

TBC Characterization Using Capacitive and Inductive Sensors with Multivariate Inversion Methods

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Abstract

This paper describes flexible inductive sensors, such as the Meandering Winding Magnetometer (MWM[®]) and MWM-Arrays for characterization of conductive nonmagnetic, conductive magnetic and nonconductive magnetic materials; and capacitive sensors, such as the flexible Interdigitated Electrode Dielectrometer (IDED[®]) (MWM and IDED are registered trademarks of JENTEK Sensors, Inc.) for characterization of dielectric materials. These sensors and multivariate inversion algorithms can provide effective nondestructive characterization of thermal spray coatings on complex shape components.

Introduction

Life-cycle costs of critical engine components in the turbine section are affected in large measure by the condition of the thermal barrier coatings (TBCs). Realistic assessment of the TBC condition, based on measured intrinsic properties, could significantly reduce these costs. Condition observability is important for run/rework/retire decision support at the intermediate level, for depot inspections of components, and for accurate assessment of the coatings in as-fabricated and refurbished components. Reliable coating condition assessment would enable improved prediction of remaining component life and reduce likelihood of premature failures. This would provide a basis for implementation of retirement-for-cause practices for TBCs. Improved TBC and bond coat characterization methods could also be used for objective screening of new coating systems.

Because of the severe environment in which they operate, turbine section components are subject to a variety of damage mechanisms during their service lives. Their typical operating temperature of up to 2000°F (~1100°C) causes migration of alloying elements and accelerates inward diffusion of oxygen. Oxidation of the bond coat can introduce substantial stress at

the bond coat/ceramic interface and result in spallation of the ceramic top coat [1]. The combination of this high operating temperature and the high mass flow rate experienced by the turbine blades results in thinning of the top coat, which can produce hot spots in the underlying blade or vane resulting in nonuniform degradation of the thermal barrier coating.

The need for improved quality and in-service condition assessment of TBCs has been clear for some time. Characterization of coatings poses challenges because of the large number of variables associated with their layered structure. Variations in the properties and/or dimensions of the coatings or substrate have the potential to obscure other conditions. Characterization of TBCs and bond coats with conventional eddy current sensors is impractical due to the lack of sensor reproducibility, the difficulty in modeling the complex winding interactions with layered media, and the complex shape of turbine blade surfaces. Advanced conformable eddy current sensors alone can provide characterization of the bond coat [2] and TBC thickness measurement, but cannot meet all TBC characterization needs. The combination, however, of JENTEK's MWM and IDED technologies with multivariate inversion methods has the potential to provide a comprehensive solution for TBC quality control and condition assessment.

Meandering Winding Magnetometer (MWM) and MWM-Arrays

Several examples of MWM and MWM-Array eddy current sensors are provided in Figure 1. Each sensor has a single drive winding, consisting of one, two or several rectangular loops, and a number of rectangular inductive sensing loops. For these sensors, the transimpedance defined as sensing element voltage divided by drive current is measured independently for each sensing element.

These sensors are carefully designed to enable accurate and rapid modeling from basic physical principles and to minimize unmodeled contributions to the sensor response. Each sensing element response at one or more input current frequencies is used by a multivariate inversion algorithm to determine absolute property values, such as electrical conductivity, magnetic permeability, or coating layer thickness, at the location of the sensing element on the test specimen or component.

The sensor in Figure 1(a) averages measured properties over a $7\text{ mm} \times 9\text{ mm}$ footprint area and is typically used for point-by-point measurements at selected locations. Multi-channel MWM-Array sensors, such as the one shown in Figure 1(b), are often used for scanning complex geometry regions. During scanning, data are taken at each sensing element as it traverses a part to produce an image of each unknown property of interest. These images reveal spatial variations of measured properties/material conditions.

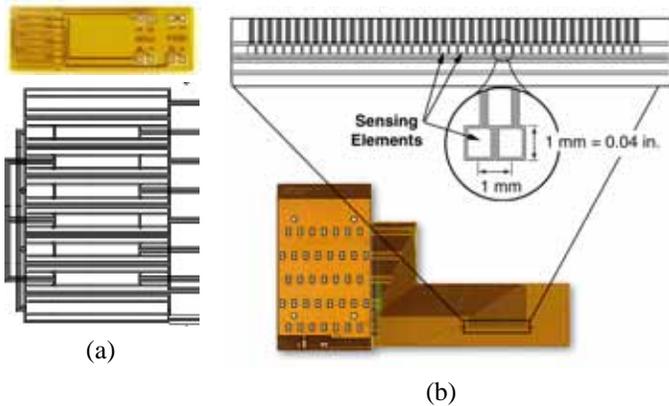


Figure 1. (a) Single-channel FS35 MWM sensor; and (b) multi-channel FA28 MWM-Array sensor.

Databases of precomputed sensor responses, known as measurement grids, are used with an algorithm to convert complex impedance data into two or more unknown property estimates at each sensing element.

The MWM sensors and MWM-Arrays are used for bond coat quality assessment [2] in production and for bond coat degradation assessment [3]. For a family of MCrAlY coatings, MWM sensors provide nondestructive measurements of bond coat thickness on as-manufactured parts that statistically match results of destructive metallographic measurements [2], [4]. MWM sensors and MWM-Arrays can be used for bond coat aging characterization and remaining life assessment as well as for hot corrosion assessment [unpublished data].

Interdigitated Electrode Dielectrometer (IDED)

The basic idea behind periodic field electroquasistatic dielectrometers is that the electrodes are laid out in a spatially periodic pattern on a substrate, making one-sided contact with the dielectric material under test. The imposed spatial period (wavelength) λ determines the rate of decay of the fields away from the sensor and is chosen to achieve the desired depth of sensitivity. The frequency of excitation does not affect this depth of sensitivity for low loss dielectrics. The periodic nature of the potentials and fields allows for the use of Fourier series methods in the semi-analytical models.

The IDED is suitable for measurements on insulating or slightly conducting dielectric materials. It is in use in several practical applications:

- Cure monitoring of polymers, epoxy, etc. [5].
- Measurement of porosity and thermal conductivity in ceramic thermal barrier coatings [6].
- Moisture measurement in transformer oil and pressboard [7], [8], [9].
- Thin film characterization.

The spatially periodic quasistatic sensors have several advantages over alternative sensing technologies:

- Control over the depth of sensitivity allows for measuring profiles of material properties by combining the results of measurements at varying depths, controlled by varying sensor wavelength.
- The layout allows for a good match between simulated and measured sensor response with the simulations carried out with efficient collocation point methods. This reduces the need for elaborate calibration standards and procedures.
- The new flexible substrate makes it possible to measure on curved surfaces, with the curvature having no appreciable effect on sensor response.
- The sensor geometry allows for the creation of sensor arrays, to allow scanning over large areas with good uniformity between individual array elements.

The basic structure for the capacitive IDED sensor is shown in Figure 2(a). A voltage V_D is applied to the driven electrode, while the sensing and guard electrodes are kept at ground potential. This results in a spatially periodic electric field that penetrates the material under test. The electric field lines originate on the driven electrode and terminate on the sensing or guard electrodes. The sum of the changing displacement and conduction currents to the sensing electrode are equal to the terminal current I_S . The sensor's complex transadmittance, defined as $Y_{21} = I_S/V_D$, is directly linked to the dielectric, conduction, and geometric properties of the material under test. A planar, nonconformable IDED sensor and enclosure are shown in Figure 2(b).

For layered media or materials having dielectric properties that vary with depth, the measured transadmittance between the drive and sense electrode, or the effective complex

permittivity of the material, is a thickness and depth-weighted response of the dielectric properties of the various regions. Typical excitation frequencies range from 0.005 Hz for highly insulating materials to 10 MHz for semiconducting materials. The depth of penetration of the electric field into the material is proportional to the spatial wavelength of the periodic electrodes. The periodic variation of electric potential along the surface in the x -direction produces an exponentially decaying electric field that penetrates into the medium in the z -direction. The depth of sensitivity is considered to be approximately $\frac{1}{3}$ of the fundamental spatial wavelength. This implies that small wavelength sensors will primarily respond to changes of material properties near the sensor-material interface, while larger wavelength sensors respond to changes farther from the sensor interface. Thus multiple wavelength sensors can be used to measure spatial profiles of dielectric properties [10].

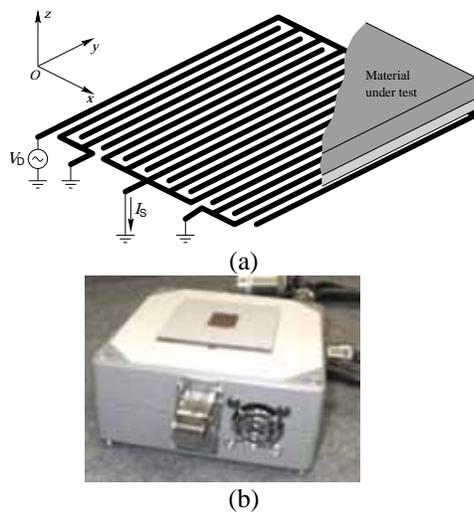


Figure 2. (a) Schematic diagram of an interdigitated electrode (IDED) sensor in contact with a test material; and (b) commercially available JENTEK sensor and enclosure for capacitive sensing of dielectric samples.

Several types of multiple wavelength sensors have been developed. In one approach, multiple sets of interdigitated (see Figure 2a) spatially periodic electrodes are laid out on a common substrate, as shown in Figure 3(a), placed in proximity to the test specimen. While this provides distinct wavelength IDEDs, each IDED is sensitive to different regions of the test material. As a result, if there is a spatial variation in the thickness or dielectric properties of the test material, or if there is an air gap variation, for example, due to uneven pressure against the material or dust particles, it can be difficult to combine the measurements for meaningful property estimates.

The solution, developed by JENTEK, is a segmented field sensor that integrates multiple sensing elements into a single sensing structure so that all of the sensing elements interrogate the same region of the material under test, as illustrated in

Figure 3(b) which shows a co-located two-wavelength IDED. [11]. A schematic for the electric field distribution is shown in Figure 4, where multiple sensing electrodes are placed within each interdigitated electrode period and respond to different effective wavelength (short or long) modes of the electric field. Thus, for this sensor, the lift-off and dielectric constant can be measured independently.

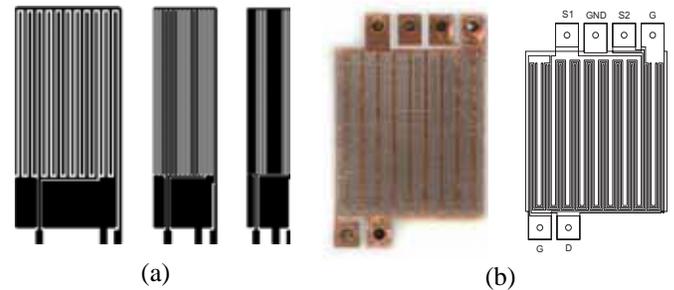


Figure 3. (a) A three-wavelength sensor with three separate sensing regions of different wavelength formed on a Teflon substrate with wavelengths of 5 mm, 2.5 mm, and 1 mm.; and (b) photograph and corresponding schematic for a two-wavelength co-located interdigitated electrode sensor.

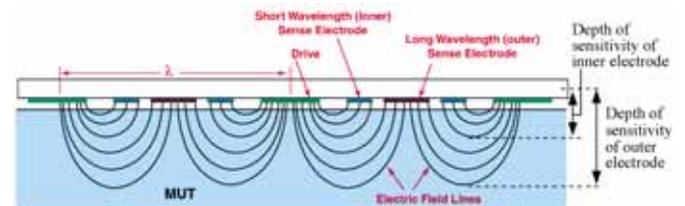


Figure 4. Multiple co-located dielectric sensors sense the same region of the test material (MUT), ensuring that the longer and shorter wavelengths have the same average lift-off or air gap thickness.

The multiple-unknown estimation methods have also successfully been applied to measurements with the segmented-field IDED. A segmented-field IDED with three effective wavelengths is shown in Figure 5(a) and another with five effective wavelengths and circular geometry is shown in Figure 5(b).

The sensor from Figure 5(a) and the models used to predict its response were tested by performing a two-unknown measurement (permittivity and lift-off) with a Teflon specimen. The experimental setup is shown in Figure 6. The results of the measurement are shown in Figure 7. As can be seen in the figure, the value of the relative permittivity reads about 2.05, in agreement with published Teflon properties, and it is independent from the applied pressure, which acts to change the air gap (lift-off) between the sensor and the Teflon. This confirms the validity of the multivariate methods as applied to the simultaneous measurement of more than one dielectric system property, using a segmented field sensor.

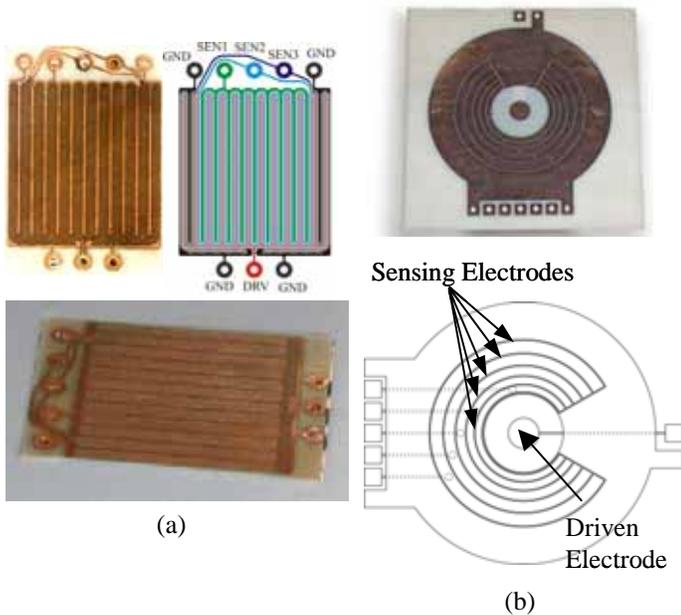


Figure 5. (a) Schematic and photograph of three-wavelength co-located segmented-field DS03 dielectrometer; and (b) segmented-field IDED sensor with rotational symmetry.

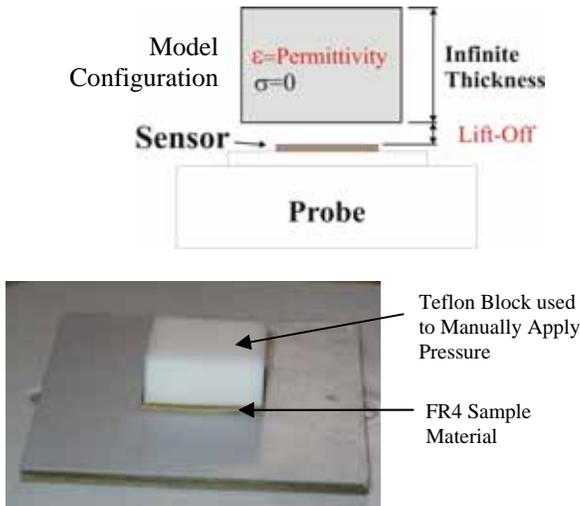


Figure 6. Two-unknown IDED measurement setup.

The next step was to measure three unknowns independently, which is a much more difficult problem than the two-unknown problem. All three wavelengths of the sensor in Figure 5(a) were used to measure the permittivity and thickness of a separate dielectric layer, simulating an insulating coating layer, such as a TBC, as well as the lift-off. The experimental setup is shown in Figure 8. The results in Table 1 illustrate once again the value of the multivariate approach. The permittivity measurements do not vary with layer thickness, and the thicknesses are within 10 μm of the micrometer readings.

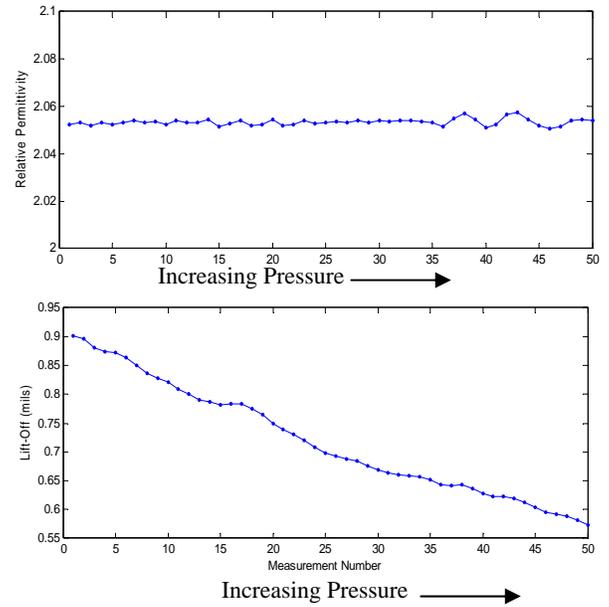


Figure 7. Dependence of the results of the two-unknown measurement on the applied pressure. The material under test was Teflon.

Figure 9 shows a photo of the DS04 flexible dielectrometer. This dielectrometer was fabricated on a flexible polyimide substrate and can conform to curved surfaces. The flexible DS04 sensor also features three spatial wavelengths.

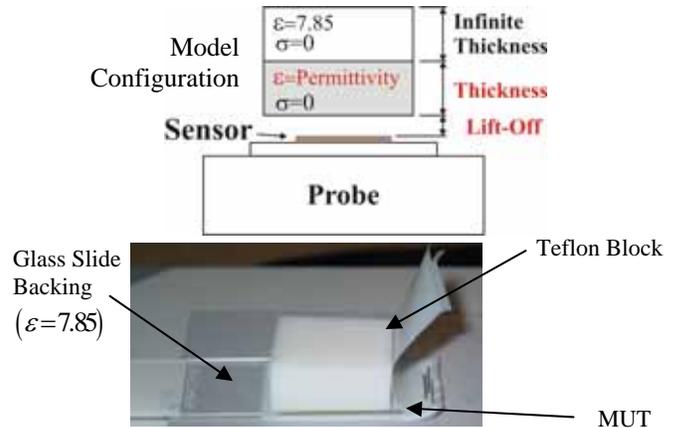


Figure 8. Three-unknown measurement setup.

Table 1: Three-unknown measurement results

Reference Relative Permittivity	Reference Thickness (micrometer) (μm)	Measured Thickness (μm)	Measured Relative Permittivity	Measured Lift-Off (μm)
2.0 - 2.1	442	450	1.93	6.6
		452	1.93	6.6
	516	523	1.94	6.6
		523	1.94	6.9
	589	590	1.95	6.4
		594	1.95	6.6

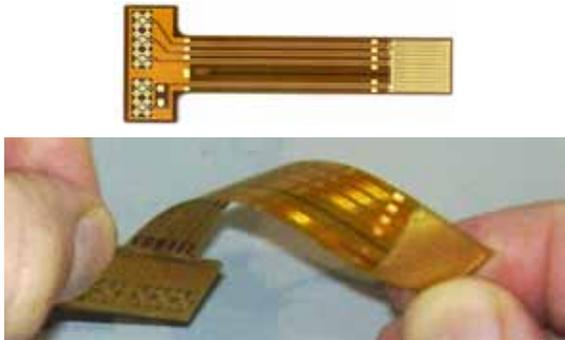


Figure 9. DS04 Flexible dielectrometer.

Repeatability of Measurements with the Flexible IDED

As a part of the flexible IDED performance demonstration, we have made permittivity measurements on samples of different dielectric materials on ten different days. These samples included a Teflon block, a 3-mm thick stack of paper, printed circuit board material, a stack of three glass slides, a block of zirconia toughened alumina (ZTA), an alumina block, stacks of acrylic plates, Teflon sheets, and Kapton sheets. IDED measurements were taken at the same locations on each sample and in the same orientation. The results of these repeated measurements are shown in Figure 10. The scatter of the data, shown by ± 2 standard deviations bars, is very small, except for the paper and ZTA. The results indicate that the flexible dielectrometer can provide very reproducible results for a wide range of materials, including ceramics, e.g., alumina. The scatter of the data for the paper could be caused by the behavior of the thick multilayer stack comprised of thin paper sheets and effects of humidity on permittivity measured on different days. The scatter in the ZTA data could have also been caused by the variable humidity, although it should be noted that, due to the nature of dielectric measurements, the absolute error in the permittivity estimate of materials with high dielectric constants is correspondingly higher.

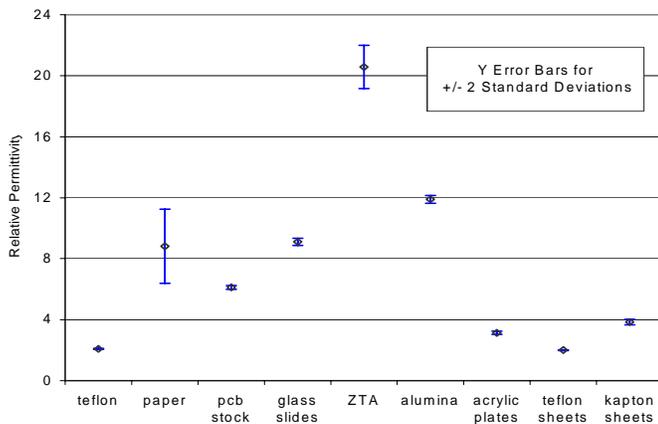


Figure 10. Permittivity for nine different dielectric material samples measured with a flexible IDED on ten different days.

Flexible IDED Arrays

Figure 11 shows the design of a flexible dielectrometer array, based on the electrode layouts of the DS03 and DS04 sensors. The multiple channels of the array are formed by isolating the sensing electrodes in every three spatial periods into separate groups. Thus, the width of each element is 1/3 of the width of the single-element IDED with the same depth of sensitivity, for three times higher spatial resolution.

Similar to MWM-Array sensors that are used in two different modes: (1) mounted at selected locations and (2) scanning/imaging mode, IDED-Arrays can be used for monitoring in time and for generating property images, e.g. for revealing material degradation patterns.

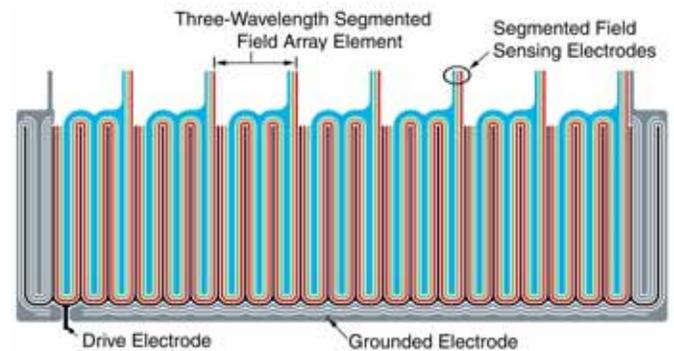


Figure 11. An IDED-Array sensor.

Characterization of TBC Systems Using the FS33 Magnetometer and DS03 Dielectrometer

Measurements with a magnetometer and dielectrometer can be combined for the independent characterization of various components of a TBC coating system. A representative scenario showing the unknown properties to be estimated by such a hybrid method is shown in Figure 12.

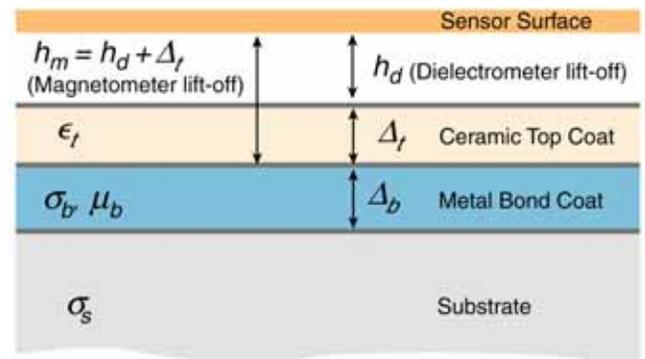


Figure 12. Multi-layered coating system that includes a ceramic top coat and a metal bond coat.

The magnetometer (MWM) is sensitive to the magnetometer lift-off (h_m), which is the sum of the “physical” MWM lift-off

and the ceramic thickness (to magnetic fields a dielectric material is indistinguishable from air), the thickness of the bond coat (Δ_b), the permeability of the bond coat (μ_b), and the conductivities of the bond coat and the substrate (σ_b and σ_s , respectively). Multiple-frequency operation, possibly together with a segmented-field design, can be used to simultaneously estimate four or more unknowns. In turn the dielectric sensor (IDED) is sensitive to the lift-off (h_d), the ceramic top coat thickness (Δ_t), and its dielectric permittivity (ϵ_t), which in turn may be correlated with the microstructure, microstructural defects, and/or thermal conductivity of the coating. With two different dielectric wavelengths, two of these properties may be estimated independently. The hybrid operation makes it possible to eliminate one of the unknowns in the IDED by using the top coat thickness information from the MWM.

To demonstrate this method, we made measurements on a set of specimens obtained earlier from NASA GRC. The specimens were 1¼ in. × 1¼ in. (32 mm x 32 mm) squares, with a stainless steel substrate and 10 mil (254 µm) thick YSZ top coat. These samples had a 5 mil (127 µm) thick MCrAlY bond coat between the YSZ layer and the substrate. An uncoated substrate specimen was used to characterize the substrate properties, which were needed for generation of the measurement grids. In each set of nine, there were three groups of three specimens. Each set of three corresponded with a different setting for the application of the top coat, presumably resulting in top coats with distinct porosities and/or other characteristics.

First, we measured on the specimens using an MWM sensor to obtain the bond coat thickness. Using the top coat thickness measurements determined from MWM measurements, we used the DS03 dielectrometer to measure the permittivity and lift-off of the ceramic top coat. The dielectric sensor and probe are shown in Figure 2(b). Each specimen was measured at two orientations (0° and 90° relative to the sensor), in order to look for anisotropy of the top coat properties. In the initial data collection, the measurements in the two orientations were made in order of ascending specimen name and then in descending order (36 measurements). The IDED was recalibrated and the procedure was repeated.

The results of the dielectrometer measurements are shown in Figure 13. One can see in the figures that on the whole the permittivity measured for each group of the three specimens does show a difference, indicating that we are sensitive to the process differences in the application of the ceramic top coat.

Thermal Barrier Coatings (TBCs)

Figure 14 shows a flexible IDED sensor (DS04) placed on a turbine blade with a thermal barrier coating (TBC), and the combined MWM - IDED dataset used to characterize the condition of the layered media. This capability to measure with MWM and IDED sensors is being incorporated into a

hybrid MWM-IDED sensor. In the case of thermal barrier coatings, improved condition assessment capability within an Adaptive Damage Tolerance (ADT) framework [12] offers potential to lower maintenance costs and improve safety margins.

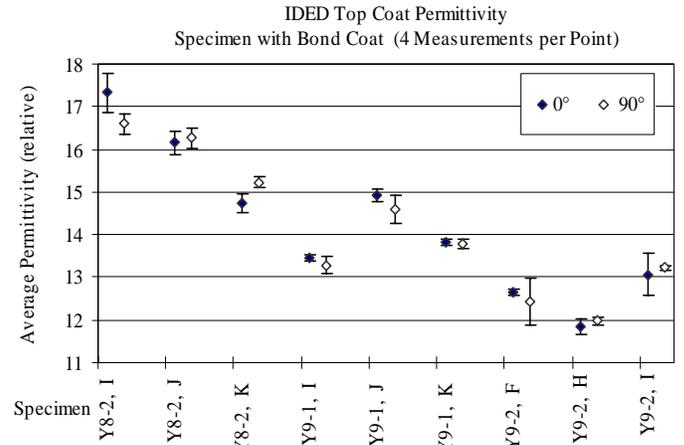
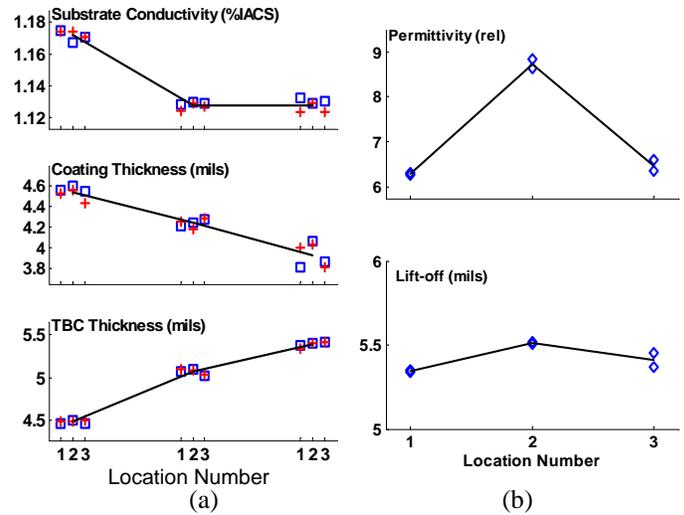
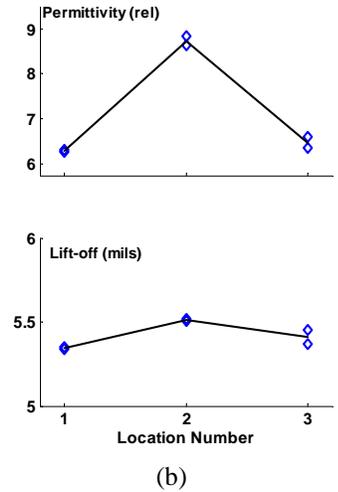


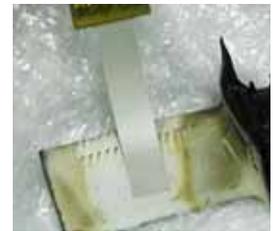
Figure 13. TBC permittivity of the nine specimens with bond coat and YSZ top coat – measurements in two perpendicular orientations.



+ Measurement with 1 mil shim
 □ Measurement without shim
 Average



(b)



(c)

Figure 14. Results of the combined measurement with the FS35 magnetometer and DS04 dielectrometer on a 1st stage high-pressure turbine blade with TBC: (a) three-unknown magnetometer results, (b) two-unknown dielectrometer results; (c) photograph of the JENTEK patented flexible IDED sensor on the turbine blade.

The use of composite materials and nonconductive coatings in aircraft structures and engines presents a variety of potential applications for capacitive sensing. For example, IDED sensors have been used to assess porosity in ceramic parts, to detect disbonds or cracks in composite materials, and to monitor moisture ingress below corrosion protective coatings (patents issued and pending).

Concluding Remarks

Results presented in this paper show some of the current capabilities of the interdigitated dielectrometers, including preliminary demonstration of the flexible dielectrometer application for TBC characterization on complex geometry components. This capability is expected to be significantly enhanced in a hybrid MWM-IDED sensor. The hybrid sensor would provide characterization of both bond coat and ceramic top coat in the same set of measurements. Similar to proven MWM-Array capability to generate images of measured properties for the metallic bond coats and substrates the IDED-Arrays are expected to reveal spatial patterns in aged ceramic top coats.

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