Proceedings of IMECE'03
2003 ASME International Mechanical Engineering Congress
Washington, D.C., November 15–21, 2003

IMECE2003-42258

SPECIFYING EB-PVD PROCESS PARAMETERS FOR COATING OF A SECOND STAGE TURBINE BLADE USING AN EXPERIMENTALLY VERIFIED CAD MODEL OF THE PROCESS

William C. S. Weir,
Mechanical Engineering, Worcester Polytechnic Institute

Richard D. Sisson, Jr.,
Mechanical Engineering, Worcester Polytechnic Institute

Sudhangshu Bose,
Pratt and Whitney

ABSTRACT:

A model was developed to predict the thickness of the thermal barrier coating (TBC) applied to specific points on a rotating PW4000 second stage turbine blade using electron beam physical vapor deposition (EB-PVD). The theoretical model of coating deposition rates as a function of position in the PVD vapor cloud (Knudsen cosine law) was experimentally verified. The experimental work consisted of a series of four turbine blades coated under various coating conditions. Based on the verified model, a UniGraphics (UG) CAD model of the process was built. A UG User Function (UFunc) was programmed to predict coating thickness for a wide variety of EB-PVD process parameters to populate a database of contoured coating profiles. A software tool was then developed to specify the manufacturing process parameters to fabricate a contoured EB-PVD TBC of partially stabilized zirconia. A coating profile matching routine was included in the software to identify the process parameters closest to the desired coating profile. The focus of this paper is on the experimental methods, the CAD model and the software tool.

INTRODUCTION:

In the gas turbine industry new process development of Electron Beam Physical Vapor Deposition (EB-PVD) depends largely on the experience of the process engineers and multiple trials. A system capable of specifying the process parameters required to yield a given partially stabilized zirconia thermal barrier coating thickness (TBC) on complex curved surfaces could reduce the time and expense of new process development and expand the utility of the EB-PVD coating process in the gas turbine as well as general industry.

A mathematical model capable of predicting TBC thickness on a rotating turbine blade as a function of position in a coating chamber was developed based on the application of the Knudsen's cosine law of emissions [1]. The was done specifically for a PW4000 second blade in a Pratt and Whitney coater, but the same approach could be applied to other complex shapes in a variety of EB-PVD coating chambers.

A UniGraphics (UG) User Function (UFunc) was written using the theoretical model to calculate the accumulated coating thickness at a series of 30 distinct points on three cross sections of the second stage blade. This UFunc ran the model repeatedly to populate a database with TBC thickness data and the associated EB-PVD process parameters used to create the virtual coating profiles.

The output of the UFunc was compared to the experimental results of four EB-PVD coated blades in order to validate the model.

Once the model was verified, a program was written to search the database of virtually coated blades created by the UG UFunc. Given the desired TBC thickness at one or more points on the blade, the database can be queried to find the EB-PVD process parameters required to produce the coating distribution. In addition, a normalizing scheme was devised to simplify and expand the utility of the searchable database.

THEORETICAL MODEL:

Equation 1 [1] states that the coating thickness deposited from a point on the surface of the evaporating ingot to any point (r, ϕ, φ) from an ideal point source is a function of the mass evaporated (M_e), the coated material density (ρ) and the radial distance from the point source (r). Figure 1 is a line drawing of the relationship between the emission source and the coated surface.

$$d = \frac{M_e}{\rho\pi}\left(\frac{\cos\phi * \cos\theta}{r^2}\right) \qquad [1]$$

Since the emission source in the coating chamber was not an ideal point source, the contribution of the entire emitting surface was accounted for by dividing the surface into 400 evenly distributed point sources.

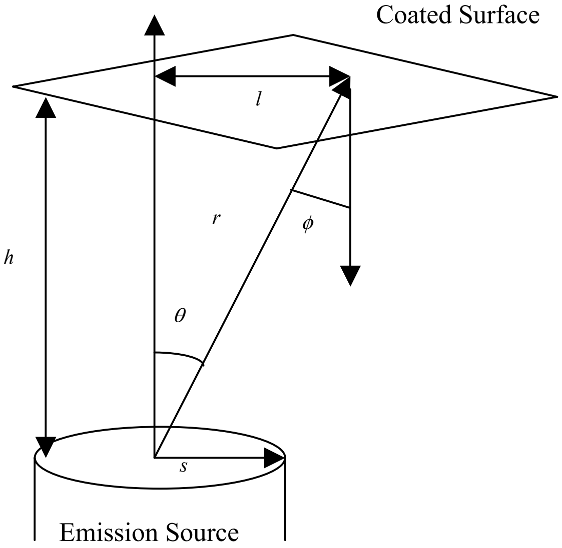


Figure 1: Coating Chamber

Data from previous experimental work in the same EB-PVD coating chamber were used to develop the bests fit parameter (0.88) found in Equation 2. This factor is the result of a simple linear regression comparison of better two thousand measured samples and the associated model predictions. These prior results were collected from coated flat plates and cylinders coated in the same coating chamber. Based on this prior work, Equation 2 was developed [2]. Equation 2 including the experimental constant (0.88) is referred to in this paper as the improved prediction model. The authors believe that the 0.88 constant is the result of several things, most notably an inability to accurately measure the amount of coating material or ingot that is used during each run, and uncertainty with respect to the density of the coated material which plays a material role in the model.

$$d = \frac{M_e}{\rho\pi}\left(\frac{\cos\phi * \cos\theta}{r^2}\right) * \boldsymbol{[0.88]} \qquad [2]$$

UNIGRAPHICS UFUNC:

The simplest way to determine the cosine terms for Equation 2 would have been to take the gradient of the equation of the three dimensional airfoil to find the unit normal vector to the surface of the airfoil. Unfortunately, the equation of the surface of a PW4000 second-stage blade would have been extremely difficult to determine was not already known. However, since the entire coating chamber had been drawn in UG, including the turbine blade, it was possible to properly place a blade in the CAD drawing of the coating chamber and query the CAD model to find the required cosines and distances.

Since the information was not easily exported out of UG, a UFunc was written inside UG to calculate the coating thickness applied to the turbine blade. The User Function queried the user for the mass evaporated, the emission source or sources and the surface to be coated. Using that information, the User Function queried the CAD model for the angles and distances needed to calculate the coating thickness accumulated at the 30 points on the blade.

A series of nested loops allowed the program to model the emission surface by dividing it into 400 evenly distributed point sources, each making its own contribution to each of the 30 blade points. The UFunc calculated the contribution of each emission point source to each blade point, summed the contributions and output it to a text file. After storing the summation, the UFunc repeated the calculation for each of the remaining points on the blade.

After calculating the contribution of all the emission sources to each of the 30 points, the UFunc rotated the blade a prescribed number of degrees, typically 10 degrees, and repeated the work from the beginning in order to model the rotation of the blade. For the purposes of simplifying the model, it was assumed that the rotation of the blade could be modeled as a single rotation instead of the multiple rotations that occurred during the actual coating process.

EXPERIMENTAL PLAN:

The experimental constant in the improved coating thickness prediction model shown in Equation 2 was based on results from static samples rather than rotating blades. Therefore, it was necessary to test the model using more realistic dynamic conditions. Pratt and Whitney donated four PW4000 second stage blades to be tested under varied coating conditions.

A central location in the coating chamber was chosen as it corresponded loosely to the position of a blade during production coating. All four blades were coated at the same position.

The amount of coating material, and the selection of emission sources used were chosen as the variables to test. In the coating chamber a selection of emission sources were available, and their impact on the coating distribution had not yet been investigated.

During the previous experiments the emission sources had not been varied, so a significant database already existed. Two experiments were undertaken using the same combination of emission sources that were used for the prior static test. In the remaining two experiments combinations of the original set of emission sources were used to investigate the impact emission sources had across the coating chamber.

EXPERIMENTAL PROCEDURE:

The second stage blades were made of a nickel-based super alloy and were cast as a single crystal. They were prepared using the same techniques and equipment used for production blades.

In each of the four experiments, a blade was welded to a short rod in the center of the rotating axis as shown in Figure 2. For each of the four experiments it was positioned in the coater with its axis of rotation at the nominal height above the surface of the emission source or sources. The blade was rotated at the standard rotational speed and along the central axis of the coating chamber.

Figure 2: Blade prior to coating

After coating, three cross-sections were cut from each of the blades. Each cross-section was mounted in an epoxy mount and polished using standard Pratt and Whitney techniques. Photomicrographs were taken at each of the 30 blade points that were modeled by the UFunc. Templates printed from the UG CAD model were used to ensure that the measurements were taken close to the correct locations.

EXPERIMENTAL RESULTS:

Figure 3 shows the results of all four rotating blade experiments plotted against the improved prediction model shown in Equation 2. The best-fit line is also shown along with the correlation coefficient in the upper right hand corner of the plot.

Section 1	Thickness	2	Thickness	3	Thickness
BP21	2.12	BP11	2.35	BP1	3.52
BP22	2.12	BP12	2.73	BP2	3.49
BP23	2.21	BP13	2.67	BP3	3.78
BP24	2.18	BP14	2.56	BP4	3.49
BP25	2.24	BP15	2.38	BP5	3.05
BP26	2.50	BP16	2.82	BP6	3.92
BP17	2.03	BP17	2.35	BP7	3.55
BP28	2.00	BP18	2.56	BP8	3.52
BP29	2.15	BP19	2.62	BP9	3.66
BP30	2.18	BP20	2.62	BP10	3.66

Figure 3: Normalized Coating Thickness Results for a PW4000 blade [2]

Figure 4 is a plot of the results of the UG UFunc model prediction versus the experimental results for all four blades.

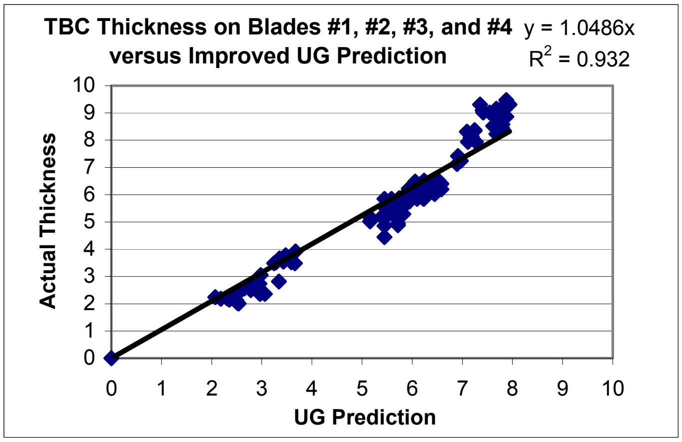


Figure 4: Improved Prediction versus Measured Thickness on Blades 1 through 4 [2]

The coating thickness results plotted against the improved prediction model for each individual blade still represent significant improvement over the current state of the art, but do not compare quite as favorably. An example is shown in Figure 5.

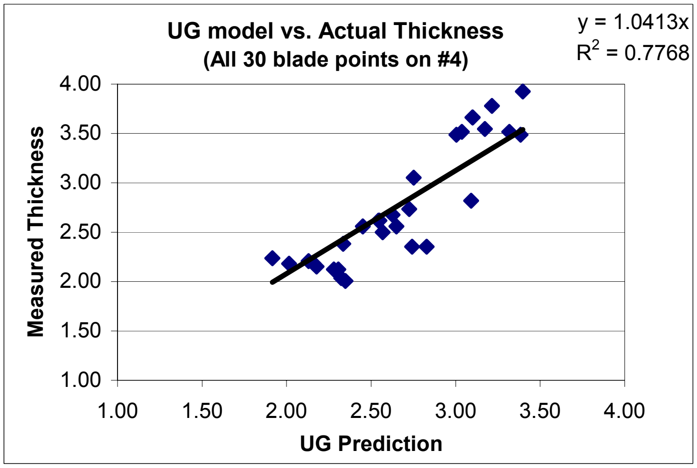


Figure 5: UG Model versus Actual Thickness for Blade #4 [2]

SOFTWARE SYSTEM:

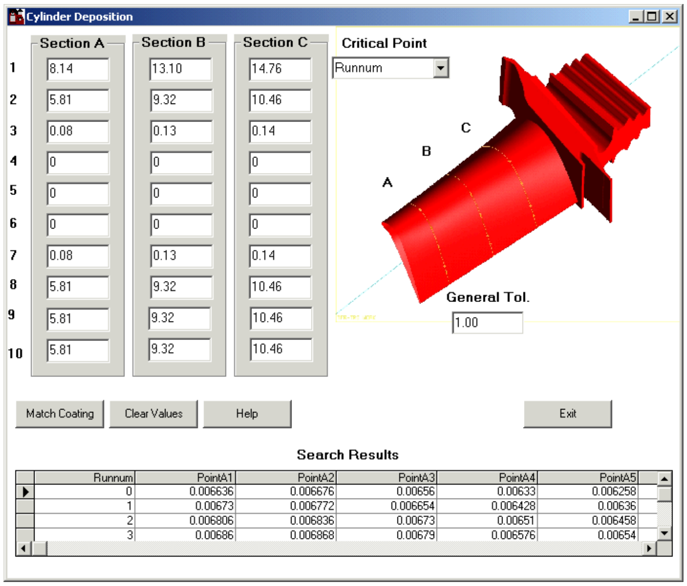
Since one run of the model could take up to twelve hours, a database and associated search routine were required to make the prediction capability of the model a time-efficient tool. With this in mind, the improved prediction model was run repeatedly using the UG UFunc to populate a database of virtually coated turbine blades at a variety of locations in the coating chamber. A software system was created to search the database and return the coating process parameters required to generate the requested coating.

The software system consists of two parts that are linked together, a graphical user interface (GUI) and a Microsoft Access database.

The GUI, written in Microsoft Visual Basic 6.0, contains the code for all the features in the form shown in Figure 6 as well as the code to search the Access database.

In its original embodiment, the search routine was capable of searching for individual thickness values instead of matching thickness distributions. The software system was thus unable to predict process parameters for the same coating profiles with different individual thickness values.

In the interest of expanding the utility of the database and correcting this shortcoming, a normalizing technique was conceived. If each virtually coated profile in the database were normalized by the thickest coating in the profile, then all the results would have the same magnitude. This would permit the search routine to search for matching distributions rather than distribution and magnitude as it does in the current system. That being the case, normalizing the designer's requested coating by dividing by the thickest requested coating would allow the search routine to find the most appropriate distribution. Once the best distribution is found, the linear nature of the mass of evaporated material can be exploited to determine the mass of coating material needed to obtain the requested coating profile.



	Section A	Section B	Section C
1	8.14	13.10	14.76
2	5.81	9.32	10.46
3	0.08	0.13	0.14
4	0	0	0
5	0	0	0
6	0	0	0
7	0.08	0.13	0.14
8	5.81	9.32	10.46
9	5.81	9.32	10.46
10	5.81	9.32	10.46

Critical Point: Runnum

General Tol.: 1.00

Search Results

Runnum	PointA1	PointA2	PointA3	PointA4	PointA5
0	0.006636	0.006676	0.00656	0.00633	0.006258
1	0.00673	0.006772	0.006654	0.006428	0.00636
2	0.006806	0.006836	0.00673	0.00651	0.006458
3	0.00686	0.006868	0.00679	0.006576	0.00654

Figure 6: The GUI for the Software System [2]

ACKNOWLEDGMENTS:

The authors are grateful to Mr. Mark Zelesky, Pratt and Whitney, for his technical advice and enthusiastic support of this work, and to Mr. Steve Burns, Pratt and Whitney, for providing manufacturing support. Also, we would like to specifically thank Mrs. Rachel Peled for her assistance and expertise with UG.

REFERENCES

1. Glang R., “Vacuum Evaporation,” In: Maissel LI, Glang R, editors, 1970, *Handbook of Thin Film Technology,* McGraw-Hill, New York, pp 1-3 to 1-123.
2. Weir, W.C.S., 2001, “Development of a rule based software system for the fabrication of a contoured EB-PVD TBC on a PW4000 second stage blade,” Ph.D. thesis, Worcester Polytechnic Institute, Worcester, MA.