Evolution of Surface Deposits on a High-Pressure Turbine Blade—Part II: Convective Heat Transfer

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A thermal barrier coating (TBC)-coated turbine blade coupon was exposed to successive deposition in an accelerated deposition facility simulating flow conditions at the inlet to a first stage high pressure turbine (T = 1150°C, M = 0.31). The combustor exit flow was seeded with dust particulate that would typically be ingested by a large utility power plant. The turbine coupon was subjected to four successive 2 h deposition tests. The particulate loading was scaled to simulate 0.02 parts per million weight (ppmw) of particulate over 3 months of continuous gas turbine operation for each 2 h laboratory simulation (for a cumulative 1 year of operation). Three-dimensional maps of the deposit-roughened surfaces were created between each test, representing a total of four measurements evenly spaced through the lifecycle of a turbine blade surface. From these measurements, scaled models were produced for testing in a low-speed wind tunnel with a turbulent, zero pressure gradient boundary layer at Re = 750,000. The average surface heat transfer coefficient was measured using a transient surface temperature measurement technique. Stanton number increases initially with deposition but then levels off as the surface becomes less peaked. Subsequent deposition exposure then produces a second increase in St. Surface maps of St highlight the local influence of deposit peaks with regard to heat transfer. [DOI: 10.1115/1.2752183]

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Introduction

Land-based and aircraft gas turbines ingest large quantities of air during operation. Contaminants found in the atmosphere or in the fuel are known to generate deposits on the blade surfaces [1,2]. Once formed, these deposits roughen the blade surfaces resulting in an increase in skin friction and in the convective heat transfer rate between the exhaust gases and the turbine blades [3,4]. Deposits can also clog vital coolant passages, thus further aggravating the thermal load of the turbine components [5]. The effects of elevated levels of surface roughness on turbomachinery performance have been studied for over 25 years. These studies include fundamental flat-plate wind tunnel research [6], multiblade cascade facilities [7], and full system level tests [8] in addition to numerous computational studies [9]. These studies all support the expected result that roughness increases surface drag and heat transfer (though to varying degrees). For turbomachinery, this translates to higher heat loads, accelerated part degradation, and lower stage efficiencies.

Unfortunately, because this deposition process takes place over thousands of hours (for a land-based turbine), little is known about the evolution of deposition on turbine blade surfaces. A companion paper [10] reports on a combustor simulator that was used to evolve deposits on a turbine coupon with thermal barrier coating (TBC). This was done in the Turbine Accelerated Deposition Facility (TADF) which is a specialized combustor capable of creating deposits at a vastly accelerated rate and under controllable conditions. The facility is described in detail in Ref. 11, but

the essential principle is that of matching the product of the particle concentration in the air flow (measured in parts per million weight, ppmw) and the number of hours of operation. Deposits were generated at constant operating conditions over four successive 2 h tests, simulating 3 months of gas turbine operation for each test. The companion paper Part I [10] reviewed the evolution of surface roughness character with successive deposition for the three most common material systems found on modern gas turbine airfoils: uncoated superalloy, thermal barrier coating (TBC), and oxidation resistant coating. A significant observation from this study was that deposit roughness size (Rz) and shape (Ra) experienced a temporary lull in growth during deposit evolution for the conditions studied. This occurred as deposits filled the isolated peaks created during initial operation. Because of the well-documented link between roughness size and surface heat transfer, the objective of this study is to explore the implications of this surface evolution on the heat load to the turbine.

Roughness Models

Of the three surface treatments included in the Part I study, the TBC1 coupon was selected for this convective heat transfer study due to its relevance to modern gas turbines. After each 2 hour deposition test (denoted as “burns” in what follows), the surface topology of the coupon deposit was measured using a Hommel Inc. T8000 profilometer equipped with a TKU600 stylus. The stylus tip was conical in shape and had a 5 μm tip radius. Three-dimensional surface representations were constructed from a series of two-dimensional traces separated by 10 μm. Data points within each trace were also separated by 10 μm, yielding a square data grid. Three-dimensional surface representations and roughness statistics were produced with the Hommelwerke Hommel Map software. The statistics of most interest for this study were the centerline averaged roughness, Ra, the average roughness of the surface.

height, \( R_c \), and the average forward-facing surface angle, \( \bar{\alpha}_f \). The centerline averaged roughness was calculated using the following

\[
Ra = \frac{1}{IJ} \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} \left| z_{ij} \right|
\]  

(1)

\( R_z \) was calculated as the mean of the vertical distance between the highest peak and deepest valley every 10 mm of a 2D surface trace. Based on the scaled roughness model images shown in Fig. 1, this appeared to be a representative roughness dimension for the deposits in this study. The average forward-facing angle was calculated using the methodology proposed by Bons [12] in which the surface is traversed in the flow direction and forward-facing angles are averaged with all leeward-facing angles set equal to zero (Eq. (2))

\[
\bar{\alpha}_f = \frac{1}{J} \sum_{j=0}^{J-1} \bar{\alpha}_j
\]  

(2)

where, if \( (z_{i+1} - z_i) > 0 \)

\[
\alpha_i = \tan^{-1}\left( \frac{z_{i+1} - z_i}{y_{i+1} - y_i} \right) \quad \text{else, } \alpha_i = 0
\]

Typically, \( R_z \) and \( \bar{\alpha}_f \) are calculated as the average of multiple 2D surface traces.

The TBC1 coupon experienced continuous deposit growth over the entire four-burn sequence in the TADF. In addition, during the third and fourth burns, significant TBC spallation occurred near the coupon edges. Since spallation roughness was not the focus of this study, scaled roughness models were made from a region at the coupon center, where spallation was minimal. Figure 1 contains a series of 3D topologies showing the deposit evolution on a 3.3 mm × 4.2 mm region away from the spallation at the coupon edges. Burns 2–4 appear to fill the valleys between the initial deposit peaks created during the first period of exposure. This trend is even more evident when reviewing the evolution of roughness statistics for the scaled models of the TBC1 coupon (Fig. 2). As outlined previously, the roughness height (i.e., \( R_a \) and \( R_z \)) on the TBC1 coupon increased markedly during the first burn. This was then followed by a gradual increase over the next two burns. Finally, the roughness height again increased rapidly with Burn 4. The average forward facing angle followed a similar trend. The initial rise in \( \alpha_f \) with Burn 1 was followed by a slight decline with Burn 2 and a leveling off with Burn 3. Finally, the average forward facing angle climbed back above 7 deg with Burn 4. It is noteworthy that the levels of \( R_a, R_z, \) and \( \bar{\alpha}_f \) shown in Fig. 2 are comparable to those reported for measurements on actual turbine hardware [3,4], as discussed in Part I.

The topological measurements from the Hommel profilometer shown in Fig. 1 were used to create the CNC-compatible code and produce the scaled models. Model scaling was guided by the ratio of roughness height to boundary layer momentum thickness, \( R_z/\delta \). This ratio was maintained near a value of 0.5 [4,13,14]. With this as guidance, a scaling factor of 20 was determined to be appropriate. Because of this scaling factor, and due to the limited size of the largest usable rectangular region of roughness, the original data formed 25% of the total model surface. The remaining 75% of the 22 cm × 38 cm wind tunnel space provided for the model was filled by mirroring this section of data.

With the CNC code, the roughness models were cut out of 2.54-cm-thick Plexiglas acrylic sheets using a modified countersink. The countersink was chosen because it most closely approximated the tip of the profilometer stylus that scanned the surface originally. Both are conical in shape with a 90 deg included angle. This was to ensure that the model contours would be as close as possible to the original surface measurements. A comparison of the scaled model surfaces to the original coupon roughness indicated that while the roughness height was well matched (within 10%), the angle was not. The countersink tool that was used, with a 0.5 mm tip radius, flattened out the transitions in the surface producing a 25% drop in mean forward facing angle. These adjustments are reflected in the roughness statistics for the scaled model shown in Fig. 2.

### Experimental Facility

A schematic of the research facility used for the experiments is shown in Fig. 3. The open loop wind tunnel uses a main flow...
an adjustment length equivalent to 3–4 boundary layer thicknesses to the appropriate rough-wall values. Both researchers report

conditioning, 2D flow uniformity of the 0.38 m by 0.38 m acrylic test section. With this conditioning, 2D flow uniformity of ±0.4% in velocity and ±1°C is obtained over the center 0.18 m of the test section span. The freestream turbulence level in the wind tunnel is 0.5%.

At 1.52 m from the plenum exit a knife-edge boundary layer bleed with suction removes the bottom 2.7 cm of the growing boundary layer. The top wall of this final section pivots about its forward end in order to adjust the pressure gradient in the tunnel. For the tests presented here, the wall was adjusted to produce zero freestream acceleration over the roughness test panels. At 2.5 cm from the boundary layer suction point, a 2-mm-diameter cylinder spans the test section to trip the boundary layer to turbulent. The leading edge of the roughness panel is located 1.04 m from the boundary layer suction point. The roughness panels are installed in a 0.22 m streamwise gap in the lower wall as shown in Fig. 1. The tunnel then continues 0.3 m beyond the trailing edge of the roughness panels. In this configuration, the flow in the tunnel experiences a transition from a smooth to rough wall condition at the leading edge of the roughness panels. This experimental setup departs from traditional roughness experiments in which the entire development length of the boundary layer is roughened. Studies by Antonia and Luxton [15] and more recently by Taylor and Chakroun [16] show that this smooth to rough transition results in an initial overshoot in $c_T$ and $St$ followed by a fairly rapid adjustment to the appropriate rough-wall values. Both researchers report an adjustment length equivalent to 3–4 boundary layer thicknesses with up to 20% initial overshoot. To mitigate the effect of this transition region, the heat transfer data were taken on the downstream half of the roughness section (beyond the expected adjustment length of approximately 9 cm).

As additional verification of this testing procedure, heat transfer data were also acquired with multiple upstream roughness panels extending to 1 m upstream of the measurement point, and the data showed no perceptible effect beyond the uncertainty of the measurement. Thus, all data were acquired with the smooth to rough transition at 1.04 m from the tunnel boundary layer bleed. The mean elevation of the roughness panel was aligned vertically with the upstream smooth panel to prevent acceleration or deceleration of the bulk flow ($U_\infty$).

Flow velocity was measured using a pitot-static probe with a co-located flow thermocouple with 0.13 mm bead diameter for flow temperature measurement. The two instruments are positioned at midspan just outside the boundary layer and downstream of the roughness panel during the transient testing. A second thermocouple was located upstream of the test panel and further away from the wall in the freestream, as shown in Fig. 3. Uncertainty in the velocity measurement was within ±1.5% at flow rates of interest.

A boundary layer pitot probe with a co-located 0.13 mm bead diameter flow thermocouple was used to determine the boundary layer velocity and thermal profiles at the St measurement location. With the smooth test panel installed at the test section, the velocity boundary layer thickness was approximately 22 mm, with momentum and displacement thicknesses of 2.7 mm and 3.6 mm, respectively (shape factor=1.36). The thermal boundary layer shape varies during the St measurement due to the transient testing procedure and nonconstant wall temperature. However, the thermal boundary layer thickness remains roughly equivalent to the velocity boundary layer thickness (approximately 2 cm).

**St Measurement.** For the heat transfer measurements, a FLIR Thermacam SC 3000 infrared (IR) camera system is mounted with the lens fit into a hole in the acrylic ceiling of the tunnel. The camera has a sensitivity of 0.03°C (at 30°C) and allows framing rates of approximately 1 Hz. The IR camera was focused on a 67 mm (crosstream) × 83 mm (streamwise) field of view. This limited field of view was centered at a distance of $L=1.21$ m from the leading edge of the tunnel floor. This puts the streamwise position of the heat transfer measurement roughly 6 cm downstream of the center of the roughness panel. The 240 × 320 pixels of the FLIR camera allowed excellent resolution of the roughness features during the transient experiments.

The Stanton number was determined from this surface temperature history by using a three-dimensional unsteady conduction finite-volume algorithm with time-varying boundary conditions. The time-varying surface heat flux is calculated from the surface normal temperature gradient in the solid. This technique assumes the panels are a semi-infinite solid at constant temperature at time $t=0$. To accomplish this, the entire test section was soaked at room temperature for several hours before testing. Using the main flow heat exchanger, a hot-gas air flow (50°C) was then initiated instantaneously while monitoring the freestream velocity and temperature, as well as the average surface temperature (with the IR camera).

Radiative heat flux from the test plate to the surrounding tunnel walls was always less than 1% of the calculated convective heat flux. The thermophysical properties, thermal conductivity ($\kappa$) and thermal diffusivity ($\alpha=k/\rho c_p$), for the plastic panels were determined experimentally by Thermal Properties Research Laboratory. The measurements yielded the following values: $\kappa=0.196$ W/m K ≥ 6% and $\alpha=1330$ J/kg K ≥ 3%. The plastic density is 1188 kg/m$^3$ ± 2%.

During testing the 25-mm-thick acrylic roughness panel was mounted on a second 25-mm thick smooth acrylic panel with the same material properties. A thermocouple sandwiched between

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**Fig. 2 Roughness statistics for the scaled model surface**

Flow from blower, heater, and conditioning plenum

Freestream Thermocouple

Downward Looking IR Camera

Pitot Probe and flow thermocouple

Leading edge boundary layer suction

Roughness Panel

St Measurement at $L=1.21$ m

Boundary layer trip

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**Fig. 3 Wind Tunnel Facility**
the two panels indicated no change in temperature during the first 5 min for the typical test case. Due to the low thermal diffusivity of the acrylic plates, test times shorter than 5 min yield a Fourier number ($Fo=\alpha t/b^2$) less than 1/16, which is the semi-infinite limit. This confirmed the use of the semi-infinite conduction assumption in the data processing. Also, it was discovered that the infrared measurement is sensitive to the temperature of the surfaces surrounding the roughness panels. This occurs because some of the radiation that is incident on the camera originates from the wind tunnel enclosure and is reflected off the roughness panel. The magnitude of this component of radiation changes as a function of the tunnel wall temperature. The FLIR software accounts for this by allowing the user to specify the ambient enclosure temperature. The FLIR software accounts for this by allowing the user to specify the ambient enclosure temperature. The FLIR software accounts for this by allowing the user to specify the ambient enclosure temperature. The FLIR software accounts for this by allowing the user to specify the ambient enclosure temperature.

Results and Discussion

Heat transfer measurements were made at constant flow velocity ($Re_L=750,000$) for each of the four deposit models and a smooth baseline panel. Figure 4 shows the Stanton number computed using the area-averaged surface temperature as obtained from the IR camera measurement described above. Each data point in Fig. 4 represents the average of at least three separate transient tests, usually conducted on different days. Error bars show the range of measurements for each data point. The Stanton number values are presented as a percent difference between the rough surface value ($St_R$) and the smooth surface reference value ($St_0$). The smooth reference panel used in the wind tunnel study had a centerline average roughness of $R_a=0.5$ $\mu m$. This is significantly lower than the roughness level of $R_a=12$ $\mu m$ that would have been obtained if the preburn polished TBC surface had been cooled by the same factor of 20 used for the roughness panels. However, the roughness Reynolds number ($Re_{L,R}$) for both cases is well below the aerodynamically smooth limit for these wind tunnel conditions. Thus, the percent change in St would be similar with either reference. Also shown in the figure are the model roughness statistics from Fig. 2 for comparison. These statistics are computed for the portion of the roughness model surface in the direct field of view of the IR camera and may differ somewhat from those presented in Part I.

The trend in Stanton number follows closely the trend in roughness statistics. The St augmentation levels off between Burns 2 and 3 followed by a marked rise with Burn 4 as the roughness height and mean angle experience a resurgence. Data accumulated by Bons [12] using roughness characterizations obtained from serviced turbine components indicate that the effect of roughness on $c_f$ and St is reduced as the average forward facing angle decreases for the same mean roughness height ($R_z$). Bons proposed a correlation for the dependency of $k_s/k$ on $\alpha_f$.

$$\frac{k_s}{k} = 0.0191\alpha_f^{-1} + 0.0736\alpha_f^{-0.5}$$ (3)

Though the skin friction coefficient was not measured for the roughness models, an empirical correlation proposed by Schlichting was used to estimate its value [17].

$$c_f = [2.87 + 1.58 \log (L/k)]^{-1.25}$$ (4)

This was combined with a correlation for Reynolds analogy ($RA$) factor ($RA=2St/c_f$) proposed by Bons for a turbulent boundary layer over rough surfaces [12] to obtain an empirical estimate for St.

$$\frac{RA}{RA_0} = 0.5 \left[ 1 + \exp \left( -0.9 \frac{k_s}{\bar{u}_f} \right) \right]$$ (5)

The value for $RA_0$, the smooth wall value of Reynolds analogy, for a turbulent boundary layer was 1.2.

The results of this empirically based St correlation (Eqs. (3)–(5)) are shown with the experimental data in Fig. 5. The predictions are higher than the experiment in all cases. A different correlation based on the roughness Reynolds number ($Re_{L,R}$) by Dipperly and Sabersky [18] is also shown for comparison.

$$St = 0.5c_f - \frac{0.5c_f}{1 + 0.05c_f(5.19 Re_{L,R}^{0.2} Pr^{0.44} - 8.5)}$$ (6)

Both models capture the general trend of increasing roughness with repeated exposure, although Eq. (6) shows better overall agreement.

The spatial resolution of the infrared camera combined with the 3D finite-volume analysis technique allows a detailed evaluation of the heat transfer around specific roughness features in addition to the area-averaged St measurements presented above. The unsteady conduction algorithm properly accounts for lateral conduction within the three-dimensional roughness features on the scaled model. Table I contains the minimum, average, maximum, and standard deviation of St for each of the roughness surfaces. The
values in the table represent only a 20 s time average from 80 to 100 s after flow initiation, whereas the area-averaged data in Figs. 4 and 5 are averaged over the full 250 s test time. In all four cases, there is a substantial variation in heat transfer over the rough surfaces. In general, roughness peaks can experience 2–3 times higher heat transfer than the area average. These results are consistent with measurements from Henry et al. [19] who reported up to a factor of 2.5 heat transfer augmentation at the leading edge of spherical protuberances in a turbulent boundary layer. This effect is partially due to the energetic interaction between the flow and the roughness peak as the flow accelerates to navigate around the obstruction. In addition, roughness peaks reach further from the wall into the thermal boundary layer where higher temperature fluid (on average) is present; thus, the elevated measurements in these regions. This is actually welcome news for turbine thermal load management. Since a substantial portion of the heat transfer augmentation occurs at these elevated peaks of the deposit, the path to the metal substrate (through the deposit peak) is longer, resulting in a greater thermal resistance. Thus, the increase in local metal temperature beneath the deposit (and TBC) will be less severe. Unfortunately, flow separation behind the deposit roughness peaks generates highly turbulent flow in the wake of the protuberances. This is shown in Fig. 6 which contains side-by-side surface height and St contour plots for the region near roughness peaks on the Burn 1 and 2 models. Though not as high as the heat transfer at the roughness peak, the wake regions (indicated by circles in Figs. 6(a) and 6(d)) still experience heat transfer augmentation that is 75% higher than the surrounding surface when compared to the smooth surface heat transfer. And if the deposit is thinner in this wake-affected region, the lack of added insulation from the deposit could result in a local hot spot penetrating deep into the TBC layer. Finally, the standard deviation data in Table 1 show a trend similar to that exhibited by the mean forward-facing angle in Fig. 4. As might be expected, the heat transfer variations become more pronounced as the deposit surface becomes more peaked.

Conclusions

Successive deposits were generated on a TBC coupon in an accelerated test facility at a gas temperature and velocity representative of first stage high-pressure turbines. The coupon was subjected to four successive 2 h deposition tests. The particulate loading was scaled to simulate 0.02 ppmw of particulate over 3 months of continuous gas turbine operation for each 2 h laboratory simulation (for a cumulative 1 year of operation). Convective heat transfer measurements were made using scaled models of the deposit roughness after each exposure period. Based on the results presented in this study, the following conclusions are offered:

1. For the conditions studied, deposit roughness size ($R_z$) and shape ($\alpha_j$) experienced a temporary lull in growth during the deposit evolution. This produced a comparable plateau in measured heat transfer coefficient (St) as deposits filled the valleys between isolated peaks created during initial operation. The implication is that heat load management may be most severe during the initial phase of deposition, when the deposit peaks are distributed over the relatively smooth surface. The subsequent valley filling reduces the roughness signature as well as provides additional insulation to the blade. Existing Stanton number correlations based on various roughness statistics captured the trend in the experimental data; and

2. Surface roughness features can create local St variations of up to a factor of three from the area average. Isolated peaks result in substantially elevated levels of convective heat transfer in the wake directly downstream of the protuberance.

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Nomenclature

- $I$: total number of y direction surface measurements
- $J$: total number of x direction surface measurements
- $L$: wind tunnel length from bleed to measurement location (1.21 m)
- $M$: Mach number
- $Pr$: Prandtl number
- $Ra$: Reynolds analogy factor ($2St/cf$)
- $R_0$: centerline averaged roughness (mm) (Eq. (1))
- $Re_L$: flow Reynolds number $U_L/L/v$
- $Re_{ks}$: roughness Reynolds number $u_{ks}/v$
- $R_t$: maximum peak-to-valley roughness (mm)
- $R_z$: $k$=mean peak-to-valley roughness (mm)
- $St$: Stanton number ($h/\rho c_p U_s$)
- $T$: flow temperature ($^\circ$C)
- $U_w$: wind tunnel velocity (13 m/s)
- $b$: plate thickness (25 mm)
- $c_f$: skin friction coefficient
- $c_r$: specific heat
- $i$: y direction indexing variable
- $j$: x direction indexing variable
- $k$: average roughness height ($=R_z$)
- $k_e$: equivalent sandgrain roughness
- $t$: time
- $x$: surface dimension perpendicular to the gas stream
- $y$: surface dimension parallel to the gas stream
- $z$: height of an individual roughness element
- $\alpha$: thermal diffusivity
- $\alpha_{ef}$: average forward-facing angle (Eq. (2))
- $\kappa$: thermal conductivity
- $\nu$: kinematic viscosity
- $\theta$: boundary layer momentum thickness
- $\rho$: density

Subscripts

- $0$: flat plate baseline
- $R$: roughness
- $s$: surface
Fig. 6  Heat transfer coefficient and surface height plots for a 67 mm × 83 mm region on the Burn 1 and 2 roughness models. (Flow direction is from top to bottom as indicated.) Wake regions with elevated $St$ values are circled: (a) Burn 1 surface height contour plot (mm); (b) Burn 1 $St$ contour map; (c) Burn 2 surface height contour plot (mm); and (d) Burn 2 $St$ contour map.

$\infty = \text{freestream}$

References
ary Layer to a Step Change in Surface Roughness. Part 1: Smooth to Rough,”
Boundary Layer with a Short Strip of Surface Roughness,” AIAA Paper No.
92-0249.
York.
Smooth and Rough Tubes at Various Prandtl Numbers,” Int. J. Heat Mass
Transfer, 6, pp. 329–353.
ation on Protuberances and Surface Roughness Elements,” J. Thermophys. Heat