Optimization of Heat Transfer on Thermal Barrier Coated Gas Turbine Blade

Abdul Aabid\textsuperscript{1}, and S. A. Khan\textsuperscript{2}
Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia

Corresponding author: \textsuperscript{1}aabidhussain.ae@gmail.com, \textsuperscript{2}sakhan06@gmail.com

Abstract- In the field of Aerospace Propulsion technology, material required to resist the maximum temperature. In this paper, using thermal barrier coatings (TBCs) method in gas turbine blade is used to protect hot section component from high-temperature effect to extend the service life and reduce the maintenance costs. The TBCs which include three layers of coating corresponding initial coat is super alloy-INCONEL 718 with 1 mm thickness, bond coat is Nano-structured ceramic-metallic composite-NiCoCrAIY with 0.15 mm thickness and top coat is ceramic composite-La\textsubscript{2}Ce\textsubscript{2}O\textsubscript{7} with 0.09 mm thickness on the nickel alloy turbine blade which in turn increases the strength, efficiency and life span of the blades. Modeling a gas turbine blade using CATIA software and determining the amount of heat transfer on thermal barrier coated blade using ANSYS software has been performed. Thermal stresses and effects of different TBCs blade base alloys are considered using CATIA and ANSYS.

1. Introduction
The blades are responsible for extracting energy from the elevated temperature, high pressure gas produced by the combustor. To survive in this difficult environment, turbine blades often use exotic materials like super alloys and many different methods of cooling, such as internal air channels, boundary layer cooling, and thermal barrier coatings. Thermal barrier coatings (TBCs) as a kind of temperature-resistance material have been widely applied in super elevated temperature components in aircraft engines due to its low thermal conductivity. Prediction of the stress distribution on a 3D turbine blade coated with thermal barrier coatings (TBCs) plays a key role in analyzing the failure of TBCs [1]. Due to their low thermal conductivity, a temperature drop can be up to 200 °C through thermal isolation in TBCs as well as an inner cooling system [2, 3]. Thermally grown oxide on the stress distribution and evolution under cyclic thermal loading, a three-dimensional finite element model of a turbine blade with thermal barrier coatings is developed, in which the coating deposition process and elevated temperature behavior are considered [4].
The aging and degradation mechanisms of a present standard TBC system (AM1 single crystal super alloy / NiPtAl bond coat / 8YPSZ EB-PVD top coat), advanced thermal barrier systems operating at higher temperatures and for very long durations (commercial aircraft applications for example) needs further developments [5]. Effects of Compositional Changes on the Performance of a TBCs System; As part of continuing effort to develop thermal barrier systems for advanced aircraft gas turbine engine components, systems consisting of Ni-base bond coatings containing about 16Cr, 6Al, and from 0.15 to 1.08Y (all in wt.%) and zirconium oxide layers containing from 4.0 to 24.4Y$_2$O$_3$ (in wt.%) were evaluated. The data indicate that the best thermal barrier systems consisted of combinations involving the Ni-16.4Cr-5.1Al-0.15Y and Ni-17.0Cr-5.4Al-0.35Y bond coatings and the 6.2Y$_2$O$_3$ and 7.9Y$_2$O$_3$ (all in wt. %) stabilized zirconium oxide layers. In furnace, cyclic tests these thermal barrier systems withstood 1500 1-hour cycles between 990° - 280° C and over 100 1-hour cycles between 1095° - 280° C. In a natural gas-oxygen torch rig these systems on solid specimens withstood approximately 590 to 790 1-hour cycles between 1200° - 100° C. On air-cooled blades, the NiCrAl-O.15Y/ZrO-6.2Y$_2$O$_3$ (in wt. %) at 1580° C surface temperature and the NiCrAl-0.35Y/ZrO-7.9Y$_2$O$_3$ (in wt. %) at 1550° C surface temperature withstood over 1300 and 1500 1-hour cycles without failure, respectively [6]. Non-destructive evaluation of as-sprayed APS TBCs was carried out by pulsed thermography. The results showed that pulsed thermography can be employed to evaluate the quality [7].

The restrictions of phase compatibility with the thermally grown aluminum oxide and the TBC coating itself place severe constraints on the possible luminescence sensor materials and suggest that the best chromophores are likely to be those that are incorporated into the crystal structure of the thermal barrier coating. For both YSZ and the rare-earth pyrochlore coatings, rare-earth dopants can serve as chromophores and several concepts for visualization and quantitative luminescence sensing are demonstrated based on the optical properties of these coating materials and the luminescence properties of the rare-earth dopants. For temperature sensing, the choice of rare-earth dopants is much more restrictive as will be described elsewhere [8]. TBCs have evolved from the laboratory to negligible risk turbine section application and then on to an integral part of engine design. These coatings applied to advanced air-cooled, super alloy components will be the materials system of choice in advanced engines for the foreseeable future. Even as non-super alloy components gradually came into service, these new materials will still require the protection of TBCs [6]. The distribution patterns of existing elements both in the matrix of base alloy and in the successive coatings of used and refurbished turbine blades were determined by scanning proton microscopy. The results of these analyses revealed the cluster distribution of rather enormous amounts of Si in the refurbished coating layer. The cluster distribution of Si, which could reduce the lifetime of the component, is more likely due to the preparation of blades by sandblasting prior to the deposition of the final protective layer [9].

The problem is to study steady state conjugate heat transfer through different layers of TBC and to find the best TBC combination of different layers.

2. Approach
Using ANSYS parametric design language tool the different layers of TBC over a blade base super alloy is modeled and boundary conditions are defined and analyzed. The results obtained from the computation compared with the combination of different layers of TBC and best combination for the
TBC is determined. The following method used for simulation as shown in below figure 1.

![Figure 1. Method for Simulation](image)

The different layers of TBC for this case are listed below. The thickness of the respective layer along with their thermal conductivities is mentioned. The film co-efficient and the temperature of the turbine inlet gas is 2028 w/m2k and 1373 K.

| Coating layers                | Thickness [mm] | Thermal conductivity (W/m K) |
|------------------------------|----------------|-----------------------------|
| Convective Element [Hot Gas] | 0.01           | -                           |
| Top Coat [La₃Ce₂O₇]          | 0.15           | 0.6                         |
| TGO                          | 0.01           | 4.0                         |
| Bond Coat [NiCoCrAlY]        | 0.09           | 17.0                        |
| Super Alloy [Inconel 718]    | 1.0            | 25.0                        |

3. Gas Turbine Blade Material

Gas turbine blade materials have always been a major concern and which are highly capable to withstand elevated temperature service and hence the engine efficiency; for the materials with elevated temperature to weight ratio helps in weight reduction [10–13].

3.1. Inconel

Inconel is a family of austenitic nickel-chromium-based super alloys. Inconel alloys are oxidation and corrosion resistant materials well suited for service in extreme environments subjected to pressure and heat.

3.2. Thermal Barrier Coating

Progress in Gas Turbine Engine (GTE) manufacturing is continuously linked with a rise of operating
temperature and stresses of engine gas path elements, especially the turbine parts. To provide simulation of loading conditions for the hot engine parts with a TBC under service conditions, the test procedure shall ensure the possibility of cyclic surface heating of the object under testing (simulating its heating in hot gas flow) up to temperatures of 11500 °C and more at heating rates of 150-2000 °C/s and subsequent cooling [14].

3.3. Structure of TBCs

Generally, TBC is a two-layer’s system which incorporates about 250 μm thickness layer of ceramic top coating applied to the outer surface of the substrate and about 150 μm thickness underlying of metallic bond coating. The metallic bond coating performs two functions:

- To provide oxidation resistance and
- To adhere the ceramic to the super alloy substrate physically and chemically.

The oxide that is commonly used is Zirconia oxide (ZrO$_2$) and Yttrium oxide (Y$_2$O$_3$). The metallic bond coat is an oxidation/hot corrosion resistant layer. The bond coat empirically represented as MCrAlY alloy.

Where;
- M - Metals like Ni, Co or Fe.
- Y - Reactive metals like Yttrium.
- Cr-Al - Base metal.

Figure 2. Structure of thermal barrier coating

Bond coat: The bond coat is typically a metallic layer made of a Nano-structured ceramic-metallic composite-NiCoCrAlY, the layer to the metal substrate and is responsible for generating the second
coating layer of thermally grown ceramic oxide, which occurs when the coating is subjected to an elevated temperature.

When Nano-particles of aluminum oxides and nitrides are distributed throughout the bond coat or along its surface, the formation of thermally grown oxides is catalyzed. This ceramic layer is responsible for forming a uniform, thermally protective barrier by acting as an oxygen diffuser which prevents the substrate from becoming thermally oxidized.

**Top coat:** The last layer of the coating is the ceramic top coat, which is made of top coat is ceramic composite-La$_2$Ce$_2$O$_7$. The top coat protects the substrate by keeping the other coating layers at a lower temperature than the surface.

3.4. **Fabrication Method**

Method used to find the presence of TBC is Coloration method

- Masking
- Degreasing
- Vapour blasting
- Heating the blade at 650 degrees Celsius for 1 Hr.

3.5. **Heat Transferred Blade**

Heating the blade at 650 degrees Celsius for 1 Hr

![Figure 3. Turbine blades before heat treatment](image1)

![Figure 4. Turbine blades after heat treatment](image2)

In figure 3 and figure 4 are Illustrates the two-different heated blade. The difference between the two blades are colour slightly changed after one hour of heating and the property of the material is also
changed. The material temperature resisting capacity is observed and it is quite good compared to the normal blade. The selection of material for three layers of coating which chosen and it is affected.

3.6. Air Plasma Method (APS)
The APS process can obtain high deposition rates and the capability to spray varied geometries. Plasma spraying also allows composition control and can produce coatings with high mechanical strength and durability. In the plasma spraying process, a high intensity arc is operated between a stick-type cathode and a nozzle-shaped water-cooled anode. Gas, introduced along the cathode, is heated by the arc to plasma temperatures and then exits the anode nozzle as a plasma jet. Powder injected into the plasma jet is accelerated and heated to a molten state. As the molten particles in the jet strike the selected substrate, they form splats that build up, particle by particle, into a co-mating. Among the many spraying parameters, the standoff distance, powder size distribution, power level, and arc gas selection strongly influence the microstructure of coatings. The particle velocity at substrate impact is governed by the plasma velocity and density, which are dependent on the type and volume of the gases being used and the energy being input to the gases [15]. The figure 5 shows fully coated turbine blade.

![Coated turbine blades](image)

**Figure 5.** Coated turbine blades

4. Analytical Study of Heat Transferred

4.1. Hot Air Blade Surface (Convective Heat Transfer)

\[ Q = h_c A dT \]  
\[ Q = \text{Heat transferred per unit time (W)} \]
\[ A = \text{Heat transfer area of the surface} \]
\[ h_c = \text{Convective heat transfer coefficient of the process, W/m}^2\text{K or W/m}^2\text{°C} \]
\[ dT = \text{Temperature difference between the surface and the bulk fluid (°K / °C)} \]
\[ h_c = 10.45 - V + 10 \times V^{0.5} \quad (2) \]

V= the relative speed of the object through the air.

4.2. **TBC to Blade Base Alloy (Conduction Heat Transfer)**

\[ HT = \frac{Q}{\dot{t}} = \frac{(KA(T_{\text{hot}} - T_{\text{cold}}))}{d} \quad (3) \]

\[ dT = T_{\text{hot}} - T_{\text{cold}} \quad (4) \]

K= Thermal conductivity
A= Surface area of the blade
d= TBC Thickness

4.3. **Faurier’s Law**

\[ q = -KA \frac{dT}{dx} \quad (5) \]

q = Heat flow
K = Thermal conductivity
A = Cross sectional area
\[ \frac{dT}{dx} = \text{temperature gradient in the direction of flow.} \]

5. **Results and Discussion**

5.1. **Outlines for Temperature Distribution**

**Figure 6. Temperature Distribution**

Figure 6 illustrate the outline of temperature distribution on the sample of coated blade, as per the experimental work, applied to the three-different material coat for validation purpose in simulation and observed with the different temperature variation. In simulation, our aim is to find out the temperature effect on coated material blade and figure 5 is only modeled as per the coated material thickness not with material blade dimension.
5.2. **Heat Transfer Analysis by Changing Coating Material**

Case I: Top Coat \([\text{La}_2\text{Ce}_2\text{O}_7]\) and Super Alloy \([\text{Inconel 718}]\)

When applied a \([\text{La}_2\text{Ce}_2\text{O}_7]\) and Inconel 718 on the top coat the temperature variation on the blade which resist up to 1400k which is good for normal blade.

Case II: Top Coat \([3\text{YSZ}]\) and Super Alloy \([\text{Chromium Steel}]\)

The heat transfer on the coated material blade with 3YSZ and Chromium Steel, it is seen that variation in the temperature is from minimum temperature 500k to the maximum temperature up to 1400k.

Case III: Top Coat \([3\text{YSZ}]\) and Super Alloy \([\text{Inconel 625}]\)

Super alloy the to Inconel 625 and it is observed that the change from the super alloy the to Inconel 625 from Chromium Steel the temperature changes are appreciable, however, the range of the temperature is similar as discussed earlier but variation of middle temperature is different.

Case IV: Top Coat \([\text{La}_2\text{Zr}_2\text{O}_7]\) and Super Alloy \([\text{Inconel 718}]\)

It is coated with \([\text{La}_2\text{Zr}_2\text{O}_7]\) and Inconel 718 and it has been observed that from the previous case as well as the present case the temperature changes is almost in the same range.

5.3. **Comparison of all Cases**

![Figure 7. Nodal temperature distribution for all cases](image)

Figure 7 illustrates the comparison of all four cases which has different material coating for top coating and super alloy. From the results, it seen that the coating of the gas turbine blade can resist the maximum temperature up to 1400 k and it is good for the case of thermal barrier coating using air plasma method on gas turbine blade. It is also seen that the TBC at node five is 444.02 K. Experimental work of this case still in progress and results which observed from the test in thermal conductivity test which is the TBC of temperature 450K and in the simulation case it is 444.02 K.

6. **Conclusions**

Based on the above discussions we can draw the following conclusions:

* Heat Transfer Analysis/simulation was performed by using ANSYS Mechanical APDL software by changing the coated material in four different cases.
• Out of these four cases, the finest result of coated gas turbine blade could be done by using air plasma method with three different layer initial coat-Inconel 718, bottom coat-NiCoCrAlY and top coat-La$_2$Ce$_2$O$_7$.

• When thermal conductivity test was performed the temperature was 450K. From the analytical results, it was concluded that the result of case one has performed well because of the TBC temperature at node number five is very less i.e. 444.02 K compared to other cases. Hence this combination of TBC on gas turbine blade is best suited for higher operating temperature.

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