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Geometric Effects of Thermal Barrier Coating Damage on Turbine Blade Temperatures

Shane Colon

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GEOMETRIC EFFECTS OF THERMAL BARRIER COATING
DAMAGE ON TURBINE BLADE TEMPERATURES

A Thesis

Submitted to the Faculty

of

Embry-Riddle Aeronautical University

by

Shane Colon

In Partial Fulfillment of the

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of

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by

Shane Colon

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SYMBOLS

c_p	Specific heat capacity
h	Heat transfer coefficient
k	Thermal conductivity
LM	Larson Miller Parameter
M	Mach number
Pr	Prandtl number
q''	Heat flux
R	Thermal resistance
Re	Reynolds number
St	Stanton number
T	Temperature
t	Time
TR	Temperature ratio
U	Velocity
w	Width
x	Length
y	Height
δ	Boundary layer thickness
ρ	Density
μ	Dynamic viscosity
ν	Kinematic viscosity

ABBREVIATIONS

HTC	Heat transfer coefficient
TBC	Thermal barrier coating
TGO	Thermally grown oxides
YSZ	Yttria stabilized zirconia

ABSTRACT

Colon, Shane MSAE, Embry-Riddle Aeronautical University, April 2019. Geometric Effects of Thermal Barrier Coating Damage on Turbine Blade Temperatures.

Thermal barrier coatings (TBC) found on turbine blades are a key element in the performance and reliability of modern gas turbines. During the life of the turbine components, the TBC surface may be damaged due to manufacturing imperfections, handling damage, service spalling, or service impact damage, producing chips in the coating. While a chip in the TBC coating is expected to cause an increase in airfoil temperature, it is unknown to what degree the blade will be affected and what parameters of the chip shape affect this result. The goal of this preliminary study is to identify the major driving parameters that lead to the increase in metal temperature when TBC is damaged, such that more quantitative estimates of blade life and refurbishing needs can be made.

A 2-D computational Conjugate Heat Transfer model was developed; fully resolving the hot gas path and TBC, bond-coat, and super alloy solids. The most sensitive driving parameters were identified to be the chip width and Mach number. In cases where the chip width reached 16 times the TBC thickness, temperatures increased by almost 30% when compared to the undamaged equivalents. While the Reynolds number based on the distance from the leading chip edge was deemed negligible, the Reynolds number based on the chip width was found to have a noticeable impact on the blade temperature. In conclusion, this study found that chip edge geometry was a negligible factor, while the Mach number, chip width, and Reynolds number based on the chip width had a significant effect on the total metal temperature.

1. Introduction

The gas turbine has become an essential machine that powers everything from the modern jet liners to homes across the world. These engines can take many forms depending on their applications. For instance, the turbofan, which is a variation of the classical turbojet, has a large fan that is driven to efficiently produce thrust. Another example, the turboshaft, is coupled to a large driveshaft to power electrical grids. While applications of this technology can vary widely, the internal thermodynamic cycle, the Brayton cycle, is the common denominator among all of them, which is shown in Figure 1.1 (Moran, Shapiro, Boettner, & Bailey, 2011).

Figure 1.1 (a) Example of the Brayton cycle in a turbojet. (b) T-s diagram an ideal Brayton cycle (Moran, Shapiro, Boettner, & Bailey, 2011).

When analyzing the Brayton cycle, it can be shown that increasing the inlet turbine temperature, T_3 , can lead to improved thermal efficiency, η_{th} (Han, Dutta, & Ekkad, 2000).

$$\eta_{th} = 1 - \frac{T_4}{T_3} \quad (1)$$

However, there is a limit as to how hot the engines can operate before internal

components begin to fail. Elevated temperatures can alter the original grain structure of turbine components which in turn can reduce the diffusion of creep (Carter, 2004). The major thermal limitations are engine materials, particularly in the hot section of the engine, such as the combustor and the high-pressure turbine. Today's engines see inlet turbine temperatures of more than 1900 K. However, the superalloy material of the turbine blade will begin to soften around 1500 K. To mitigate this limitation, various cooling techniques are employed including internal blade cooling, external film cooling, and ceramic thermal barrier coatings (Bunker, 2017). Internal blade cooling bleeds air from the compressor section of the turbine and runs the air through internal channels in the turbine blade. Film cooling takes this process a step further by expelling the bleed air through small holes located around the turbine blade to create a cool film layer. Thermal barrier coatings (TBC) are applied to metal turbine blades to act as a thermal insulator. The ceramic coating has a low thermal conductivity, thus reducing the total heat flux being applied to the turbine blade.

TBC's originally entered service as a means of protecting both turbine engine components and rocket nozzles. The earliest development of TBC's were frit enamels originally designed for use in aircraft engines (Miller, 1997). One of the most notable early applications of TBC's can be traced back to the X-15 hypersonic test plane in the 1960's, which used a flame sprayed coating on the interior of the rocket exhaust nozzle. The more common plasma-sprayed TBC's were later introduced in the 1970's. Additional development of TBC technology was accomplished due the Aircraft Energy Efficiency program (Kinney, 2017). The program was an initiative to increase aircraft engine efficiencies in response to the 1975 energy crisis. The outcome of the program led

to increased turbine performance partially due to advancements in application techniques of TBC's in the hot turbine sections.

During regular service life of the engine, the TBC will wear due to elements, such as spallation from thermally grown oxides (TGO), damage from manufacturing imperfections, handling damage, or service impact damage. An example of this damage is identified in Figure 1.2 where a sizeable chip can be seen in the TBC layer of turbine blade.

Figure 1.2 Industrial turbine with a large TBC chip (Nagy & Lafleur, 2018).

Damaged blades undergo inspection from repair specialists who are tasked with the challenge of determining if repairs are required. This can potentially lead to premature servicing of the blade if it is sent for repair too early or worse, possible blade failure if it is left operating. There is a potential to examine the heat transfer effects of TBC chips to evaluate an estimate in blade life and thus the need for repair. This study is a preliminary attempt to quantify the localized temperature increase in the turbine blade at the location of the TBC chip.

2. Literature Review

2.1. Thermal Barrier Coatings

The TBC is a supplemental element to the turbine cooling system. TBC's provide lower turbine blade temperatures, which ultimately lead to increased service life of hot section parts. The most common material used for these coatings are yttria stabilized zirconia (YSZ) that can be augmented with compounds, such as alumina or CeO_2 , to alter the thermal and structural characteristics of the coating (Cao, Vassen, & Stoevers, 2003). Thermal conductivities of YSZ coatings can vary depending on the composition but typically fall below $1.0 \text{ W/m}^*\text{K}$ (Łatka, et al., 2012). TBC coatings are applied with one of two methods—plasma spray (PS) or electron-beam physical vapor deposition (EB-PVD). PS applications heat powdered material into a plasma and spray the plasma onto the part. EB-PVD vaporize an ingot of the coating material which then forms as a solid barrier on the part. The major difference between the two application techniques are the consistency of the grain structure with EB-PVD being smoother and less porous as compared to PS. To aid in TBC adhesion, a metallic bond coat is typically applied to the metal substrate prior to the TBC application. This layer often consists of a MCrAlY compound with some combination of Ni or Co as the base metals (Eds. & T.I-P, 2014).

The mechanical properties of TBC's lead to unique forms of failure, including cracking from thermal gradients and spallation from TGO's. The formation of TGO's creates a layer of α -alumina between the bond coat and TBC, which causes internal compressive stresses in the TBC (Shillington & Clark, 1999). During cooling, the α -alumina is replaced with spinel and α -chromia, causing spallation in the TBC layer. One study has shown that concentrations of Zr can produce rapid growing TGO's that can

further decrease the cyclic lifetime of the TBC (Subanovic, et al., 2009). Thermal cycling is known to be a major contributing factor to TBC life. One study attempted to identify the effects of temperature and thermal cycling on TBC delamination (Shin, et al., 2011). By testing TBC specimen at two different temperatures, the delamination area was recorded after each cycle. The concluding results showed that modest increases in temperature could significantly accelerate the delamination process of the TBC. Elements such as large thermal gradients within the TBC layer have also been shown to significantly reduce the thermal cycle life of the coating (Dong, et al., 2015). These characteristics of TBC's can create severe consequences, including decreased stage performance or even engine failure. In an analysis attempting to identify the cause of failure of a military aircraft engine, fractured turbine blades were examined for possible evidence of wear and degradation (Kumari, Satyanarayana, & Srinivas, 2014). It was found that the first stage blades developed large TGO's due to pitting in the TBC layer. This eventually led to delamination of the TBC, ultimately initiating fatigue cracks in the blade material. It was speculated that the broken pieces of the first stage impacted the subsequent turbine stages resulting in a cascading effect of additional broken components. This study highlights the need for adequate thermal protection to not only ensure longevity of the parent component, but also the safety of other areas of the engine. While this analysis shows the repercussions of TBC damage, it does not identify how long or to what degree the metal substrate was exposed to elevated temperatures.

Much of the current literature thoroughly focuses on the failure mechanisms in TBC's but has neglected to identify thermal effects on the parent component. The objective of this study will be to address this gap in the literature.

2.2. Surface Roughness

TBC's have a larger surface roughness than the metal substrate they are being applied to (Bons, Taylor, McClain, & Rivir, 2001) and that roughness increases throughout service due to wear and pitting (Tarada & Suzuki, 1993). It has been shown that excessively rough surfaces can impart a penalty on turbine performance and thus must be considered in a heat transfer analysis (Forester, 1966).

Correlations for Nusselt number show that HTC is a function of Re such as in the Chilton-Colburn analogy for turbulent over a flat plate.

$$Nu = \frac{hx}{k} = 0.0296 Re_x^{\frac{4}{5}} Pr^{\frac{1}{3}} \quad (2)$$

Therefore, an increase in Re would result in an increase in HTC. Additional HTC augmentation is found in the Reynolds-Colburn analogy for Stanton number, St (Holman, 2010).

$$St = \frac{h_x}{\rho c_p U_\infty} = \frac{C_f}{2 Pr^{2/3}} \quad (3)$$

The analogy shows that the friction coefficient and HTC are directly proportional for turbulent flow over flat plate. In one study, the HTC of a flat metal plate was compared to plates with varying TBC roughness. (Bunker, 2003). The smoothest TBC surface experienced minimal increase in HTC with no noticeable effects from changes in Re . As the TBC surface roughness increased, the HTC became more sensitive to Re , especially when $Re > 1E+06$. Another study measured and analyzed the surface roughness of over 100 used turbine components, of which 15% of them had a TBC (Bons, Taylor, McClain, & Rivir, 2001). The TBC was determined to be naturally rough, having an average roughness of 11.7 μm compared to 1.1 μm for a metal surface. Measuring the roughness

of TBC's with pitting and deposits, roughness values increased to as high as 41.3 μm . However, it was found that further deterioration of the TBC exposed the smoother metal substrate. It was concluded that while the surface roughness will reach some maximum value over time, it would likely have little impact on the flow. This claim is further reinforced by a study done by Bogard, Schmidt, and Tabbita (1998). They found that heat transfer increased by 50% when comparing rough and smooth surfaces, but little difference between varying roughness heights. Similar results were found when investigating the effects of surface roughness at various locations on turbine blades (Blair, 1994). With no direct correlation between surface roughness and heat transfer, it is difficult to quantify surface roughness effects without experimental results.

2.2.1. Thermal Life Modeling

Turbine manufacturers contribute considerable resources to predicting the lifetime of engine components. Such research has potential cost-saving benefits as the end-user is able to safely operate the engine to the maximum safe service period of the part before needing replacement or refurbishment. A recent study investigated the sensitivity of both TBC thickness and temperature loading on blade life (Reyhani, Alizadeh, Fathi, & Khaledi, 2012). The results showed that increasing TBC thickness substantially lengthened the blade life; meanwhile, operating a component at 70% load for 300 hours was equivalent to one hour of operation at base load. This research clearly shows the significant role TBC's play in the longevity of turbine blades.

Thermal cycling is one of the major variables that lifetime models. Larson and Miller attempted to reduce thermal cycling test times by finding a relation between temperature and life cycle (Larson & Miller, 1952).

$$L.M. = T(C + \log t) \quad (4)$$

In the relation above, $L.M.$ is the Larson-Miller Parameter, T is temperature in Rankine or Kelvin, C is a constant, and t is the rupture time in hours. Larson and Miller found that $C = 20$ showed the best matching for a wide variety of materials and has since been adopted for initial estimates. Independent efforts have investigated the accuracy of this value for C . One study proposed that C was not constant but rather a linear relationship based on the stress loading of the part which provided better matching (Ghatak & Robi, 2015). It has also been proposed that the value of C be based on the component materials as different materials will have varying ratings of rupture life. (Maruyama, et al., 2017). Due to the preliminary nature of this study, C was taken to be 20 since the material properties are only representative of what is commonly found in industry.

3. Objectives

3.1. Problem Statement

Chipping and spalling of the TBC are commonly found on turbine blades when they are inspected during maintenance. While undergoing repairs, additional defects in the TBC can also occur, further compromising the insulating properties of the TBC. The effects of the TBC damage and sensitivity to the damage geometry on turbine blade temperatures and service life are unknown.

3.2. Hypothesis

Chip qualities can be broken down into measurable variables and tested to find which variables have a significant impact on blade temperatures. Flow properties and chip geometry are likely to have the most substantial effect on the blade temperatures. A physics-based correlation can be developed which can be used in the field to better estimate the need to remove a component for repairs.

3.3. Objectives

- Examine the characteristics of turbine blades with damaged TBC's and discuss with industry which variables are likely to have the greatest effect on blade temperatures.
- Conduct 2D simulations which replicate a multilayered turbine blade to test the sensitivity of blade temperatures to the variables previously identified.
- Develop a correlation predicting temperature increase as a function of the identified variables based on the data procured in the simulations.
- Determine the durability of components with damaged TBC using the temperature correlation and existing life time models.

3.4. Outcomes

The influential properties of TBC chips will be identified. In addition, correlations will be drawn to predict temperature increases in blade temperatures based on the chip and flow qualities. The estimated temperature increases could then be used to predict penalties on the component lifetime ratings.

4. Methodology

4.1. Geometry Description

A 2-D model was created to represent a section of a multi-layered turbine component in the hot gas path. Figure 4.1 shows the configuration of the simulation model.

Figure 4.1 2-D model configuration.

The bottom layer represented the metal substrate. The metal thickness was chosen to be 1.5 mm with a thermal conductivity of 11.0 W/m*K. Above the metal layer was the bond coat layer followed by the TBC layer. These layers were 0.25 mm and 0.50 mm thick with thermal conductivities of 7.0 W/m*K and 0.7 W/m*K, respectively. The final top layer represented the fluid hot gas region. This layer had a thickness of 50.0 mm so that upper most boundary was far enough from the region of interest. The length of the model upstream of the chip was driven by the desired Reynolds number and inlet Mach number. The downstream length was chosen to be at least three times larger than the largest chip width to adequately capture any downstream effects caused by the TBC chip.

4.2. Parameters Investigated

To understand the effects of exposing the bond coat to the hot gas path, a semicircular chip was introduced into the TBC. Chip widths of 1.5 mm, 3.0 mm, and 8.0 mm were investigated. For each chip width, hot gas flow characteristics were varied either by Reynolds number as referenced from the leading edge of the model or Mach number. Žukauskas showed that the turbulent boundary layer acts as a thermal resistor in the fluid (Žukauskas, 1994). Varying Reynolds number based on distance from the leading edge captured the effect of the approaching boundary layer thickness. By increasing the upstream length, Reynolds numbers of 5.1×10^5 , 7.0×10^5 , and 9.0×10^5 were used with a constant Mach number of 0.59. Changes in Mach number investigated the impact of the chip at varying engine operating conditions, or engine configurations. Inlet Mach numbers of 0.30, 0.59, and 0.80 were used while holding a constant Reynolds number of 5.1×10^5 . This was also achieved by varying the upstream length.

It is common to find TBC chips of different shapes, especially near the edge of the chip, which is seen in Figure 4.2.

Figure 4.2 Detailed view of a chipped TBC layer and fractured metal layer.

For this reason, efforts were made to understand the effects of the chip geometry.

Additional edge shapes were investigated, including a square and convex edge, which are shown in Figure 4.3.

Figure 4.3 Edge geometry variation.

These shapes would illustrate any potential aerodynamic effects influencing the heat transfer in the chip area. A constant chip width of 3.0 mm was selected for this portion of the study. Each edge variation was tested at the same inlet Mach numbers as previously mentioned. A table detailing each case tested is listed in appendix A.

4.3. Data Reduction

The Conjugate Heat Transfer model was validated against a correlation based on the Chilton-Colburn analogy for turbulent flow in heat transfer. A predicted HTC was calculated using this relation.

$$h_{predicted} = 0.0296 Re_x^{\frac{4}{5}} Pr^{\frac{1}{3}} \frac{k}{x} \quad (5)$$

The simulated HTC was evaluated using Newton's law of cooling. However, the relatively high Mach numbers selected for evaluation required that the inlet recovery temperature based on inlet conditions, T_r , be used as the reference temperature.

$$\frac{T_r - T_\infty}{T_{in} - T_\infty} = Pr^{\frac{1}{3}} \quad (6)$$

In this relation for the recovery factor, T_∞ is the static freestream temperature, and T_{in} is the average inlet temperature. This can be rearranged to then find T_r .

$$T_r = T_{in} Pr^{\frac{1}{3}} + T_\infty \left(1 - Pr^{\frac{1}{3}}\right) \quad (7)$$

Finally, h_{sim} is solved for using Newton's cooling law.

$$h_{sim} = \frac{q''}{T_w - T_r} \quad (8)$$

Evaluation of the metal layer temperatures were accomplished by recording the temperatures at the interface between the bond coat and metal layers, as well as the convective side of the metal. This would produce temperature profiles along both the hot and cold sides of the metal. To aid in the comparison of this data, each of these measurements were then evaluated as a temperature ratio (TR),

$$TR = \frac{T_{chip}}{T_{fp}} \quad (9)$$

where the T_{chip} is the temperature of the chip case and T_{fp} is the flat plate temperature at the same location.

The Reynolds number, Re_x , was initially evaluated at the start of the flat plate.

$$Re_x = \frac{\rho U x}{\mu} \quad (10)$$

This method was used for determining the Reynolds number of each case. It was later found that evaluating the Reynolds number based on the chip width, Re_{chip} , provided more insight on the TR increase of the metal. Thus, it was used later when correlating the data.

$$Re_{chip} = \frac{\rho U w_{chip}}{\mu} \quad (11)$$

4.4. Modeling Parameters

The following section covers details concerning the simulation setup such as the applied boundary conditions, in addition to the mesh resolution and convergence criteria.

4.4.1. Boundary Conditions

Boundary conditions are representative of the properties usually exhibited by the hot gas path of a gas turbine (Han, Dutta, & Ekkad, 2000). A uniform velocity inlet boundary was created on the upstream side of the model. The inlet conditions included a temperature of 1600 K and a predetermined inlet velocity depending on target Mach number. On the downstream side, a pressure outlet of 15 bar was assigned. On the bottom of the metal layer, a convective boundary was applied to simulate internal air cooling commonly found in turbine blades. This convective boundary was given a temperature of 750 K and a HTC of $1500 \text{ W/m}^2\cdot\text{k}$. The temperature was estimated by using isentropic compressor relations while the HTC was taken from data provided by the industrial partner. The top side of the model was assigned a far-field boundary. All other boundaries were assigned as no-slip walls.

4.4.2. Physics Models/ Solvers

A conjugate heat transfer model was chosen to capture both the conduction and convection occurring at the chip location. This model was carried out in Star CCM+ v12.02 CFD software.

The $k-\omega$ -SST turbulence model was chosen for the simulation of the hot-gas path. This is a 2nd-order Reynolds-Averaged Navier-Stokes turbulence model (Siemens PLM Software, 2019). This model takes advantage of the $k-\omega$ solver's ability to capture interactions near the surface while using the realizable $k-\epsilon$ solver for the free stream flow

(Eds. & T.I-P, 2014). In addition, a segregated (pressure based) solver was chosen to model flow and temperature. The solver assumed ideal gas properties, and fully turbulent flow at a steady state.

4.4.3. Mesh Settings

A hexagonal mesh was utilized for the two-dimensional simulation. A mesh independence study was performed to define the minimum acceptable mesh density.

Figure 4.4 shows results of increasing the mesh resolution.

Figure 4.4 Change in heat flux as mesh resolution increased.

Little change in results is seen at around $5E+05$ cells. When the cell count surpassed $1E+06$, the change in results increased once again, suggesting that an increased resolution was still needed, likely near the boundary layer. Prismatic cells were added near key surfaces to capture any flow interactions with the boundary layer. Figure 4.5 displays the results of adding prismatic cells.

Figure 4.5 Change in heat flux with the addition of prism layers.

The first three cases, “PL 1”, “PL 2”, “PL 3”, included the prism cells that were increased in size for each case. “Mesh 2 + PL 3” incorporated the prismatic cells, as well as a slight increase in overall mesh resolution resulting in a minimal change in results. The mesh resolution was then deemed independent of the simulation results. The final global mesh settings included an average cell size of 18.750×10^{-3} mm with a prism layer thickness of 0.10 mm consisting of three layers. A sample of the mesh is shown in Figure 4.6 (a).

Additional custom controls were added near areas of interest including the inlet and outlet boundaries, the TBC surface, metal volume, and the surfaces of the chip. The chip surfaces were given increased mesh density with an average cell size of 1.875×10^{-3} mm and a prism layer thickness of 5.000×10^{-3} mm consisting of 20 layers as shown in Figure 4.6 (b). Conversely, a coarser mesh was used for the metal volume with an average cell size of 0.15 mm. For reference, the mesh for case 1.1.1 had a total cell count of 315,356 and is shown in Figure 4.7. One case was run with unsteady flow but was found to have no impact on the results.

Figure 4.6 (a) A sample of the mesh; (b) Detailed view showing resolution of the prism layers.

Figure 4.7 Final mesh setup showing all regions of the simulation. The fluid domain has been cropped.

4.4.4. Convergence Criteria

Monitors were created to ensure that the heat transfer and fluid dynamics in the simulation were stable. One monitor observed the total heat flux between the top of the TBC layer and the hot gas path while another recorded the average temperature of the TBC surface and the average metal temperature. Other monitors checked the mass flow at

the outlet and the total pressure drop from the inlet to the outlet. The simulations were deemed converged when the values of the monitors became asymptotic and when all residuals reached a value of 10^{-4} or less. Figure 4.8 shows an example plot of converged residuals.

Figure 4.8 Example of converged residuals.

5. Results Discussion

5.1. Model Validation

For validation purposes, a flat plate simulation with no TBC chip was utilized. The velocity profile in the streamwise direction of the flat plate simulation was assumed to be fully turbulent and confirmed against Prandtl's 1/7th power law.

$$\frac{V}{V_{\infty}} = \left(\frac{y}{\delta_{BL}} \right)^{1/7} \quad (12)$$

This was evaluated along a vertical plane located at the start of where the chip would be introduced in the model.

Figure 5.1 Flat plate velocity error

As shown in Figure 5.1, minor errors were found in the velocity profile comparison with only major differences found near the plate surface. These results highlight the need for a full resolution of the boundary layer.

Comparison between the predicted and simulated HTC showed an average error of 16.2%. In Figure 5.2, the trend of the HTC along the surface was well-captured but the

magnitude was under-predicted. The discrepancy was likely due to limitations in the turbulence modeling.

Figure 5.2 Flat plate heat transfer coefficient error

The conductive heat transfer was validated against 1-D resistance methods. By evaluating the thermal resistances of each element in the model, temperatures at each material interface were found.

$$R_{cond} = \frac{t}{k} \quad (13)$$

$$R_{conv} = \frac{1}{h} \quad (14)$$

$$q'' = \frac{T_{hot} - T_{cold}}{\sum R} \quad (15)$$

These results were then compared with that of the simulation model to find the percent error. The simulation results for the conduction model were indistinguishable from the predicted values as shown in Figure 5.3.

Figure 5.3 1-D Temperature Validation

The temperatures at each interface varied by less than 0.05% compared to predicted values. Likewise, the total heat flux deviated by only 0.08%. These results suggest that the mesh resolution in the solid regions were sufficient such that the heat flux in the model was accurately captured.

5.2. Effect of Chip Width

The TBC layer acts as a thermal resistor for the turbine component. As the chip size increases, the metal layer temperatures are expected to increase because of the absence of this thermal insulator. Three chip sizes ranging from 1.5 mm to 8.0 mm were simulated to analyze the temperature increase. Figure 5.4 compares the temperatures of each chip width at the same flow conditions. Solid lines labeled “Metal/BC” indicate the temperatures measured at the interface between the metal and bond coat layers while dashed lines labeled “Metal/Cooling” indicate the temperatures measured at the convective boundary of the metal layer. For reference, dotted lines indicating the start and end of the chips are included in the plot.

Figure 5.4 Temperature comparison of chip widths

A clear increase in TR is seen as the chip width increased. Cases with a chip of 1.5 mm saw a maximum temperature increase of 9% while the chip of 8.0 mm saw a temperature increase of over 25% at the metal/bond coat interface. At the highest Mach number, the TR for the 8.0 mm chip reached almost 29%. The absence of the TBC layer decreased the thermal resistance of the blade, resulting in increased metal temperatures in the exposed regions.

A visible bias in the metal temperatures developed towards the downstream side of the chip, which can be seen in Figure 5.5.

Figure 5.5 Detail of high Mach number with a 3 mm chip.

Ingestion of the hot gas into the chip in conjunction with impingement on the downstream chip edge is the cause for this asymmetric temperature profile. This is reflected in Figure 5.4, where the temperature profiles are leaning towards the respective chip edge lines. Further analysis found that a recirculating region had developed within the chips, which is shown in Figure 5.5, where the streamlines are seen circling within the chip region. The larger 8.0 mm chip developed a similar recirculation region; however, it only spanned half of the chip length, which is seen in Figure 5.6 (c). In this instance, the temperature bias was less pronounced when compared to the smaller chip cases. A “smearing” of the temperatures was also observed in the large chip cases in which the increased temperatures extended beyond the chip edges. Conduction in the stream-wise direction spread additional heat over a larger area, showing that excessively large chips have the potential to affect the surrounding regions of the chip.

Figure 5.6 Temperature contours of varying chip widths: 1.5 mm (a), 3.0 mm (b), and 8.0 mm (c).

In Figure 5.7, the freestream flow reaches the downstream chip edge and is forced back into the hot gas path, accelerating the flow as it moved past the chip edge. This resulted in the free stream region immediately downstream of the chip having a modest decrease in temperature, as seen in Figure 5.6 (c). However, this phenomenon did not have a noticeable effect on the TBC or metal temperatures.

Figure 5.7 Velocity contour detailing the flow acceleration at the downstream edge.

5.3. Effect of Reynolds Number

As indicated by the Chilton-Colburn analogy, HTC is a function of Re_x . Thus, elevated metal temperatures are expected when Re_x is increased. However, when chip width and Mach number were held constant, changes in Reynolds number had little effect on TR at the chip location. As seen with Figure 5.8, the TR plots overlap, indicating little difference between cases.

Figure 5.8 Temperature comparison of Reynolds number

Increases in Reynolds number achieved a maximum TR of 0.8% between the smallest and largest Re_x values tested. Because the upstream length was increased to raise the Reynolds number, a marginal reduction in HTC was achieved. When compared to chip width and Mach number sensitivities, it was clear that Reynolds number evaluated at the beginning of the model had negligible influence on the maximum temperature. It should be noted that the boundary layer thickness and chip depth were similar in size. Reynolds number may have a different effect on the TR if these factors were on different orders of magnitude.

5.4. Effect of Mach Number

Gas turbines will cycle through a range of operating conditions depending on the power demanded from the engine. Changes in Mach number reflect the varying engine conditions common in day to day operations. As Mach number increased, a considerable increase in the maximum metal temperature was observed. Figure 5.9 shows a

comparison of each Mach number with constant Re_x and chip width.

Figure 5.9 Temperature comparison of Mach number

The increased momentum in the hot gas path drives more of the freestream flow into the chip. In case 2.2.5, the temperature of the gas near the chip edge is nearly 1730 K or about 1.08 times greater than freestream. Following the linear relationship of ideal gas law, the pressure at the same location is 1.65 MPa; an increase by a factor of 1.08 over freestream pressure. Figure 5.10 highlights the increased pressure at the downstream chip edge.

Figure 5.10 Pressure contour of high Mach number

Therefore, at greater velocities, the gas near the downstream chip edge experiences compressibility effects due to greater impingement on the chip wall. This is coupled with increased turbulent mixing that ultimately increases the temperatures in the metal layer.

5.5. Effect of Edge Geometry

TBC chipping and spallation are a product of several factors and therefore occur in a variety of shapes. Exploring the edge geometry will highlight any effects on heat transfer these shapes may play. Cases with convex corners experienced freestream flow that marginally decreased the height of the recirculation zone in the chip, as shown in Figure 5.11.

Figure 5.11 Rounded corner TBC

This can be attributed to the enhanced aerodynamic profile of the chip. While the downstream chip edge saw reduced temperatures, the temperature of the metal remained almost the same. The exposed bond coat area was much larger than the downstream chip edge. Thus, any potential benefits of the rounded corner are negated by the heat flux going into the bond coat.

Square edge chips caused the flow to behave in a similar manner to that of the semi-circular chip. Figure 5.12 shows that the recirculation in the chip seemed largely unaffected.

Figure 5.12 Square Corner TBC

In addition, the maximum temperatures were found to be indistinguishable from one geometry to the next as seen in Figure 5.13. This is likely due to the large relative radius of the chip having very little curvature in a TBC layer of small thickness. Therefore, the semi-circular chips were already behaving like that of a square chip.

Figure 5.13 Temperature comparison of edge geometry

The chip edge geometry was concluded to have little to no effect on the metal layer temperatures assuming most of the TBC was removed, and the upper chip width was similar to the bottom of the chip width.

5.6. Effect of Surface Roughness

Surface roughness can significantly augment the HTC of a fluid, resulting in increased heat flux at the surface. TBC's have a relatively rough surface as compared to the metal substrate. Additional coarsening is seen on TBC chips. Star CCM+ applies a roughness function based on the equivalent sand-grain roughness height of the modeled material (Siemens PLM Software, 2019). This function is used to modify the specific dissipation term in the $k-\omega$ turbulence model. Implementing this roughness function requires a high nondimensional wall distance, y^+ .

$$y^+ = \frac{yU^*}{\nu} \quad (16)$$

However, a low y^+ is required to fully resolve the viscous sublayer which is crucial in

modeling conjugate heat transfer. This method of modeling surface roughness based on equivalent sand-grain roughness has been argued to be flawed for heat transfer purposes. (Bons, 2010). It has been shown that attempting to predict skin friction and heat transfer from equivalent sand-grain roughness leads to inaccuracies in one of the two properties (Aupoix & Spalart, 2003). Instead, discrete-element modeling or a fully discretized surface feature is suggested to accurately model surface roughness (Bons, 2010). These methods are computationally expensive and infeasible in the scope of this study. Therefore, a compromise must be made in either solving for the heat transfer or the flow properties over the surface. The focus of this study is on the heat transfer effects of the TBC chip and so modeling the surface roughness would not add value to the overall objective.

An attempt can be made to compare the heat transfer coefficients of a rough surface over a smooth surface. Experimental correlations for St are a function of Re_x , Pr , and C_f , such as the following correlation for turbulent flow over a flat plate (Kader & Yaglom, 1972).

$$St = \frac{\sqrt{C_f} Pr^{-1}}{4.3 \ln(Re_x C_f) + 3.8} \quad (17)$$

A relation can be made to find h_x based on equations 3 and 17.

$$h_x = \frac{Re_x \sqrt{C_f}}{4.3 \ln(Re_x C_f) + 3.8} \frac{k}{x} \quad (18)$$

A comparison can then be made between the HTC of rough and smooth surfaces given that C_f can be found for each surface. However, experimental efforts to find C_f of chipped TBC surfaces is beyond the scope of this study. It is recommended that further efforts investigate the effects of chipped TBC surface roughness on HTC.

6. Summary

Based on the results from the initial study, a correlation was created to predict the maximum TR on the exposed surface. This correlation was then applied to the Larson-Miller lifetime model to predict a modified lifetime of the affected part.

6.1. Temperature Prediction

Mach number and chip width were found to have the greatest effect on TR of the metal substrate while chip edge and Reynolds number evaluated at the leading edge of the model were deemed negligible. However, if the Reynolds number was evaluated on the chip width and inlet velocity, an effect could also be found. From these conclusions, two correlations can be made using the maximum TR of each relevant case. A least squares approach was followed to find the constants of the correlations. Using Mach number and chip width, the temperature could be found with the following relation,

$$TR = 1 + 4.697(M * w_{chip})^{0.5449} \quad (19)$$

where TR is the temperature ratio, M is the local Mach number, and w_{chip} is the chip width. The standard error of this relation was 0.0050. A second correlation was developed,

$$TR = 1 + 3.036 * 10^{-4}(Re_{chip})^{0.5437} \quad (20)$$

where Re_{chip} is the Reynolds number evaluated at the start of the chip. The standard error was 0.0049. In Figure 6.1, the maximum TR found at each chosen inlet Mach is plotted for every corresponding chip width. In addition, relations 19 and 20 are plotted and labeled “Mach/ChipW” and “Rechip”, respectively.

Figure 6.1 Maximum TR for each case of chip width and Mach number

The advantage to using the first correlation is that both Mach number and chip width would be readily known by a servicing engineer while the Reynolds number would take significant effort to determine.

These correlations can be used in conjunction with lifetime models such as the Larson Miller parameter to estimate modified lifecycles of damaged turbine blades. Furthermore, the resulting TR can be used for surface-wastage oxidation models to predict life and damage evolution. This TR would also be useful in stress analysis if the chip was in a key loadbearing area of the blade. The reader is cautioned when implementing these correlations outside of the conditions tested in this study.

6.2. Lifetime Modeling

The Larson-Miller parameter was considered for lifetime estimation modification. For the sake of this preliminary study, a constant of 20 was used as was originally proposed by the authors. Other values of C have been proposed but are not being explored in the scope of this work. Based on equation 4, the relation can be rearranged in terms of the reduced lifetime rating, t_2 .

$$t_2 = 10^{\left(\frac{20+\log t_1}{TR} - 20\right)} \quad (21)$$

t_1 is the original life rating of the part, and TR is the temperature ratio.

Values of t_1 were obtained from Liburdi Turbine Services based on average industry ratings for hot side components. Values of TR were found using the relations in section 6.1. The resulting modified lifetimes are listed in Table 6.1.

Table 6.1

Modified lifetime predictions

Case #	Chip Width (m)	Mach	Rechip	TR		Service Life (hr)	Modified Life (hr)
				f (Mach, width)	f (Rechip)		
2.1.4	0.0015	0.30	2.25E+04	1.07	1.07	10000	263
2.1.1	0.0015	0.59	4.41E+04	1.10	1.10	10000	60
2.1.5	0.0015	0.80	6.04E+04	1.12	1.12	10000	26
2.2.4	0.0030	0.30	4.50E+04	1.10	1.10	10000	58
2.2.1	0.0030	0.59	8.81E+04	1.15	1.15	10000	8
2.2.5	0.0030	0.80	1.21E+05	1.18	1.18	10000	3
2.3.4	0.0080	0.30	1.20E+05	1.18	1.18	10000	3
2.3.1	0.0080	0.59	2.35E+05	1.25	1.25	10000	0
2.3.5	0.0080	0.80	3.22E+05	1.30	1.30	10000	0

At 10,000 hours of rated service life, even a small TR of 1.07 would result in a modified rating of 263 hours; less than 3% of the original lifetime rating. As TR increases, modified service life rapidly decreases eventually reaching 0 hours; indicating the part is no longer usable. This information suggests that even the smallest TBC chips could potentially compromise the reliability of the affected parts. While these results may be true for a part fully saturated at these thermal loads, it may not hold true for the cases being studied. The chip widths and depths are on a much smaller scale as compared to the

parent component. The LM parameter may therefore be overpredicting the life penalty of the part. It is suggested that further research be conducted to verify these results.

7. Conclusion

Damaged TBC's on turbine blades were investigated by simulating a simplified 2D model. Parameters, including chip width, Mach number, Reynolds number, and chip edge geometry, were simulated to find the temperature increase in the metal layer. The simulation data has led to the following conclusions:

- Chip width and Mach number significantly increased metal temperatures.
- Upstream length-based Reynolds number and chip edge geometry were deemed negligible.
- Chip width-based Reynolds number had a measurable effect on metal temperatures.
- Simulating surface roughness can lead to inaccurate results and thus experimental values of skin friction should be used to estimate the increase in HTC.
- Two correlations based on chip width and Mach number, and chip-based Reynolds number were established to predict metal temperature increases.
- Component life could be severely affected by even small TBC chips. However, additional research is needed to verify these results.

8. Recommendations

It is recommended to further test the fidelity of the temperature ratio correlations by testing additional cases, including 3-D models. Additionally, preliminary experimental studies can be conducted to both verify the CFD results, as well as test the temperature correlation. Further examination of the chip surface roughness can also be explored during experimental trials.

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A. Test Matrix

Case #	Description	Chip Width (mm)	Reynold's Number (@ start of flat plate surface)	Inlet Mach
1.1.1	Flat plate	N/A	5.10E+05	0.59
1.1.2	Flat plate	N/A	7.00E+05	0.59
1.1.3	Flat plate	N/A	9.00E+05	0.59
1.1.4	Flat plate	N/A	5.10E+05	0.30
1.1.5	Flat plate	N/A	5.10E+05	0.80
2.1.1	Semi Circular chip	1.50	5.10E+05	0.59
2.1.2	Semi Circular chip	1.50	7.00E+05	0.59
2.1.3	Semi Circular chip	1.50	9.00E+05	0.59
2.1.4	Semi Circular chip	1.50	5.10E+05	0.30
2.1.5	Semi Circular chip	1.50	5.10E+05	0.80
2.2.1	Semi Circular chip	3.00	5.10E+05	0.59
2.2.2	Semi Circular chip	3.00	7.00E+05	0.59
2.2.3	Semi Circular chip	3.00	9.00E+05	0.59
2.2.4	Semi Circular chip	3.00	5.10E+05	0.30
2.2.5	Semi Circular chip	3.00	5.10E+05	0.80
2.3.1	Semi Circular chip	8.00	5.10E+05	0.59
2.3.2	Semi Circular chip	8.00	7.00E+05	0.59
2.3.3	Semi Circular chip	8.00	9.00E+05	0.59
2.3.4	Semi Circular chip	8.00	5.10E+05	0.30
2.3.5	Semi Circular chip	8.00	5.10E+05	0.80
3.1.1	Convex TBC Corner	3.00	5.10E+05	0.59
3.1.2	Convex TBC Corner	3.00	5.10E+05	0.30
3.1.3	Convex TBC Corner	3.00	5.10E+05	0.80
3.2.1	Square TBC edge	3.00	5.10E+05	0.59
3.2.2	Square TBC edge	3.00	5.10E+05	0.30
3.2.3	Square TBC edge	3.00	5.10E+05	0.80
3.2.4	Square TBC edge	3.00	9.00E+05	0.59