

VALIDATION OF MULTI-FREQUENCY EDDY CURRENT MWM SENSORS AND MWM-ARRAYS FOR COATING PRODUCTION QUALITY AND REFURBISHMENT ASSESSMENT

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ABSTRACT

Coatings for oxidation, corrosion, and thermal protection provide the required materials performance for gas turbine blades and vanes in state-of-the-art industrial gas turbines. These turbines must withstand severe operating conditions for well over ten thousand hours. Variations in the coating thickness, and increased porosity, can influence the lifetime of such coatings significantly. For components that have been removed from service, effective assessment of the aged coating and substrate condition is critical for refurbish/replace/continue-to-run decisions. A suitable device for coating thickness measurement and detection of unacceptable porosity is needed for ensuring the quality of such coatings. In this paper, we present new results on coating thickness measurements for metallic MCrAlY overlay coatings on gas turbine parts. These measurements were performed with a Meandering Winding Magnetometer (MWM[®]) eddy-current sensor using grid methods. This technique allows proper coating measurements even after a diffusion heat treatment for a better coating adhesive strength. The MWM technology enables measurement of the coating thickness, the absolute electrical conductivity (which may in turn be related to porosity or other properties of interest), and lift-off, which is related to surface roughness. Single-channel MWM sensors and multi-channel imaging MWM-Arrays permit capture of features of interest for a population of components. New capabilities for inspecting gas turbine components are, thus, provided. Inspection applications include metallic and non-metallic coating thickness measurements, porosity measurements, and detection of cracks on complex surfaces. Results of coating assessment for a production line of gas turbine vanes by means of a multifrequency MWM technique are presented for various combinations of coatings and base metals. A description of improved multiple frequency quantitative inversion methods is provided for simultaneous and independent measurement of multiple unknowns such as metallic bond coat thickness, metallic bond coat porosity, and top coat thickness. Ongoing research focuses on characterization of aged components using MWM sensors and imaging MWM-Arrays as well as on development of enhanced algorithms for four and five unknown coating / substrate properties. In a recent study of hot corrosion, uncoated nickel alloy specimens were characterized using an MWM sensor with grid methods. Preliminary results indicated that, within the limitations of the three-unknown single-layer model used, the method could readily identify specimens with no apparent corrosion damage, specimens with moderate corrosion damage, and specimens with severe corrosion damage.

INTRODUCTION

High-Temperature Coatings for Power Generation Components

The turbine (Figure 1) inlet temperature strongly influences the combined cycle power output, its efficiency, as well as the power output of the gas turbine. In the turbine section, rotating components such as turbine blades and stationary components such as turbine vanes, are exposed to the most extreme temperatures and mechanical stresses. Figure 2 shows a typical turbine blade and a typical turbine vane. Integrity and quality of bond coats for thermal

barrier coatings and MCrAlY overlay coatings of the blades and vanes are critical for further increase of the operating temperatures of gas turbines.

During production and/or refurbishment of coated gas turbine blades and vanes, an important aspect of the continuous improvement of coating processes is the nondestructive quality control of actual MCrAlY bondcoats and overlay coatings at the various stages of production or refurbishment. Current practice relies on integral applied coating weight information and spot-checking of coating thickness and metallurgical appearance via metallographic verification on coupons rather than actual components. This time consuming and destructive method provides limited and indirect information about MCrAlY coating quality and process stability. Both coating thickness and metallurgical quality can significantly affect the performance of the overlay coatings or bondcoat/TBC coating systems. The MCrAlY coating can have more than one function. When it is a bondcoat, it is used as a bonding agent for the thermal barrier coating (TBC), as well as a reservoir of aluminum for the formation of Al_2O_3 . When no TBC top coat is applied, the oxidation protection becomes the primary function of the MCrAlY overlay coating.

The lifetime of blades and vanes is influenced, among other factors, by the properties of MCrAlY bondcoat or overlay coating. If the MCrAlY coating is too thin, oxidation resistance will be low, while an excessively thick MCrAlY coating, either as a bondcoat or overlay coating, can be susceptible to cracking. Also, excessively thick bondcoat can lead to TBC spallation. As a result, the coating performance can influence the performance of the gas turbine, as well as the optimum use over the life of the coated blades and vanes in the turbine section of the gas turbine. The high cost of the blades and vanes in production, as well as the high cost of refurbishment combined with reliability, performance and safety concerns prompted a keen interest in techniques for effective monitoring of critical gas turbine components. Cost-effective condition and remaining life prediction for overlay, bondcoat and thermal barrier coatings require an accurate, practical, and fieldable nondestructive method that provides relevant information about thickness and degradation of the coating as well as degradation of the substrate.



Figure 1. Siemens Power Generation gas turbine models.



Figure 2. Uncoated turbine blade (rotating component) and vane (stationary component).

Conventional nondestructive testing equipment has a limited capability to characterize MCrAlY or bondcoat/TBC systems as it can measure no more than two variables independently, typically coating thickness and lift-off where lift-off is defined as the proximity of the material under test to the eddy current sensor. Moreover, reliability of these measurements may be strongly degraded in the case of components with complex geometry. This is a severe limitation, as many coated systems require measurement of additional parameters, such as the coating porosity (electrical conductivity) and/or the substrate conductivity. For refurbishment decision support, remaining β -rich layer thickness [Goldfine, 2001] or remaining aluminum content may need to be determined. Also, some aged MCrAlY coatings and superalloy substrates exhibit ferromagnetic (magnetic permeability $\mu > 1$) rather than paramagnetic behavior ($\mu = 1$), resulting in additional unknowns that need to be determined as part of coating characterization.

As indicated by Auld and Moulder [Auld 99], for conventional eddy-current sensors “nominally identical probes have been found to give signals that differ by as much as 35%, even though the probe inductances were identical to better than 2%.” Characterization of overlay coatings and TBCs with conventional eddy current sensors is rendered impractical by this lack of sensor reproducibility, difficulty in modeling of the complex winding interactions with layered media, and effects of lift-off and probe tilt on complex shaped components. These limitations for curved parts have been overcome through a combination of conformable sensors and independent determination of lift-off and other variables using the MWM. Also, high performance impedance instrumentation has been developed, specifically to provide the required capability over a wide frequency range.

MWM and Grid Methods

MWM – Using a spatially periodic, field conformable eddy-current sensor such as the MWM (Figure 3) and a quantitative model-based inversion algorithm, a nondestructive method has been developed initially for characterization of nonmagnetizable metallic coatings on nonmagnetizable substrates. The current method permits independent and simultaneous measurement of three unknown variables; in the case of TBCs, these unknowns include ceramic topcoat thickness, metallic bond coat porosity, and metallic bond coat thickness. It is applicable for manufacturing quality control of overlay coatings and TBCs and for in-service inspection of those coating/substrate combinations that do not become magnetizable in service. The method also works for some weakly magnetic coatings.

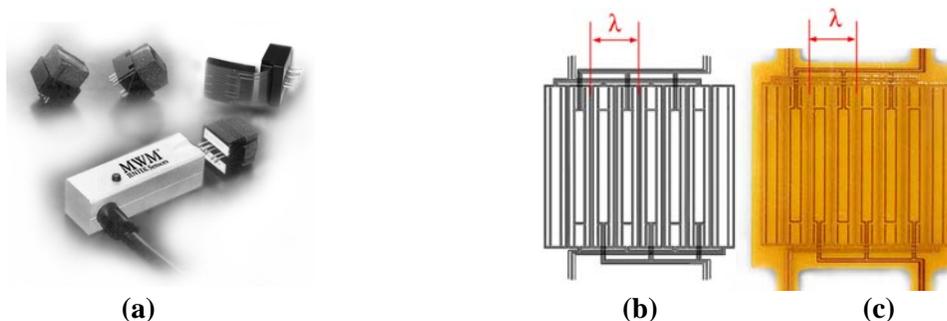


Figure 3. (a) Photo of MWM tips and MWM probe; schematic (b) and photo (c) of single sensing element MWM sensor.

The Measurement Grid-Based Inversion Method – The MWM sensor response is converted into material or geometric properties using measurement grids. These grids are used to map the magnitude and phase of the transimpedance into unknown properties of interest. The grids are two-dimensional databases, which can be displayed graphically to support procedure development. Typically, grids relate two measured parameters to two unknowns, such as the electrical conductivity and lift-off, or metallic coating thickness and lift-off. Three-dimensional versions of the measurement grids, called grid lattices, are discussed below.

For overlay coatings and TBCs, the MWM with inversion algorithm first provides a measure of effective absolute conductivity as a function of frequency. Then, for the metallic bond coat or overlay coating, thickness and conductivity are determined. The metallic bond coat conductivity reflects the porosity of the coating. In the case of TBCs, the lift-off provides a measure of ceramic coating thickness to within $\pm 2\mu\text{m}$; reproducibility of better than $\pm 1.5\mu\text{m}$, day-to-day, was demonstrated by NASA Glenn Research Center using the MWM and grid methods for ceramic thickness measurements [Miller, 2000].

Grid Lattices and Multiple-Frequency Algorithm for Determination of Three Unknowns – A multiple-frequency algorithm has been developed for the independent determination of three properties associated with the coating. This algorithm has successfully been applied to as-manufactured coatings. Enhanced versions of this approach have also been applied to aged coatings [Goldfine, 2001, Zilberstein, 2002]. In this algorithm, three-dimensional grid lattices are used. The lattices are sets of two-dimensional measurement grids, where each grid describes the sensor response to changes in coating thickness and lift-off at a given coating conductivity. The lattices shown in Figure 4 contain coating thickness – lift-off grids for four values of the coating conductivity at 1 MHz and 6.31 MHz showing a significant effect of frequency on the geometry of the lattices. Within each grid, the spacing between the grid points indicates the sensitivity for independently estimating the coating thickness and lift-off. The grid spacing depends on the difference between the coating and substrate conductivities. The lattices of Figure 4, are relatively coarse for visualization purposes, with only 140 lattice points (7 coating thicknesses, 5 lift-offs, and 4 coating conductivities), whereas a typical lattice has on the order of 20,000 points.

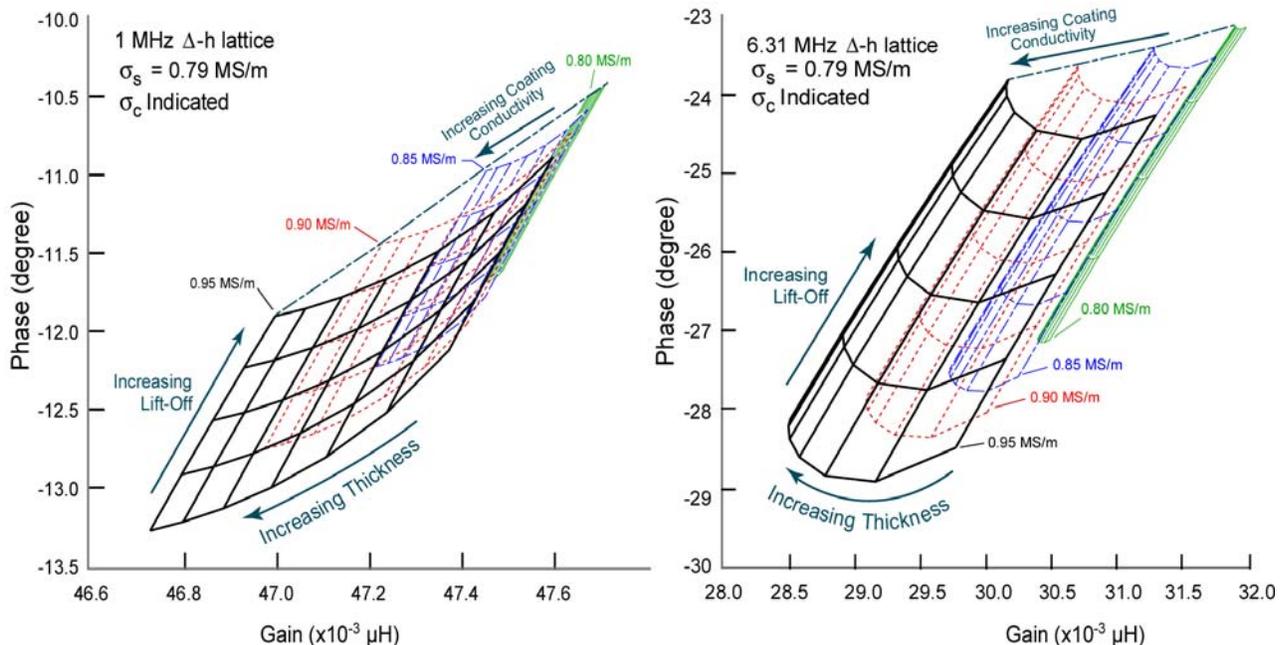


Figure 4. Coating thickness - lift-off grid lattices at two frequencies for MCrAlY coating family. Note that σ_s and σ_c are substrate and coating conductivities, respectively.

Four-Unknown Algorithm – A recently developed estimation algorithm allows independent determination of four or more parameters of interest. This capability is essential for both enhanced production quality control and condition assessment for refurbishment. For example, with the four unknowns one can characterize thickness of the bondcoat, spatial property variations of the bondcoat, TBC thickness, and spatial variations in the substrate near the coating. This four-unknown method also uses a predicted response obtained from an analytical model for an MWM sensor placed over layered media. Under an ongoing program funded by the Department of Energy, this algorithm is being adapted for rapid computation to make it suitable for commercial use.

MWM CHARACTERIZATION OF MCrAlY COATINGS

Earlier Results

The MWM technology has shown the capability to measure, nondestructively, the coating thickness for a variety of as-manufactured MCrAlY coatings, aluminide coatings, and other metallic coatings on various substrates. For example, overlay coating thickness values obtained in an earlier study [Goldfine, 2001] were shown to be in a reasonable agreement with metallography data for one of the MCrAlY coatings over a range of coating thicknesses between 100 and 350 μm . Using an early version of a five unknown method, for a degraded PWA 286 coating, the MWM outperformed other methods used in an EPRI round robin focused on measuring remaining β -rich zone thickness [Goldfine, 2001]. Based on an earlier study, the MWM can also be used to monitor thermal degradation of the overlay coatings and bondcoats, e.g., for PtAl bondcoat [Goldfine, 1999].

Evaluation of MWM with Grid Methods for Production Quality Control

The goal of this study was to evaluate and qualify MWM with grid methods for characterization of nickel-based and cobalt-based MCrAlY coatings on three different superalloy substrates. The superalloy substrates, investigated with their respective MCrAlY coatings, were:

- Alloy 1 (Co-base alloy)
- Alloy 2 (Ni-base alloy)
- Alloy 3 (Ni-base alloy)

MWM measurements were performed over a wide range of frequencies (typically 400 kHz to 16 MHz) on coated components of interest. Grid lattices for the substrate/MCrAlY combinations were used to obtain coating thickness, coating electrical conductivity, and sensor lift-off. The electrical conductivity can be used to identify areas of increased porosity. In each case, the coating thickness results derived from the MWM multiple frequency algorithm method were validated by checking them against metallography. Also, note that the final lift-off estimates correlated well with the surface roughness of the metallic coating.

It is important to note that all of the examined MCrAlY coatings had gone through the diffusion heat treatment for improving coating adherence to the substrate. Thickness measurements of MCrAlY coatings in this condition pose an especially tough problem for conventional eddy current technology.

Figure 5 shows plots of the effective conductivity as a function of frequency for a previously examined substrate/coating system and for one of the three substrate/coating systems examined in this study. The MWM measured conductivity for the substrate alloy (either measured on an uncoated part or estimated from the lower frequency measurements) and those of the coating (estimated from the higher-frequency measurements) are sufficiently different to provide coating thickness estimation using the three-unknown algorithm. Significantly smaller conductivity differences could be accommodated using this technology.

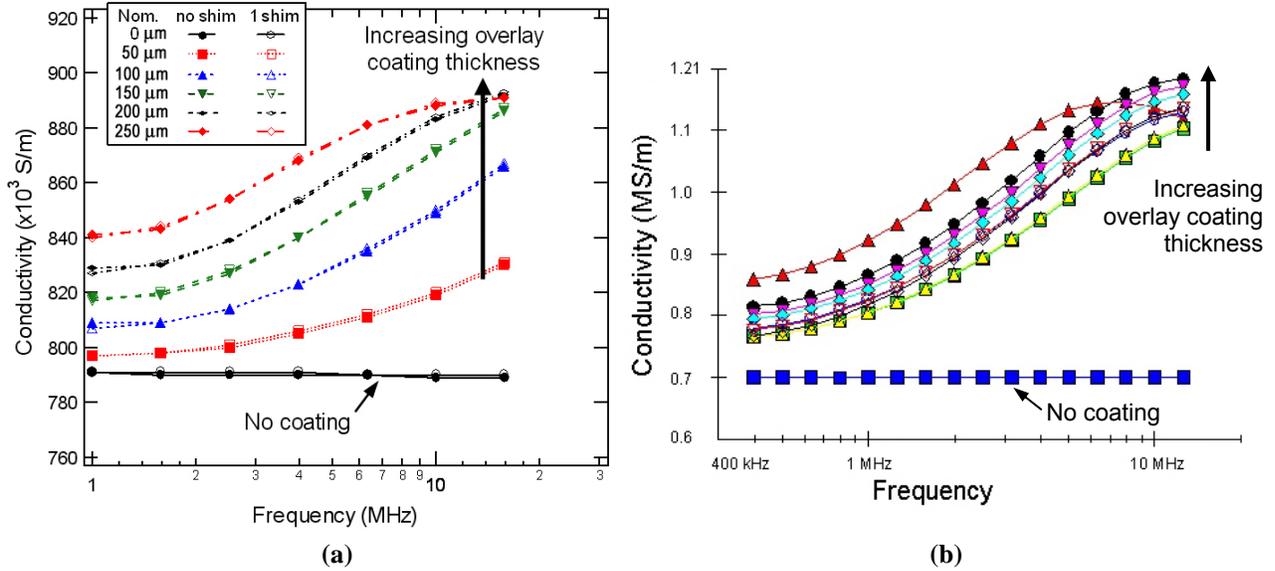


Figure 5. Effective conductivity as a function of frequency for uncoated and coated material. (a) Results from an earlier study; (b) results for coated alloy 1. Note that the results are essentially not affected by increasing lift-off, i.e., by adding a 25- μm thick shim between the sensor and part.

Figure 6 shows the comparison of MWM measured coating thickness with metallographic results. Any data points on the diagonal line in each of the three plots in Figure 6 would correspond to a perfect agreement between MWM and metallographic results. The dotted lines denote $\pm 15\%$ deviations from the ideal match of the values. When comparing MWM with metallography, note that MWM provides measurements over the area under the MWM sensor footprint, whereas measurements on a metallographic section are made at the edge of each sample. Thus, the one-dimensional thickness measurements in the metallographic cross-section may differ from two-dimensional MWM measurements that provide thickness averaged over the area under the MWM sensor footprint. Figure 6 also indicates a measurement range of 125-375 μm coating thickness over which the deviation does not generally exceed 15%. This represents an acceptable correlation between MWM and metallographic measurements for the application of MWM technology in MCrAlY coating production monitoring.

The data presented in Figure 6 were obtained as a part of MWM technology validation prior to its implementation for production quality control. After a general validation of the technology on the above-mentioned substrate/MCrAlY systems, a “10 percent coating thickness check” by MWM was implemented for a component made of Alloy 1 (cobalt-base alloy) at one of the coating suppliers. A total of twelve measurement points were defined on the pressure and suction sides of the airfoil, as well as the outer and inner platforms of the vane. Quality assurance personnel took measurements in a production environment. As a preparation for TBC coating, the measured parts were “smoothened” after a diffusion heat-treatment. Two differently qualified VPS MCrAlY coating processes were monitored in the above-mentioned manner.

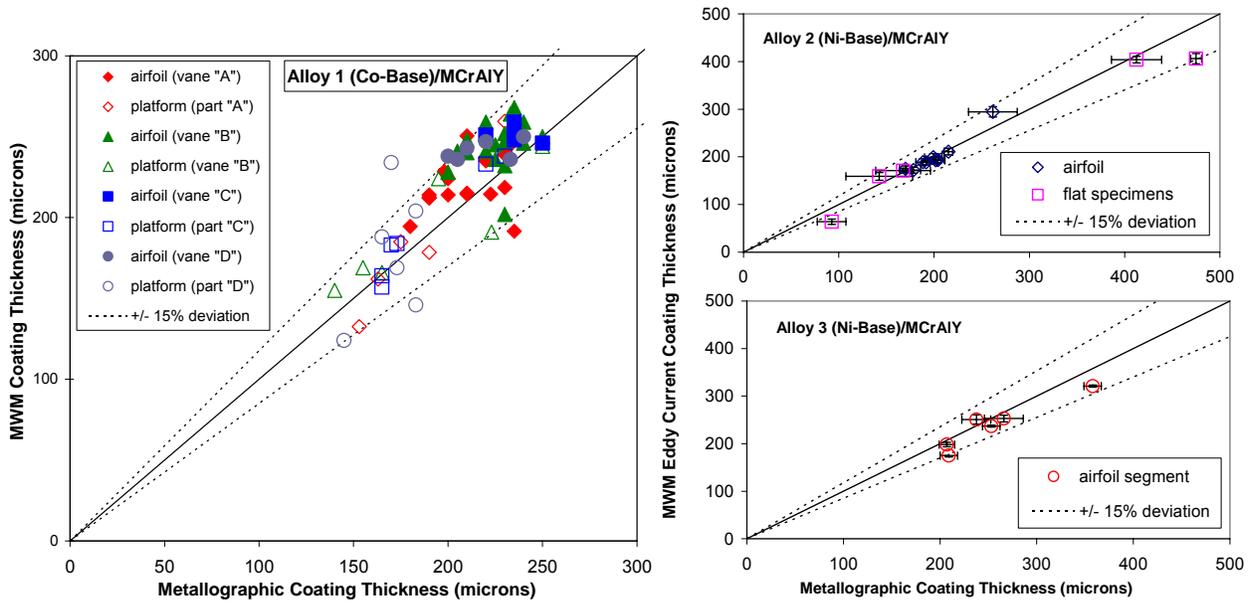


Figure 6. Comparison of MWM with metallographic MCrAlY coating thickness measurements for three different substrate/coating combinations.

Figure 7(a) and (b) shows the results for all 12 measurement points on each vane for a total of 88 and 44 parts, for Process 1 and Process 2, respectively, taken over the course of one year. Also shown is the average of all measurements at each location and the +/-15% deviation from this average value. Furthermore, shown is the average thickness of three parts determined metallographically. The average values from MWM and metallography generally match within 15% of each other, while individual measurements fall outside the +/-15% margin as a result of normal process variations.

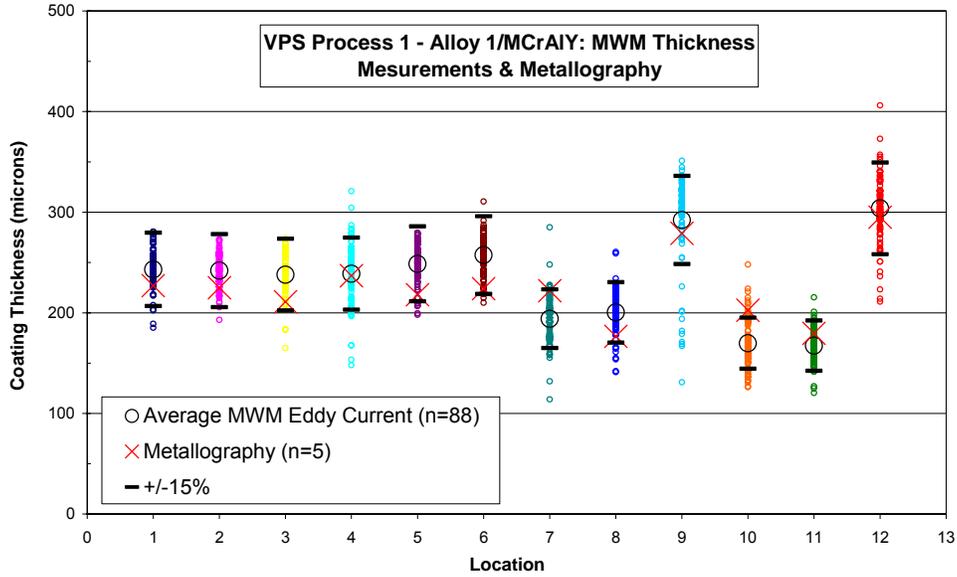


Figure 7(a). MWM results of 10% production MCrAlY coating thickness measurements for Process 1.

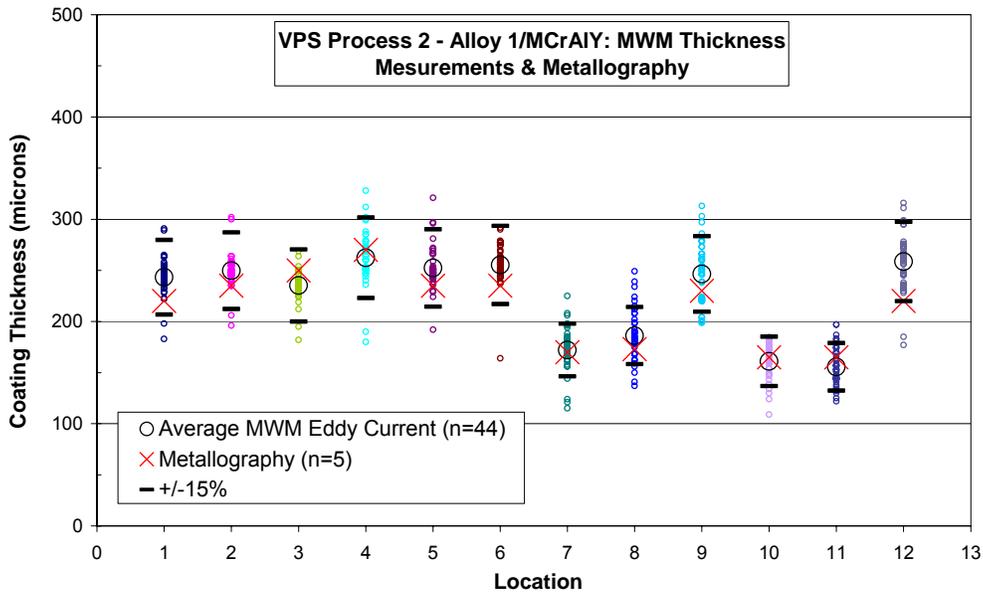


Figure 7b. MWM results of 10% production MCrAlY coating thickness measurements for Process 2.

Surface Roughness Measurements

MWM measurements of lift-off provide the capability to estimate roughness of overlay coatings at different stages of production as well as bondcoats prior to application of TBC. It is not generally sufficient simply to estimate lift-off at the highest frequency using the conductivity/lift-off grid, because it does not incorporate the presence of a coating in the model. The use of the coating algorithm that accounts for the presence of the coating, results in a better lift-off estimate and, hence, in a better roughness measurement.

Coating thickness, conductivity, and lift-off measurements were carried out with the MWM system at the specified locations on three samples. The goal was to demonstrate that the surface roughness might be determined by correlating it with the lift-off measurements. The results are shown in Figure 8. A very clear linear relationship is evident in the figures.

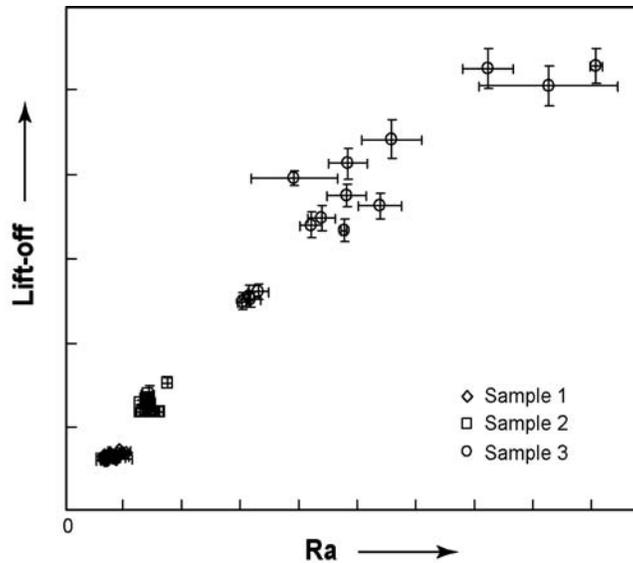


Figure 8. Correlation between surface roughness and lift-off for three samples.

PRELIMINARY RESULTS FOR HOT CORROSION CHARACTERIZATION

An MWM sensor was used in a recent study of hot corrosion on non-coated nickel alloy specimens. The results demonstrated the following:

- MWM with grid methods readily discriminated between corroded and non-corroded specimens.
- MWM measurements identified the presence of corrosion damage even for the specimen with the lowest reported corrosion layer thickness (“corrosion depth”), i.e., 15 μm .
- Within the limitations of the three-unknown single-layer model used, the results permitted separation of specimens, in terms of corrosion damage, into three groups (Figure 9):
 - No apparent corrosion damage (Damage State I);
 - Moderate corrosion damage (Damage State II); and
 - Severe corrosion damage (Damage State III).
- This capability provides a quick MWM screening method for identification of corrosion damage severity.

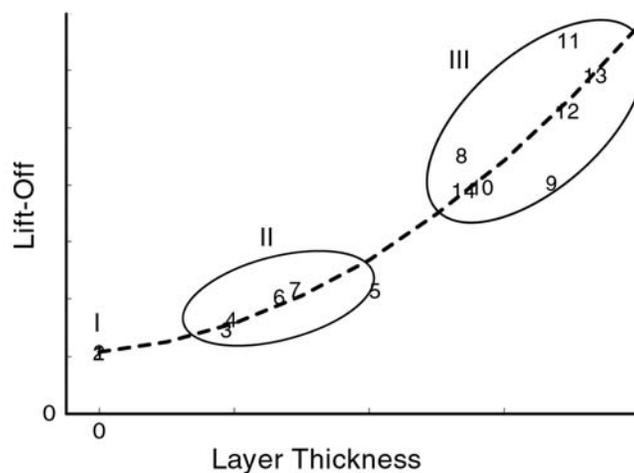


Figure 9. MWM measured lift-off vs. effective thickness using a three-unknown model. I, II, and III are the three corrosion damage states identified in the study.

CONCLUDING REMARKS

The agreement between the MWM coating thickness results and metallography shown in Figures 6(a) and 6(b) is remarkably good. In addition, MWM has significant advantages over metallography since it can provide coating thickness measurements nondestructively at any number of selected locations on actual parts in production. Furthermore, it can provide information on coating porosity variations and TBC thickness. Also of interest, the correlation of MWM lift-off measurements with surface roughness has been demonstrated. This provides a fast alternative to other profilometry methods even for complex surfaces.

A study of hot corrosion yielded promising results. Semi-quantitative measurements of corrosion severity using a three-unknown algorithm were shown to be possible. MWM technology can thus be used as a screening method. Advantages by using higher order algorithms will be explored in future investigations.

The MWM results presented in this paper are based on a three-unknown algorithm. For magnetic coatings and/or substrates as well as for substrates with spatially variable properties, an algorithm that can handle four or more unknowns can be used [Zilberstein, 2002].

Results presented in this paper were obtained using an MWM sensor with a single sensing element. Imaging MWM-Arrays provide additional powerful capabilities for inspection of coated turbine components. These arrays with multiple sensing elements have the ability to generate images that reveal cracks, microstructural or chemical variations, as well as hidden geometric features.

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