EDDY CURRENT METHODS FOR ASSESSMENT OF THERMAL PROTECTION SYSTEM MATERIALS

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ABSTRACT

Eddy current nondestructive evaluation (NDE) methods can be used for quality assessment, defect evaluation, and continuous monitoring during elevated temperature exposure of thermal protection system (TPS) materials. These inductive (magnetic field-based) sensors are suitable for examination of carbon-based TPS materials to provide both scanning assessment and in-situ monitoring capabilities. The sensors can be used on both flexible materials, such as felts, and rigid materials, such as reinforced carbon-carbon composites and Phenolic Impregnated Carbon Ablator (PICA).

These methods use a combination of physics-based models of layered media, multivariate inverse methods, and innovative sensor array constructs to enable independent measurement of geometric and material properties of interest. Since the penetration depth of the interrogating magnetic field into the material can be adjusted via the sensor dimensions and excitation frequencies, these sensors are capable of through-thickness measurement of material properties, including total thickness measurement and far-side surface recession monitoring of ablator materials.

This paper reviews these methods and describes several condition assessment applications. These include thickness measurement, orientation determination for anisotropic materials, and material uniformity and presence of flaws based upon electrical conductivity measurements. This paper also briefly describes capacitive (electric field-based) sensors for assessment of relatively insulating materials, such as resins, foams, and ceramic matrix composites.

1. INTRODUCTION

Thermal Protection Systems (TPS) protect space vehicles from the extremes of atmospheric entry conditions. Both structural strength and thermal protection are necessary attributes of the heat shield. The performance of modern heat shield structures is being expanded to enable more aggressive pursuit of asteroid and interplanetary exploration activities throughout the solar system. Risk mitigation dictates that the assembly and manufacture of the TPS be carried out specifically as designed. Human error and unpredictable curing anomalies are two of the leading reasons for manufacturing inconsistencies. In-process and post-cure nondestructive evaluation (NDE) is critical for the detection of defects associated with these process failures. Life management and risk mitigation are compromised when material behavior becomes unpredictable. Thus, if the structure is inadvertently manufactured such that it is out of compliance with the design specifications, it can lead to mission-ending and potentially catastrophic results.

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One of the NDE methods that can play an important role in ensuring the integrity of the TPS systems is eddy current methods. Eddy current methods use time-varying magnetic fields to inspect the material of interest. The magnetic fields induce eddy currents in conducting materials, such as reinforced carbon-carbon composite (RCC) or Phenolic Impregnated Carbon Ablator (PICA). The thickness of the conducting material, the presence of flaws or damage that can affect the flow of the eddy currents, and the proximity to a conducting substrate for electrically insulating TPS materials (e.g., foams) can affect the response measured by the eddy current sensor. The orientation of the anisotropic conductivity can also be measured with eddy current sensor designs that have a directional response. This paper reviews one such eddy current method often called the Meandering Winding Magnetometer (MWM®). The MWM sensor and MWM-Array technologies were originally and primarily conceived as sensors whose response could be accurately modeled, and could therefore be used to simultaneously obtain both geometric and absolute material property estimates, such as the material electrical conductivity, sample thickness, and gap ('lift off') between sensor and sample. In some cases, useful estimates can be obtained without the use of reference standards. The MWM-Array TPS measurements can be performed in either a surface mounted (in-situ) or scanning configuration; the MWM-Arrays are thin enough that they could be mounted between the TPS material and structural panels if necessary, with only the leads to the MWM-Array passing through the panel. In scanning mode, this method has been used for the Space Shuttle leading edge RCC inspection [1]. This paper reviews the technology behind this method and provides representative data for several TPS inspection applications.

2. EXPERIMENTATION

This section reviews key features of the experimental configurations. The experiments described below used a JENTEK impedance instrument (7000 or 8200 series) to generate the drive signal and to measure all of the sensing element channels in parallel (i.e., simultaneously). A probe electronics unit was placed between the instrument and the sensor for signal amplification. The data acquisition and analysis were controlled by a computer running JENTEK's GridStation[®] software. For the assessment of carbon-based TPS materials, a magnetic field-based eddy current sensing technology was used. For the assessment of insulating and weakly conducting dielectric materials, an electric field-based capacitive sensing technology was used. In both cases, the sensor responses were converted into meaningful geometric and material properties, such as material thickness and electrical conductivity, through multivariate inverse methods.

2.1 Magnetoquasistatic Sensing: The Meandering Winding Magnetometer (MWM[®])

The MWM is an inductive eddy current sensor designed specifically for the nondestructive characterization of material properties in the relatively near-surface region (e.g., up to several inch thicknesses for carbon-based TPS materials, with significantly higher sensitivity closer to the inspection surface). For carbon fiber reinforced materials, the directional response of the MWM-Arrays permit the orientation of anisotropic material properties to be determined. Printed circuit microfabrication techniques are employed to produce the sensors, resulting in highly reproducible (i.e., essentially identical) sensors. By fabricating the windings on a thin and flexible substrate, a conformable sensor can be produced. These thin, conformable sensors can be scanned across a surface, mounted on an exposed surface, or embedded within a TPS material [1-4]. The sensor geometry can be altered to allow the interrogation of near surface electrical

properties (and dependent properties such as damage and stress), or to provide deeper penetration enabling sensitivity to properties far below the accessible surface, such as the total sample thickness.

The basic geometry of the original MWM (first conceived by the late Prof. James R. Melcher in the early 1980s) is shown in Figure 1 (left). The sensor has a meandering primary winding, which generates a spatially periodic magnetic field when driven by an electrical current. The two secondary windings (with leads exiting, separately, from the left and right sides of the figure) inductively respond to the time-varying magnetic fields. Note that the electromagnetic and geometric properties of the interrogated volume of material influences local magnetic field and the sensor response.

Substantial improvements have been made to this basic design, including arrays of sensing elements within the drive winding (an 'MWM-Array'), and also relaxing the requirement for a periodic drive. Accurate knowledge of the primary winding shape, and also of the position and shape of the associated sensing elements, enables potential for accurate modeling of sensor interaction with the material under test (MUT). Such modeling accuracy can often significantly reduce calibration requirements, so that in some situations an "air calibration" can be used, permitting measurement of a component's absolute electrical conductivity without calibration standards [5-6]. The relatively simple layout for the windings permits operation over a wide frequency range, typically between 10 kHz and 40 MHz. This is in the magnetoquasistatic frequency range where the excitation is a current through the drive windings and the sensing fields are dominantly magnetic fields.

The depth of penetration of the magnetic field into the test material depends upon both the input current frequency and the sensor geometry (drive winding dimensions or spatial wavelength λ) as shown in Figure 1 (right) for several sensor constructs. This can be observed from an analysis of the equations for the physical response of the sensor. For example, the fields decay exponentially with distance into the test material. The depth of penetration for the magnetic fields into a material layer can be expressed as $1/\text{Re}\{\gamma_n\}$ with $\gamma_n = \sqrt{(2\pi n/\lambda)^2 + j\omega\mu\sigma}$ where *n* is the Fourier Series mode number, λ is the spatial wavelength for the sensor, $\omega = 2\pi f$ is the angular frequency for a frequency f, μ is the magnetic permeability, σ is the electrical conductivity, and $j = \sqrt{-1}$. The conventional skin depth is $\delta = \sqrt{2/\omega\mu\sigma}$. At low frequencies, the depth of penetration is limited by the geometry of the sensor (i.e., spatial wavelength) and occurs for the fundamental spatial mode (n=1), while at high frequencies it is limited by the conventional skin depth, which decreases as the frequency and electrical conductivity increase. The sensor arrays are typically sensitive to material property variations up to about 3 times the penetration depth, depending upon noise levels of the instrumentation.

In summary, the penetration depth is limited by the skin depth at high frequencies and by the sensor geometry at low frequencies. At low frequencies, the magnetic fields from a larger spatial wavelength sensor will penetrate further into the MUT than the fields from a shorter spatial wavelength sensor. Thus, while small sensor arrays can be used to create high spatial resolution property images, large sensor arrays are needed to examine thick materials. Also, with the nominal electrical conductivity for carbon-based ablative thermal protective materials (at room temperature) in the 500 to 1000 S/m range and a relative permeability near one, significant eddy currents are only generated at relatively high excitation frequencies of 100 kHz or higher.



Figure 1. (left) Basic MWM geometry; (right) depth of penetration variation with sensor dimension. Nominal depth of penetration chart for the FA212, FA24, and VWA003 MWM-Arrays. A 0.5 in. drive-sense gap was assumed for the VWA003.

Several MWM-Arrays are shown in Figure 2. The FA24 has two rectangular drive windings placed adjacent to each other, with a total drive length of 0.955 in. and a linear array of thirty-seven sensing elements that are 0.10 in. wide each. The sensing elements are not centered within a drive loop; the gap between the sensing elements and the drive winding is 0.080 in. The VWA003 has a single rectangular drive approximately 3.0 in. long and a (separate) linear array of fifteen 0.25 in. square sensing elements. The drive winding and sense element array are fabricated onto separate substrates, so that the spacing between the drive winding and sensing elements can be adjusted. For ablative TPS thickness measurements, a spacing of 0.5 in. between the drive winding and the sense element is typically used [8].

While the FA24 and VWA003 have multiple sensing elements (linear arrays of sensing elements) all located at the same distance from the primary drive winding, the FA212 and FA226 have sensing elements arrayed at multiple, distinct distances from the drive windings. Since the sensing elements are at distinct distances from the drive winding, they are sensitive to different components of the magnetic field, which penetrate to different depths within the test material, with the "very-far" sense element coupling to the deepest-penetrating components [9]. The FA212 has two rectangular drive windings placed adjacent to each other, with a total drive length of 0.982 in. and several sensing elements that are "near" the central part of the drive winding, in a "far" position, or "very-far" from the central part of the drive winding. Each sensing element is 0.40 in. wide. The effective spatial wavelengths are approximately 0.59 in., 0.73 in., and 0.99 in. for the near, far, and very-far sensing elements, respectively. This sensor also has some sensing elements centered within the drive winding and others offset from the centerline; the offset sensing elements can be used to provide complementary information about anisotropic material properties and conductivity in directions perpendicular to the high electrical conductivity direction. Similarly, the FA226 is a circular sensor construct having a 0.5 in. drive winding diameter and near, mid, far and very-far sense element widths of 0.024, 0.034, 0.044, and 0.103 in., respectively.



Figure 2. Images for FA24, FA212, FA226, and VWA003 MWM-Arrays.

2.2 Electroquasistatic Sensing: The Interdigitated Electrode Dielectrometer (IDED)

Although this paper is primarily focused on TPS materials with relatively conducting carbon fibers, the IDED is a capacitive, electric field-based sensor suitable for characterizing weakly conducting or insulating materials such as foams, epoxies, and glass fiber composites. A typical IDED sensor construct is shown in Figure 3(a). In operation, one set of electrode fingers are driven by a sinusoidal time varying voltage with known amplitude, while the second set of interdigitated fingers is virtually grounded. The terminal current of the second electrode constitutes the sensed signal. For layered or non-homogenous materials, such as composites, in which dielectric properties vary with depth, the measured signal is a thickness and depth-weighted function of the dielectric properties (effective complex permittivity) of the various regions. Typical excitation frequencies range from 0.005 Hz to 10 MHz. This is in the electroquasistatic frequency range, where the excitation is the voltage on the drive electrodes and the sensing fields are dominantly electric fields.

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 extends into the medium in the *z* direction. The depth of sensitivity is considered to be approximately 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 [7-10]. Figure 3(b) shows a multiple depth sensing IDED, the DS08, which enables monitoring of

properties at multiple depths into a layered material. The DS08 has a relatively large spatial wavelength (for dielectric sensors) of 0.135 in., which leads to a nominal depth of sensitivity of 0.045 in. It has three sensing elements, denoted by "near", "mid", and "far." The prototype fixture in Figure 3(c) improved the usability of the sensors as an NDE tool.



Figure 3. (a) Schematic of an IDED sensor near a test material, (b) flexible, three-wavelength IDED, and (c) prototype probe fixture.

2.3 Grid-based Inverse Methods

The MWM sensor responses are converted into material or geometric properties using measurement grids. These grids are used to convert two measured quantities, such as the magnitude and phase (or real and imaginary parts) of the sensor transimpedance, into the unknown properties of interest, such as electrical conductivity and sensor lift-off. Grids are two dimensional databases of precomputed (modeled) sensor responses at a specific excitation frequency, which can be displayed graphically to support procedure development. Grids are often generated using a quasi-analytical forward model and the expected property ranges of the MUT. For problems requiring simultaneous estimation of three unknown properties, three dimensional lattices of sensor responses are precomputed (and similarly, for more unknowns). Three dimensional lattices can be visualized as a set of grids at multiple, distinct values of the third lattice dimension. For example, Figure 4 shows multiple thickness/lift-off grids for several distinct test material electrical conductivities; this is an example lattice for the simultaneous determination of the electrical conductivity, thickness, and lift-off.



Figure 4. Schematic of grid generation using a forward model for the MWM. The collection of thickness/lift-off measurement grids for several electrical conductivity values forms a lattice. Note that the thickness ranges from 0.1 to 3.98 in. and the lift-off ranges from 0.0005 to 0.2 in. for this example.

2.4 Sample materials

Measurements were performed on several different sample materials. Several specimens of phenolic impregnated felt (PICA Flex) and PICA were obtained from Fiber Materials Incorporated (FMI). The PICA samples were fabricated by impregnating a FiberForm[®] carbon matrix with phenolic resin, whereas the PICA Flex specimens were fabricated by impregnating a carbon felt with phenolic resin. Three of the PICA samples (labeled as 1, 2, and 3) had dimensions of 9.125 in. by 9.125 in. by 1.375 in. thick. These samples had the lower thermal conductivity direction along the shorter dimension, which is consistent with the standard installation orientation on spacecraft. One PICA sample (labeled as 0) was approximately 5 in. by 6 in. by 1.7 in. thick, and, for this sample, the low thermal conductivity direction was along one of the longer dimensions of the sample. The three PICA Flex samples had dimensions of 10.875 in. by 10 in. by 0.375 in. thick.

Unimpregnated materials included FiberForm and rayon graphite felt. The FiberForm samples were obtained from FMI and were approximately 11 in. by 11 in. by 3.43 in. thick. The low thermal conductivity direction is along the thin dimension. Several felt samples were obtained from CeraMaterials. These felts were relatively thin, being nominally 0.25 or 0.5 in. thick. In addition, NASA provided a felt sample with nominal dimensions of 12 in. by 12 in. by 0.875 in. thick. To simulate thicker materials, the felts were stacked on top of one another. From the material data sheets, the electrical conductivity is in the range of 560 to 710 S/m. For safe keeping, all of these samples were measured while inside 0.004 in. thick plastic bags.

3. RESULTS

3.1 TPS Thickness Assessment

To demonstrate thickness sensitivity for typical TPS materials, measurements were performed with the circular FA226 sensor on the PICA samples and layered stack-ups of carbon felt. Measurements were performed primarily on the nominally 0.25, 0.5, and 1.0 in. rayon graphite felt samples with various stack-ups to represent thicknesses ranging from approximately 0.25 in. to 2.5 in. Measurements were also performed on the PICA specimens and the PICA Flex specimens. For this test, an air/shunt calibration was performed; this procedure uses measurements of the sensor response to air and measurements with the sensing elements shorted to adjust the instrument to provide a known and reproducible response. Measurements were performed at excitation frequencies of 164 and 655 kHz. The data acquisition procedure involved placing the specimens on an insulating support with the sensor and a ream of paper behind the sensor for five measurement locations on each specimen. The measurement data was processed using conductivity/thickness/lift-off lattices. This data processing combined all of the data from each sensing element and both excitation frequencies to obtain a single estimate for the conductivity, thickness, and lift-off.

Figure 5 shows the estimated properties for each felt stack-up and for each of the other specimens. The conductivity of the felts are all approximately 500 S/m, except for the nominally 0.5 in. thick felt which appears to have a slightly higher conductivity of approximately 800 S/m; this leads to an increase in the effective conductivity of the stack-up when the higher conductivity felt is placed closest to the sensor. These grid lattices do not account for a non-uniform electrical conductivity through the thickness, but it is possible to exercise the model to generate grid lattices that may be able to provide information about spatial profiles of the

electrical conductivity. Most of the data points that underestimated the thickness had the higher conductivity felt nearest the sensor. Nevertheless, the estimated thickness tracks with the actual thickness for both the felts and the PICA materials.



Figure 5. Estimated properties for the FA226 to various thicknesses and types of ablative materials. These estimates used all four outside sensing elements with excitation frequencies of 163 and 655 kHz along with an air calibration.

The correlation between the estimated and actual thicknesses of the ablative materials is shown more clearly in the scatter plot shown in Figure 6. This shows that the estimated thicknesses are reasonable for ablative materials up to approximately 1.5 in. thick for the FA226. However, this range is expected to increase for larger circular sensors. Most of the felt data and all of the PICA data fall near the direct correlation curve. This suggests that the thickness measurement is possible both before and after impregnation with resin. There are some outlier points which may be associated with the non-uniformity of the electrical conductivity for the stack-ups.



Figure 6. Correlation plot between the thickness estimated from the FA226 and the actual thickness for several ablative material configurations. These estimates used all four outside sensing elements with excitation frequencies of 163 and 655 kHz along with an air calibration.

Similar results were obtained with a relatively large MWM-Array. While the circular sensor is convenient for local measurements, the MWM-Arrays are better suited to wide area assessment and imaging of material condition. In this case, different thicknesses and layered stack-ups of carbon felt were placed on top of the relatively large spatial wavelength VWA003 MWM-Array. Figure 7 (left) shows an impedance plane view of relevant measurement grids and air-calibrated data for rayon graphite carbon felts as well as the felt sample provided by NASA. The nominal thickness of each felt layer is indicated in inches. The front label ("F") indicates that the outside of the rolled material is placed against the sensor. In general, similar results were obtained independent of which side was placed against the sensor. The measurement data for each material showed a consistent change in the response away from the air point (the air point is a measurement of the sensor response in air, away from any conducting materials) as the thickness increased. Similar results were obtained at frequencies ranging from 316 kHz to 10 MHz.

Note that Figure 7 (left) shows a standard conductivity/lift-off grid for a thick material (which in this case was taken as 3 in. thick). The data generally falls below the standard conductivity/lift-off grid, which is a direct result of the sensor seeing through the thickness of the felt. A separate thickness/lift-off grid is also shown for comparison. This thickness/lift-off grid assumes a fixed nominal conductivity of 730 S/m and (like the data itself) generally falls below the conductivity/lift-off grid. This thickness/lift-off grid is consistent with measurement data where the data falls along a line of roughly constant sensor lift-off as the thickness changes.

The air-calibrated measurement data for the rayon graphite material was then converted into thickness estimates using a reference part calibration. The data was recalibrated using the thinnest specimen (0.25 in. thick) and an intermediate thickness stack-up (1.55 in. thick, for the NASA felt with two of the rayon graphite felts), assuming a reference conductivity of 560 S/m and lift-off of 0.020 in. The recalibrated data was then processed using thickness/lift-off grids which assumed the same conductivity. Figure 7 (right) compares the estimated and expected felt thicknesses for the NASA felt and the rayon graphite felts. The estimated thickness is in good agreement with the expected thickness. In some cases, the estimated thickness underestimates the expected thickness, but this may be due to compression of the felt during the measurement. These results demonstrate sensitivity to the thickness over the thickness range of interest for these materials. This also indicates that the thickness can be measured locally for a spot inspection, for example with the circular FA226, or it can be measured over large areas using a multiple sense element array, such as the VWA003.



Figure 7. (Left) Impedance plane view for rayon graphite carbon felts at a frequency of 500 kHz. (Right) Estimated thickness data using a reference calibration compared to expected felt thickness.

3.2 Orientation Assessment of Anisotropic Properties

Directional eddy current sensors are sensitive to the orientation of low and high electrical conductivity associated with the anisotropic properties typical of TPS materials. The induced eddy current density is higher, along with a higher effective electrical conductivity, when the drive is oriented parallel to the conducting fibers or planes of fiber layers. Conversely, the conductivity is lower when the drive is perpendicular to the fibers. Typical ablative TPS materials have anisotropic properties as illustrated in the two schematics shown in Figure 8 (left). For both the vertical and horizontal planar layer schematics, the sensor is assumed to be measuring from above (i.e., from the upper portion of the page). The horizontal planar layers represent the standard configuration for TPS materials, where the low thermal conductivity (and low electrical conductivity) direction is perpendicular to the top face of the material. The vertical planar layer configuration represents measurements on the side of a typical TPS material, where the low conductivity direction is along the x' direction. This vertical orientation is found in the sample PICA 0.



Figure 8. (Left) Schematic views of two different anisotropic material conditions. (Right) Photograph of prototype fixture for determining material orientation.

Measurements were performed on the sample PICA 0 using the fixture of Figure 8 (right). An FA212 sensor connects to an adapter board, with the face of the sensor mounted onto a support block. With foam inserted between the sensor and the support block, the sensor can conform to the test material surface. The fixture was designed to provide a modest curvature for the sensor leads and the narrow end of the fixture makes it useful as a probe into tight areas. Measurements were performed at an excitation frequency of 10.48 MHz as the sensor orientation angle was varied over the top of the specimen over a range of 180°. An air calibration was performed, which used measurements of the sensor response in air to adjust the instrument to provide known and reproducible responses for measurements on the part. The data was then processed through standard (infinite thickness) conductivity/lift-off measurement grids. The impedance data from all three of the centered sensing elements and all three of the offset sensing elements were used to determine the effective properties.

Figure 9 shows the effective property values obtained from the FA212 for the PICA 0 sample. Measurements were taken with a nominal lift-off of 0.005 in., which includes the thickness of a plastic layer that was used as a template for the sensor directions (every 15°) as well as the internal thickness of some of the sensor substrate materials, and also with a nominal lift-off of 0.015 in., where an extra 0.010 in. thick plastic shim was placed between the sensor and the PICA in order to shift the impedance response in a known (i.e., lift-off) direction. The electrical conductivity is relatively high (near 800 S/m) except when the sensor array is oriented perpendicular to the low thermal conductivity direction (perpendicular to the planes of the carbon fibers), where the conductivity is relatively low (near 300 S/m). The electrical conductivity values are approximately a factor of 2 to 2.5 smaller in the low thermal conductivity direction. The same electrical conductivity variation with orientation angle is obtained with and without the 0.010 in. shim. This confirms that the FA212 can be used to determine orientation of these anisotropic TPS materials.



Figure 9. Effective conductivity and lift-off responses for a FA212 rotated over the PICA 0 specimen. Measurements were performed with and without an extra 0.010 in. plastic shim placed between the sensor and the sample.

For the effective lift-off, the expected nominal lift-off values are obtained over the range of 0° to 90°, but there is an increase in the effective lift-off over the range of 90° to 180°. There is also a modest reduction in the lift-off values for sets 2 and 15 (at 15°). It is consistent for measurements both with and without the shim. These lift-off variations do not affect the conductivity estimates. This suggests that there are some surface variations on the PICA, such as surface roughness, that are influencing the sensor response. However, it is still possible to determine the anisotropic material orientation with the conductivity values, even in the presence of this type of surface roughness variation.

3.3 Carbon Felt Damage Assessment

MWM-Arrays can also be used in a scanning mode, to inspect large areas. In this case, a VWA003 was scanned along the length of a 0.5 in. thick carbon felt that was approximately 4 ft long and 1 ft wide. To simulate crack-type damage, a razor blade was used to introduce two cuts into this felt sample. Each cut was made in the down-scan direction (the X direction in Figures 10 and 11). A 1 in. long by 0.5 in. deep cut was introduced from about X = 11 in. to 12 in, and a 3.25 in. long by 0.25 in. deep cut was introduced from about X = 36.75 in. to 40 in.; a sharp crease, which led to a visible hole, was also made at X = 28 in. A 0.003 in. protective plastic layer was placed between the VWA003 and the felt. The VWA003 was held snugly against the felt with a layer of foam and then pressed gently by hand against the foam. The goal was to minimize potential lift-off variations without compressing the felt. The array was then scanned along the length of the felt by moving both the array and the probe electronics cart

simultaneously. Here, the cart was rolled along the side of the felt so that the wheels on the cart would not compress the felt itself. For these measurements, a two-point reference calibration was performed using two known felt thicknesses (0.5 in. and 1.0 in.). The reference calibration assumed a conductivity of 361 S/m and a lift-off of 0.015 in. To obtain the effective property values for the electrical conductivity, thickness, and lift-off, a two step procedure was used. First, the thickness was estimated (along with the lift-off) at the relatively low frequency of 250 kHz, assuming a material conductivity of 361 S/m. Then, the low frequency thickness value was used as an input to estimate the conductivity and lift-off at a higher frequency of 630 kHz.

Figure 10 shows plots of the responses from all of the sensing elements in the array for a scan along the relatively undamaged side of the felt. The 1 in. long slice damage is visible in all of the estimated properties, though most notably in the lift-off and conductivity responses. The 3.25 in. long slice is visible in all of the properties as well, although it produced a particularly large effective lift-off response signature. The through-wall crease damage is apparent between the two slice-damage indications, at about X = 28 in. along the scan. Figure 11 shows the same data in the form of C-scan images. The C-scan images are useful for showing the presence of flaws when large areas are being examined and enable some analysis of the extent of the flaws in the channel (vertical) direction. In this case, the color scale for the images is adjusted so that the red threshold primarily indicates the largest flaw responses. Smaller flaws appear as local changes in the effective lift-off images. In particular, the extent of the 3.25 in. slice appears as a dark shadow of increased effective lift-off. Thus, these plots and images clearly show that the surface-breaking and subsurface flaw conditions can be detected with this eddy current-based MWM-Array method.



Figure 10. A scan over damaged 0.5 in. rayon graphite felt with the VWA003 on the lessdamaged side.



Figure 11. C-scan images for a VWA003 scan over damaged 0.5 in. rayon graphite felt from the less-damaged side.

3.4 Dielectric Property Assessment

The same type of measurement grid methods can be applied to the dielectric sensors for the assessment of electrically insulating and weakly conducting materials. Several tests were performed with a DS08 single-sided sensor on several materials. These materials included air (relative permittivity of 1.0), Teflon (relative permittivity of 2.1 and 0.5 in. thick), borosilicate glass (relative permittivity of approximately 5 and 0.125 in. thick), alumina (relative permittivity of 9.7 and thicknesses of 0.060, 0.20, and 0.50 in.) and zirconia (relative permittivity of 28 and thickness of 0.50 in.). In each case, the sensor was placed directly against the specimen surface. An air/zirconia reference calibration was performed; this calibration used the response of the sensor in air and the response of the sensor to zirconia (assuming a lift-off of 4.00 μ m, and a relative permittivity of 28.0) as reference responses. This reference calibration bracketed the responses obtained for the other dielectric materials. Figure 12 shows the estimated permittivity obtained from these measurements. The measured relative permittivity is essentially the same as the expected value for each material and the value is essentially constant over the entire frequency range. Note that for these materials, the electrical conductivity value was essentially zero. For monitoring the cure state of materials such as foams and resins, the electrical conductivity can also be monitored since it typically varies with the transient chemical and cure state. Similarly, this type of measurement can be used to assess the condition of several types of ceramic matrix composites.



Figure 12. Relative permittivity from DS08 measurements on several insulating materials with an air/zirconia reference calibration.

4. CONCLUSIONS

This paper reviewed the use of linear drive eddy current sensing methods for the NDE of carbonbased TPS materials. More specifically, the model-based methods used with the MWM-Arrays allow the material thickness and condition (e.g., electrical conductivity) values to be determined independently and, in some cases, without the use of reference standards. MWM-Array TPS measurements can be performed in either a surface mounted (in-situ) or scanning configuration. This flexibility of the measurement method, for contact or non-contact measurements in scanning or surface-mounted configurations, implies that the same method should be useable for laboratory testing during material development, during manufacturing quality control, and inservice measurements. In addition, since the linear drive geometry is inherently directional, rotational measurements allow directions of anisotropic material properties to be determined. Ongoing work is aimed at refining the measurement procedures and developing larger sensors to provide improved sensitivity to thicker materials.

5. ACKNOWLEDGMENTS

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