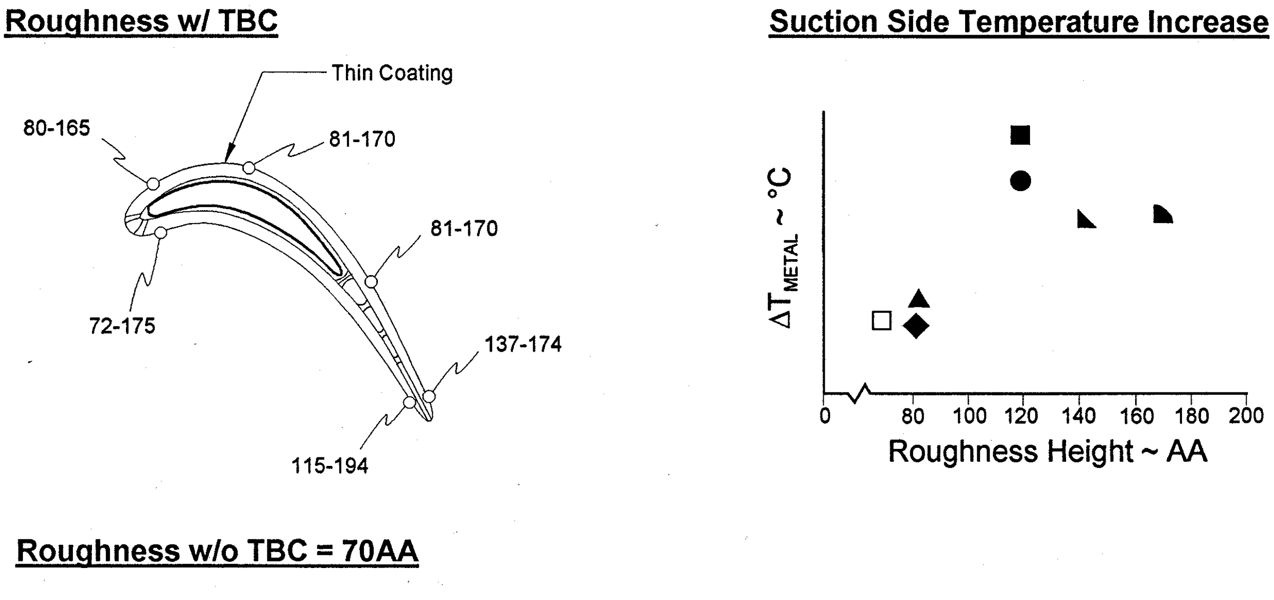


Fig. 13 Increased operating metal temperatures produced by increased surface roughness

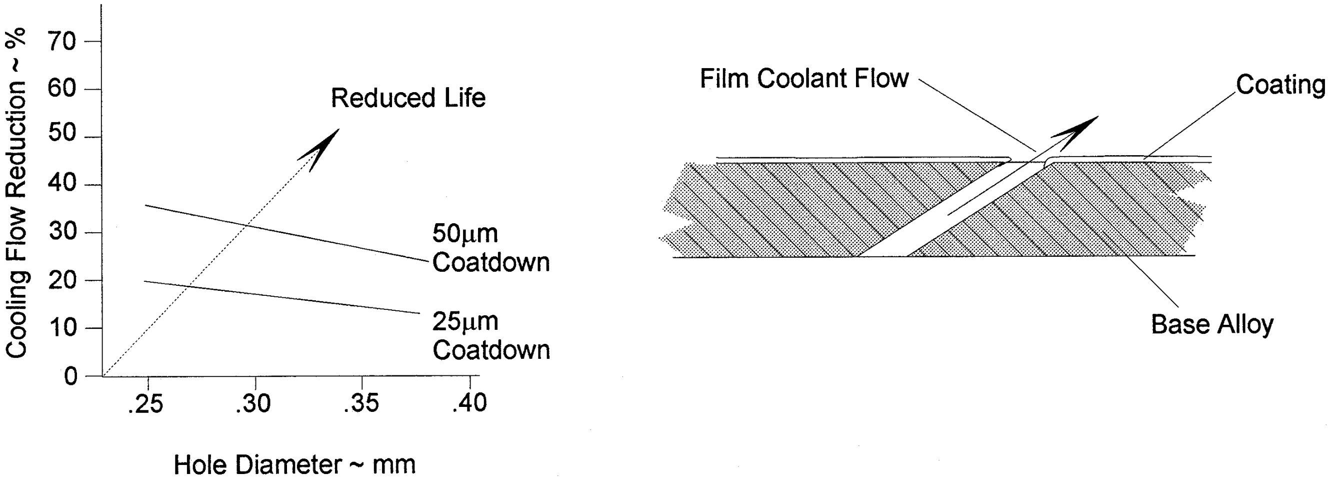


Fig. 14 Impact of coating application on flow control and durability

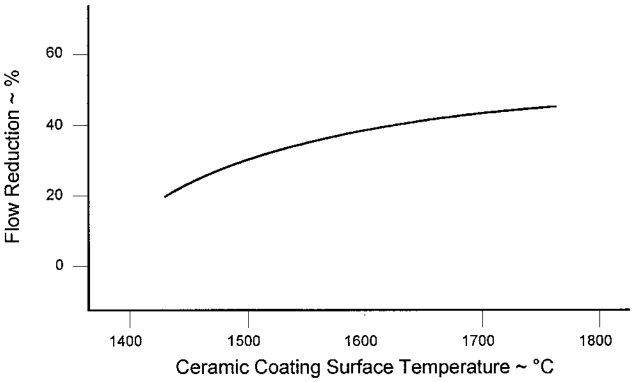


Fig. 15 Large potential of high temperature, thin thermal barrier coating system

Particulate erosion poses another concern for TBC durability. These particles can be injected at the engine inlet, or they can be derived from abradable materials released during a compressor rub. These particles enter the turbine at a low axial velocity. Because they are more dense than air, inertial forces hinder their acceleration in the vane passage, and as a result, they exit the vane passage with a swirl velocity that is less than the freestream gas. Therefore, these particles impinge on the vane leading edge at low velocities but impact the suction side of the blade with high relative velocities. This is readily understood when the velocity triangles of a typical turbine blade are examined with particles exiting the vane at reduced swirl velocities relative to the mainstream gas (Fig. 12). The impact zone for particulate erosion is downstream of the leading edge on the suction surface of the blade. It is important that the erosion resistance of new coating systems be maximized to ensure that thermal protection is not diminished by erosion effects.

2.4 Thermal Barrier Coating Deposition Techniques

A TBC was applied using plasma spray, electron beam physical vapor deposition, or chemical vapor deposition processes. The different processes produced dissimilar surface roughness levels. The surface roughness was significantly greater for the plasma spray process. Increased roughness resulted in higher aerodynamic losses as well as increased heat transfer to the airfoil. Figure 13 presents a comparison of the measured metal temperature from an uncoated vane with engine data obtained on turbine vanes with a plasma spray TBC. Both the concave and convex surfaces of the vane were instrumented with thermocouples imbedded into the metal. Plasma spray deposition is a line-of-sight process. Because the vanes were cast as a pair, a uniform thickness of TBC could not be achieved for the convex surface of the vane, which was shielded by the concave surface of the adjacent vane. The result was a thin coating application with increased local roughness on the convex surface on one vane in the pair. As shown in Fig. 13, these combined effects caused the actual metal temperature beneath the coating to increase in this area. The objective in developing deposition processes should be to obtain uniform thicknesses of coating with a surface roughness no greater than the substrate.

2.5 Thermal Barrier Coating Process Design Considerations

Turbine airfoils residing in the highest heat flux regions typically use film cooling in conjunction with internal convective cooling. The principle of film cooling is to discharge spent cooling air out on the airfoil surface to provide a buffer between the airfoil surface and the hot mainstream gas flow. Because the heated cooling air is significantly cooler than the mainstream gas flow, reductions in the heat load and metal temperatures are obtained. However, to maximize the film cooling benefit, small hole sizes are used to distribute the convectively spent cooling flow along the entire airfoil surface. The meter area of these small film holes regulates the amount of cooling flow used in the airfoil for both convective and film cooling. Therefore, any closedown of these holes by the deposition of a TBC can result in large cooling flow reductions and increased part-to-part variations, which deleteriously affect the durability of the coated airfoil. Figure 14 shows the flow reduction obtained by coating deposited on the surface of the cooling hole (termed coatdown) as a function of hole diameter. This figure demonstrates that a robust process is required to minimize the amount of coating deposited within a cooling hole. This again indicates that a low thermal conductivity TBC, requiring reduced thickness relative to today's state-of-the-art coatings, is the logical direction to focus development efforts. A thinner coating will naturally result in less potential deposition within cooling holes.

The surface temperature capability of TBCs needs to be increased. Recommended maximum operating temperature limits are imposed on the designer to maintain the stability of ceramic matrices used in current state-of-the-art coatings. However, to maximize the potential benefit TBCs can provide, a focused effort is required to increase the stability of the ceramic composition at elevated temperatures. The potential cooling flow reduction as a function of the maximum ceramic surface temperature is shown in Fig. 15 for a first-stage turbine vane application operating at stoichiometric conditions. This figure shows that large gains can be made with moderate temperature improvements. However, as the temperature capability increases, an associated reduction in the thermal conductivity is desired to minimize the coating thicknesses for turbine vanes, especially the rotating turbine blades. The challenge and benefits of such a system are unlimited.

3. Conclusions

Significant advances in gas turbine propulsion capability can be obtained by incorporating the synergistic effects of improved materials, cooling, and advanced thin TBCs into the next generation of turbine airfoils. However, to maximize the potential, there needs to be a focused and integrated technological development effort that combines the talents and expertise of airfoil designers with materials, ceramic, and production engineering. To obtain success, calibrated life-prediction methods must be developed to optimize the airfoil design. This must be accomplished with the minimum amount of coolant flow while ensuring that the protection provided by a TBC will provide the durability expected.