ASSESSING THERMAL BARIER COATINGS BY INVERSION OF EDDY-CURRENT IMPEDANCE DATA

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Abstract: The non-destructive evaluation (NDE) of high temperature coatings is one of the important factors in achieving a high level of structural integrity in advanced gas turbines. In this paper, we demonstrate that sophisticated eddy-current techniques can be utilized to measure the thickness and remaining life of high temperature coatings. Some research has been conducted to apply such techniques to the preservice case, for which the coating has one nicely defined layer, and nothing of consequence has diffused into the base metal that would create additional layers of anomalous material. We discuss the much more difficult inservice case, in which the time temperature exposure of the combustion turbine blade has created a four-layered system, in addition to the base metal. The particular coatings that we discuss are made up of NiCoCrAlY with a top aluminide coating, GT33+, and without the top aluminide coating, PWA286.

Introduction: Advanced turbines, such as the GE Frame 7FA/9FA, are used in applications ranging from aerospace to land-based power generators. These turbines are fired at higher temperatures (1850°F-1950°F), and utilize optimum cooling of hot section components. Because of the higher operating temperature, the performance and durability of the first stage blades has become one of the prime life-limiting factors. Individual blades are nickel-based GTD111 alloys, that are protected by sacrificial metallic coatings to extend service life. The first-stage blades are expecially important, and it is desirable to develop an *in-situ* NDE system to monitor, evaluate, and predict remaining coating life. The coatings used on the turbine blades include CoCrAlY and NiCoCrAlY, with a top aluminide coating (GT29+, GT33+, respectively), and a NiCoCrAlY coating, called PWA286 [1].

Victor Technologies, LLC has been performing research into the non-destructive characterization of in-service high-temperature metallic (such as MCrAlY) thermal barrier coatings (TBC) applied by vacuum plasma spray on Ni-based superalloy turbine blades. In this report we describe our efforts in applying **VIC-3D©** to the problem of characterizing the GT33+ duplex coating.

The GT33+ duplex coating has two layers of beta aluminide, an especially rich one, called β+, having a conductivity of about 1.2×10^6 S/m, and a `normal' one, called β, with a conductivity of 8.4×10^5 S/m, as in the PWA286 coating. In addition, there is the usual aluminium oxide layer (Al_2O_3) that is the actual thermal barrier above β+, and an inter-diffusion zone (IZ) with a nominal conductivity of 3.2×10^5 S/m between β and the GTD111 substrate. We have not studied the IZ in this report, because it is small (as in the case of the PWA286) and less important in determining the remaining life of the coating. The GTD111 substrate has a nominal conductivity of 7.8×10^5 S/m.

Metallurgical measurements on various samples suggest that the β and β+ layers have comparable thicknesses, which we take to be 100 microns. Trying to assess the thickness of the IZ layer in the face of the large combined thickness of the aluminide layers seemed unwise, and that is one reason for ignoring the presence of IZ in our studies.

Thus, our inversion problem becomes one of determining the thickness of the Al_2O_3 layer, which has a known conductivity of 0 S/m and determining the conductivity of the β+ and β layers, each of which is 100 microns thick.

All coatings form a thin protective adherent layer of Al_2O_3 [2], [3]. As the protective oxide spalls off during service, aluminium in the coating diffuses out to re-form the protective oxide layer, and also diffuses into the substrate and causes the interdiffusion zone to increase in thickness.

A micrograph of a typical GT33+ coating shows a top NiAl overlay coating, followed by the NiCoCrAlY bond coat and the inter-diffusion layer. The GTD111 substrate is at the bottom.

The primary objective is to estimate the equivalent conductivity of the overlay and bond coatings, assuming a fixed thickness of each coating of roughly 100 microns. This information is essential to maintaining the integrity of blades, because it allows the timely repair or refurbishment of coatings to extend the service-life of operating blades. Further, it is desirable to obtain the thickness of the β-phase depleted zone (Al_2O_3), since this information indicates the level of blade exposure to service temperature. The overall remaining coating thickness indicates the reduction of the coating thickness caused by the oxidation-induced degradation of the top β-phase depleted layer [1].

We have performed a number of model calculations of the TBC problem, using our proprietary eddy-current NDE code, **VIC-3D©,** and have determined important system features, such as operating frequency, coil characteristics, electronic test equipment considerations, and means of accelerating the computations. As a result, we have concluded that the optimum frequency range for performing the inversions required of the TBC problem is 1MHz to 50MHz. Successful inversions in this range will allow us to achieve the desired resolution for these extremely thin coatings.

We used the Hewlett-Packard HP3577A Network Analyzer that is designed to operate over the frequency range of 5Hz to 200MHz. This instrument measures the reflection coefficient of a one-port network (the loaded coil), from which the impedance data that are the input to the inversion algorithm are determined. There are several steps to be carried out during the testing, including the characterization of the probe in free-space, the collection of the impedance data, and the inversion of these data using our `8-layer algorithm.' All of these issues are dealt with in an expanded version of this paper that may be found by visiting **http://www.kiva.net/~sabbagh** .

Results: Our data measurements were taken on the `suction side' of three actual turbine blade test samples, labelled A, B, and E. Using the HP network analyzer, we measured the reflection coefficient, S_{11}, of the loaded coil, from one to fifty megahertz, in one-megahertz steps, for each of the test samples. S_{11} is recorded as a magnitude and phase. Z_W, the change in normalized impedance due to the workpiece, is then computed from the scattering coefficients. (By `normalized' we mean that the true data at each frequency have been divided by the reactance of the freespace probe at that frequency.) Z_W is recorded as a change in resistance and reactance, with the change in reactance being negative, in accordance with Lenz' Law.

Based upon the inversion of our test data, our first conclusion is that the GTD111 substrate has a conductivity of 7.8×10^5 S/m, as in the PWA286 model. This was verified at the outset, in order to remove a variable from the Sample A, Sample B, and Sample E problems. By using impedance measurements (real and imaginary components) over the frequency range of 1-50 MHz, we gain insight into the status of each coating. High-frequency measurements of the normalized reactance give us a good estimate of the thickness of Z2, which, in turn, gives us some insight into the status of the coating, because this layer consists of Al_2O_3, which grows by the `sacrifice' of the β+overlay coating and/or the β bond coat. Furthermore, these high-frequency measurements, especially of the normalized resistance, help us to estimate the conductivity of β+, which is a principal determinant of the remaining life of the coating. Lower frequencies are useful in determining the conductivity of the β layer.

Next, we conclude that the Z2 layer of Sample A has a thickness of about 55 microns, with the β+ layer having a conductivity of between 7×10^5 and 8×10^5 S/m, and the β layer having a conductivity of 6×10^5 S/m. This corresponds to a β-depleted layer.

Sample E is the best of the three, having a Z2 thickness of 30 microns, a β+ conductivity of close to 1.2×10^6 S/m, and a β conductivity of 8.4×10^5 S/m. Indeed, if we assume that an `as-coated' sample has a β+ conductivity of 1.2×10^6 S/m, and a β conductivity of 8.4×10^5 S/m, as in the PWA286 coating, then Sample E is almost in an as-coated condition.

Sample B is the most confusing to interpret. The results indicate a Z2 depth of only 15 microns, whereas the β+ and β layers have a conductivity of only about 5×10^5 S/m. These low conductivities suggest that the layer is well-worn, which should correspond to a much larger value of the thickness of Z2. Perhaps much of Z2 has been ablated during use, and we see only a small residual, but the more likely explanation is that we are sensing the presence of `crazed cracking' in the coating, which would invalidate the simple one-dimensional four-layer model that we are using. These results agree with metallurgical examinations on these same samples.

Discussion: A goal of this study was to determine whether eddy-current technology could be suitable for determining the layer structure of thermal barrier coatings, and with what precision. We have answered the first question in the affirmative, and have demonstrated, both in this study and in others, that complex-layered coatings can be reconstructed with excellent precision and resolution using this technology. For further details on the problem of using eddy-currents to reconstruct thermal barrier coatings, please visit our website **http://www.kiva.net/~sabbagh** .

References:

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[3] Strangman, T. E., `Thermal Barrier Coatings for Turbine Airfoils,' *Thin Solid Films*, Volume 127, 1985, pp. 93-105.