JMEPEG (2006) 15:484-489
DOI: 10.1361/105994906X124604

1059-9495/$19.00

Inverse Analysis of Surface Degradation Using Optical Fibers

S.G. Lambrakos, N.E. Tran, N. Lagakos, and P.P. Trzaskoma-Paulette

(Submitted January 30, 2006; in revised form February 17, 2006)

The authors present a general method based on inverse analysis of light signals from a fiber-optic sensor for in situ detection of metal, film, or coating degradation. This method, which does not, in principle, depend on the geometry of the fiber-optic sensor, is based on analysis of reflected light intensity loss as opposed to reflected or transmitted intensity modulation. Following an inverse-analysis approach, the level and rate of intensity loss are correlated with levels and rates of surface degradation. This approach allows optimization of fiber-optic sensors for specific applications and different environments. Case study analyses using experimental data are used to demonstrate the fundamentals of various aspects of this method.

Keywords: corrosion monitoring, fiber-optic sensor, inverse analysis, monitoring surface degradation, remote sensors

1. Introduction

Use of fiber optic based sensors for detection of changes in the physical characteristics of surfaces and interfaces is being developed for a wide range of applications, including corrosion monitoring, analysis of surface interactions between chemical and biological species, and monitoring of materials deterioration correlated with either damage or failure of a system or structure (Ref 1-11). The general structure of fiber optic based sensors is such that they are well suited for the distributed sampling of system responses over relatively large sets of both spatial locations of the sensor and changes in physical characteristics of the system. Therefore, by their nature, fiber optic based sensors are well posed to acquire data for purposes of inverse problem analyses (Ref 12, 13), which require data sets distributed over a sufficiently wide range of structural or physical characteristics to identify and characterize the system.

Fiber optic based sensors are generally categorized according to the method of detection used to couple changes in the light transmitted through the optical fiber to changes in a given physical characteristic of the system. These methods depend on the fiber optic sensor geometry and measurements of either intensity loss or modulated reflection or transmission at an interface. A sufficiently complete summary of the different categories of fiber-optic sensors is given in Ref 3 within the context of fiber-optic strain sensors. The present paper presents a fiber optic based sensor capability that can be applied in principle with any type of fiber-optic sensor geometry and that establishes a correlation between levels of surface degradation and intensity loss as a function of time. The method presented here is therefore a generalization of the simplest form of intensiometric sensor, where damage or failure is detected by a break in the fiber that results in a termination of all transmission of light to a detector. The method is based on inverse analysis, which eliminates the need for a detailed physical representation of the sensor. That is, analysis is accomplished by using a parameterized representation of system response characteristics relative to a given class of data sets for system identification. Therefore, through the concept of inverse modeling, the authors define two additional classifications of fiber-optic sensors. These are fiber-optic sensors where the parameterized relationships for analysis of the coupling of changes in detected light signals to changes in system characteristics are based on either direct- or inverse-problem approaches for modeling of systems.

The direct-problem approach to sensing using optical fibers can be defined as an approach in which the characteristics of the detected signal are predicted using either an explicit numerical solution to equations of electromagnetic wave propagation in materials based on different formulations or an explicit physical model based on analytical representations of the intensity distribution within the fiber-optic sensor system for a specific geometry. The direct-problem approach requires a priori knowledge of the physical characteristics of the fiber-optic sensor and of its coupling to the environment under detection. Further, this approach requires knowledge of the electromagnetic response properties, as a function of wavelength, of the materials making up the sensor system.

The inverse-problem approach to sensing using optical fibers can be defined as an approach in which the characteristics of the detected signal are predicted using a model representation whose form is relatively convenient for the adjustment of parameters. The adjustment of parameters is according to experimental data concerning a field quantity, e.g., intensity or wavelength, at various locations that are sufficiently distributed either spatially throughout the environment under detection or parametrically relative to the parameter space representing a specific characteristic of the system. The model representations adopted for an inverse problem approach can be based on parametric formulations that range from those that include detailed

S.G. Lambrakos, Materials Science and Technology Division, Code 6390, Naval Research Laboratory, Washington, DC 20375; **N.E. Tran,** Chemistry Division, Naval Research Laboratory, Washington, DC 20375; **N. Lagakos,** Acoustics Division, Naval Research Laboratory, Washington, DC 20375; and **P.P. Trzaskoma-Paulette**, Engineering and Physical Sciences Division, The National Academies, 500 5th Street NW, Washington, DC 20375. Contact e-mail: lambrakos@nrl.navy.mil.

descriptions of the underlying physical interactions or couplings to those characterized by multidimensional interpolation functions whose mathematical-function forms are relatively simple. It is noted therefore that an inverse-problem approach to sensing using optical fibers can be applied via any conveniently adjustable parametric representation of the field quantity to be detected. This makes sense because any "well-behaved" function representing sufficiently distributed field values, where these values have been obtained from measurements, will represent an accurate interpolation function for regions of interest.

Direct-problem and inverse-problem formulations posses an interrelationship that is important with respect to analysis based on the inverse-problem approach. An aspect of this interrelationship is that all direct-problem based parametric representations may be adopted for inverse analysis, and that in general, direct-problem analyses can be interpreted as inverse-problem analyses. This interrelationship implies that a reasonable starting point for the formulation of an inverse-problem based parametric representation is to adopt a direct-problem based parametric representation as an initial ansatz for further modification (or optimization) according to the characteristics of the experimental data concerning the field quantities of interest, e.g., intensity or wavelength in the case of sensing using optical fibers.

In the next section, the authors present the formulation of their method for inverse analysis, which is based on the concept of an intensity function (Eq 2) and the general characteristics of all the processes involved in surface degradation or dissolution. Relative to systems identification theory, all processes concerning surface degradation represent systems whose parameter identification is that of step responses. The relationship between system input, process characteristics, and output for these types of systems is well established in terms of parametric representation and analysis (Chap 3 in Ref 14).

2. Inverse Analysis of Surface Degradation

Inverse analysis requires construction of a sufficiently general parametric representation of the system whose response characteristics are to be identified. For the present development, a general parametric representation of fiber-optic response is adopted based on the construction of an intensity function that for a given fiber-optic sensor system defines the relationship between the input and detected signal as a function of geometry and material properties. The concept of an intensity function has provided the foundation for a wide range of analysis using fiber-optic sensors whose interpretation of signal response is in terms of an explicit model representation of the coupling of changes in detected light signals to changes in system characteristics (Ref 2). This method, based on inverse analysis, adopts as a general parametric representation of the fiber-optic sensor system the basic intensity function defined by Fig. 1. Further optimization of the fiber-optic sensor system is according to the characteristics of the experimental data concerning the field quantities of interest. It is significant to note that essentially all direct-problem analyses using fiber-optic sensors are based on a generalization of the intensity function concept represented schematically by Fig. 1. This function is characterized in general by the reflectivity properties of the reflecting plane and the basic quantities I, I_0, D, and θ_c, which are the detected intensity, the input intensity, the distance between the receiving fiber and reflecting plane, and the cutoff angle for coupling of light rays into the transmitting and receiving fibers, respectively. The cutoff angle is related to the material constants of the system by the expression:

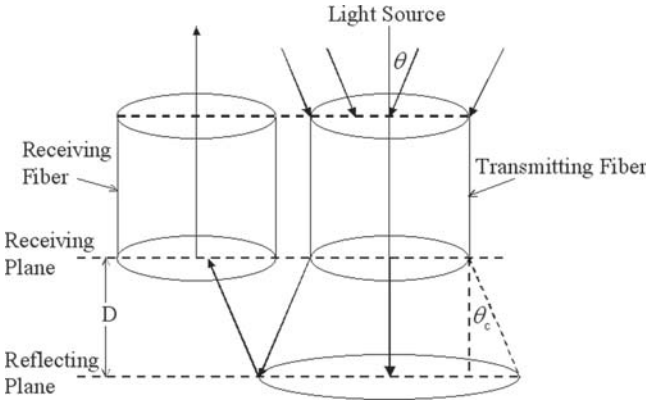

Fig. 1 Schematic representation of general parameterization of intensity function

$$\sin(\theta_c) = \frac{\sqrt{n_{core}^2 - n_{clad}^2}}{n} \quad \text{(Eq 1)}$$

where n, n_{core}, and n_{clad} are the refractive indices of the surrounding medium and the core and cladding of the optical fibers, respectively, and the quantity $\sqrt{n_{core}^2 - n_{clad}^2}$ is defined as the numerical aperature of the optical fiber. The general form of the intensity function is given by:

$$\frac{I}{I_0} = C_N I_B(D, \theta_c), \quad \text{(Eq 2)}$$

where the form of the basis intensity function $I_B(D,\theta_c)$ will depend on the coupling and reflection into two component transmitting and receiving fibers, respectively, of the sensor system. The intensity function $I_B(D,\theta_c)$ is the sum of the intensities of the distribution of light rays originating from an individual transmitting fiber and reflected into an individual receiving fiber (Fig. 1). The factor C_N will depend on the geometry of the sensor system, the number of transmitting and receiving fibers comprising that system, and the reflectivity properties of the reflecting plane. It is significant to note that these reflectivity properties are in general a function of the wavelength λ of the light and permittivity function, ε, of the reflecting plane, i.e., $C_N = C_N(R_{rp})$, where the reflectivity function of the reflecting plane R_{rp} is a function of λ and ε. Following the direct-problem approach, the parametrization defined by Eq 1 and 2 is for interpreting system response characteristics based on modulation of values of the parameters D or C_N, according to the nature of the coupling between sensor and environment. Following the inverse-problem approach, the parametrization defined by Eq 1 and 2 is for the encoding of system response characteristics based on a given set of experimental data. Accordingly, the parameters defined in this expression are interpreted as phenomenological, effective or as specifying a system transfer function for the purpose of establishing a well-behaved interpolation function within parameter space.

Referring to Eq 2, it follows that a general inverse-analysis method for detection of surface degradation may be developed

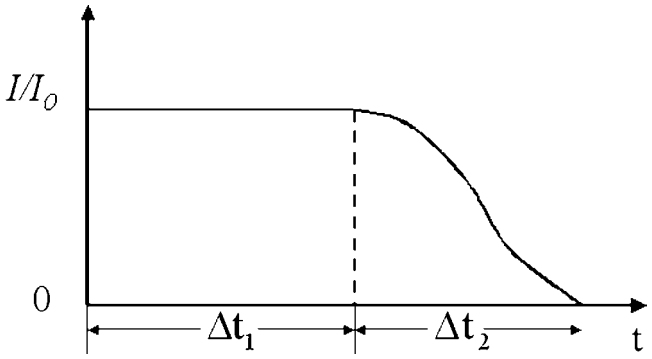

Fig. 2 Graphic representation of signature profile of surface degradation and of feature variables Δt_1 and Δt_2

that is based on the encoding of system response characteristics according to changes in C_N. Accordingly, it is assumed that environmental influences that can be correlated with changes in $I_B(D,\theta_c)$ remain constant, e.g., changes in sensor geometry or the relative positioning of the reflecting plane caused by influences other than surface degradation. Therefore, fiber-optic sensor geometry represents an aspect of the sensor system adaptable to optimization relative to specific applications concerning different types of environments. An important aspect of inverse analysis based on changes in C_N that correlate with levels of surface degradation is that the detector sensitivity is determined according to changes in detected signal that are relative to a zero output signal rather than according to a specified fractional change in signal. This implies that, in practice, many issues associated with the relative roughness of the reflecting plane, e.g., requirements of highly polished surfaces, may be minimized in that the basic criterion for detection is the establishment of a nonzero detectable signal.

The signature profile that in general characterizes fiber-optic sensor response to surface degradation is composed of two dominant features. This signature and associated dominant features follow from the fact that surface degradation, by its nature, assumes a characteristic trend in time. With respect to inverse analysis, this characteristic trend provides a foundation for the definition of two feature variables that correlate with levels and rates of surface degradation. These feature variables are defined schematically by Fig. 2.

2.1 Feature Variable Δt_1

Deterministic inverse analysis based on Δt_1 requires a priori knowledge of the thicknesses of samples or, in general, some quantifiable state variable characterizing an aspect of their surfaces, e.g., uniform adherence of a coating to the surface defining the reflecting plane in Fig. 1. Given that a data set of sufficient size has been observed establishing a correlation between values of Δt_1 and a sufficiently distributed set of the states of samples and their associated environments, system identification based on construction of a well-behaved interpolation function within parameter space may be applied. Statistical inverse analysis based on Δt_1 requires construction of a parametric representation of the statistical distribution of Δt_1. In principle, a priori knowledge of the distribution of thicknesses of samples, or surface states in general, is not required for a sufficiently large sample space. The issue to be addressed is the sensitivity of parameters representing the distribution of Δt_1 with respect to changes in environmental factors influencing surface degradation. This is necessary in that the distribution of thicknesses, which is unknown explicitly, is an implicit weight function of environmental influences represented by the Δt_1 distribution. Insensitivity of parameters to changes in environmental factors implies the need for filtering based on additional measurements.

2.2 Feature Variable Δt_2

An important aspect of the time window defined by Δt_2, and the associated state of the surface during that period, is that this window has built into itself the necessary surface preparation for analysis of atomic-scale phenomena. In principle, the degradation trend observed during this period should be independent of the initial thickness of the sample and shown to be a function only of environmental influences. This inherent characteristic of the Δt_2 phase of the surface degradation provides the opportunity for both deterministic and statistical inverse analysis depending upon the nature of a priori knowledge and assumptions concerning the system.

2.3 Statistical Inverse Analysis

A sufficiently general parametric representation for purposes of nondeterministic inverse analysis is that of the normal distribution:

$$P(\Delta t_i) = A_N \exp\left[-\frac{(\Delta t_i - \langle \Delta t_i \rangle)^2}{\sigma_N^2} \right] \quad \text{(Eq 3)}$$

where the index $i = 1$ or 2 and the normalization factor A_N is such that $P(\langle \Delta t_i \rangle) = 1$. The prototype analyses that follow serve to demonstrate both statistical and deterministic inverse analyses using optical fibers. Each of the surface response curves presented in the analyses that follow can then be interpreted as being a member of a set of experimental trials wherein certain conditions, such as coating thickness, are not quantified.

3. Prototype Analysis

In this section, the fundamentals of a prototype sensor system and a series of prototype analyses are presented that have been constructed to demonstrate the general inverse-analysis methodology for detection of surface degradation using optical fibers. A schematic representation of a prototype sensor system and its experimental arrangement are shown in Fig. 3 and 4, respectively. The prototype sensor system consists of the following components and associated instrumentation.

The sensor surface was defined by a glass slide (0.25 × 18.0 × 18.0 mm) with a vapor-deposited thin film (20 nm thick) of metal or alloy on its surface. A height-adjustable Teflon mount was used for housing the glass slide and fiber-optic probe within an isolated compartment. The fiber-optic probe was sealed off from the acid solution external to the isolated compartment by several thin, flat, Teflon O-rings, which were pressed onto the glass slide by a cylindrical Teflon screw. The distance between the fiber-optic probe (handmade) and the glass slide was adjustable for optimal sensitivity. This was effected by manually lowering or raising the fiber-optic probe

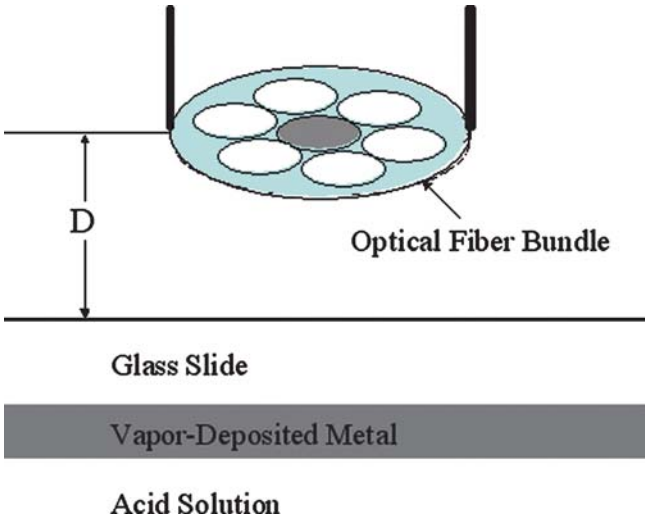

Fig. 3 Schematic representation of prototype sensor system; the glass slide measures 0.25 × 18.0 × 18.0 mm.

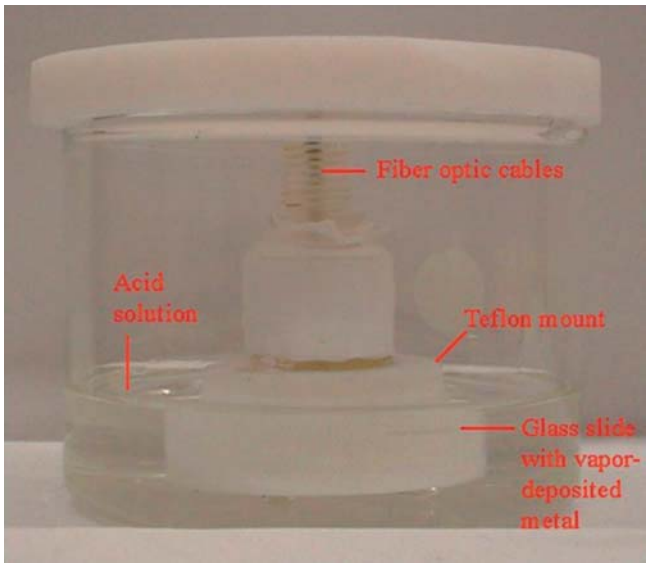

Fig. 4 Prototype of a fiber-optic sensor system for detection of surface degradation (58.0 cm in height; 70.0 cm in diameter). The fiber-optic probe uses a multimode fiber, which consists of a 200 μm glass core, a 230 μm plastic (HCS, Spectran Specialty Optics) clad, and a 500 μm Tefzel coating with a 0.37 numerical aperture (Eq 1).

through a small opening in a stainless steel cylinder that was attached to the Teflon top of the fiber-optic sensor system. The fiber-optic probe was connected via a fiber-optic cable (HCS, Spectran Specialty Optics, Avon, CT) to a light-emitting diode (LED) light source (Optek OPF37A, $\lambda = 850$ nm) (Optek Technologies, Carrollton, TX), which in turn, was connected to a model 370S optometer (United Detector Technology, UDT, Culver City, CA). The optometer was controlled by Labwindows (Dos) software developed by UDT. A typical record of reflected power loss resulting from metal or alloy film degradation as a function of time and the corresponding change in the vapor-deposited metal film at the beginning and end of the record are shown in Fig. 5 and 6, respectively.

Experimental data to test our method was collected by separately dissolving two metals in acid solution, aluminum

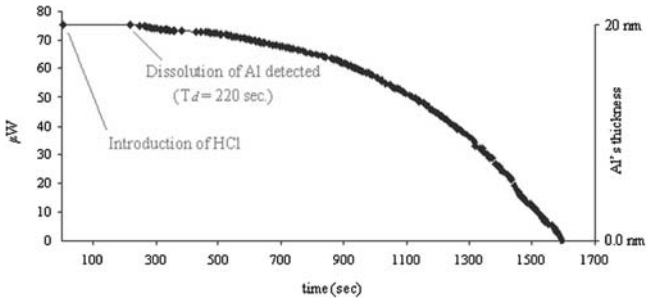

Fig. 5 Dissolution of aluminum in 6 M HCl solution as a function of time

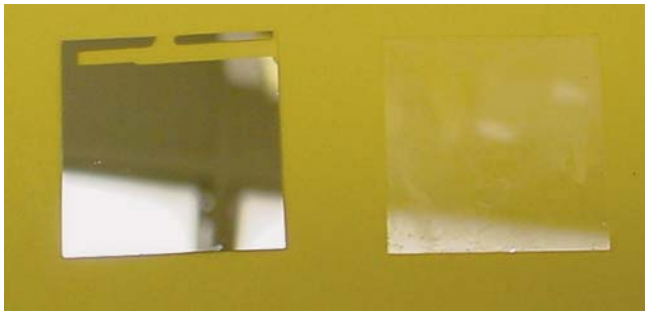

Fig. 6 Thin film of vapor-deposited aluminum (20 nm thick) on microcover glass (0.25 × 18.0 × 18.0 mm), before and after exposure to a 6 M HCl solution for 26 min

(99.9999%) and permalloy (20% iron and 80% nickel), and following the change in reflected light intensity as a function of time. This represents an accelerated procedure to demonstrate proof of concept. Accordingly, aluminum and permalloy were vapor-deposited separately on several glass slides. Each slide was inserted into the Teflon mount and sealed with the Teflon O-rings and then subsequently tested overnight for leaks (Fig. 4). Each leak-free fiber-optic sensor device was then lowered into the testing chamber, where the distance between the fiber-optic probe and glass slide was adjusted for optimum sensitivity, i.e., the distance D in Fig. 3. The test chamber was then filled with a solution of acid at various concentrations. Data were recorded for parameter values $\lambda = \lambda_{LED} = 850$ nm and $I_0 = I_{LED} = 100.22$ mA and then subsequently analyzed to determine characteristic times for initial detection of dissolution Δt_1 (e.g., $\Delta t_1 = T_{cd}$ in Fig. 5) and for comparison of the different characteristic trends of surface degradation during time Δt_2, which in this case is due to dissolution (Fig. 7 to 9). Referring to Fig. 7 to 9, note that levels of degradation during exposure to acid solutions are correlated with loss of the reflected power as a function of time.

Shown in Fig. 7 is the reflected power loss correlated with the level of surface dissolution of aluminum in 6, 3, and 1.5 M HCl solutions as a function of time. Similarly, shown in Fig. 8 is the reflected power loss correlated with the level of surface dissolution of permalloy for the same set of HCl solutions as a function of time. Comparison of Fig. 7 and 8 shows that aluminum is much more resistant to dissolution by HCl than is permalloy. Shown in Fig. 9 is a comparison of the reflected power loss correlated with the levels of dissolution of permalloy and aluminum in 1.5 M H_2SO_4 solutions as a function of time. Permalloy appears to be more susceptible to dissolution in both H_2SO_4 and HCl solutions as compared with aluminum.

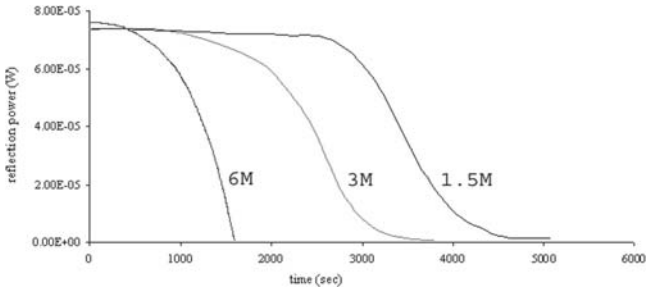

Fig. 7 Dissolution of aluminum in 6, 3, and 1.5 M HCl solutions as a function of time

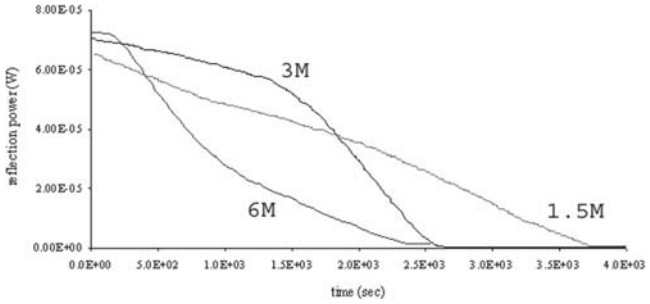

Fig. 8 Dissolution of permalloy in 6, 3, and 1.5 M HCl solutions as a function of time

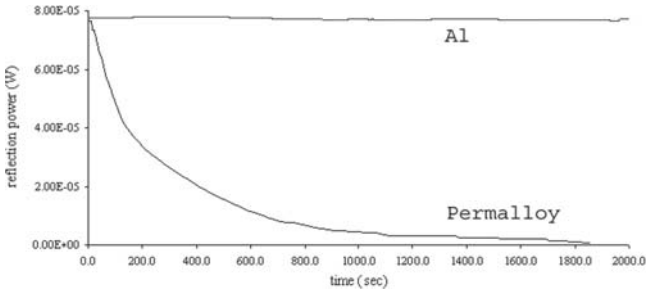

Fig. 9 Dissolution of permalloy and aluminum in 1.5 M H_2SO_4 solutions as a function of time

3.1 Remark

Permalloy is a magnetic alloy that contains 20% iron and 80% nickel. It is used in transformer laminations and anisotropic magnetorestrictive (AMR/MR) sensors. A version of the fiber-optic sensing device shown in Fig. 4 could be used to investigate corrosion- and/or oxidation-resistant coating materials for permalloy, which then can be used to prolong the life of many electronic devices such as CD-ROMs (currently estimated to be 3-5 years), computer hard disk read/write heads, and electronic AMR/MR-based sensors.

3.2 Discussion

As discussed above, the methodology presented here is a generalization of the simplest form of intensiometric sensor, where damage or failure is detected by essentially a yes/no criterion, such as a break in the fiber. The comparison shown in Fig. 9, which shows the relative rates of dissolution of permalloy and aluminum in H_2SO_4 solution, demonstrates this property. The inverse analyses shown in Fig. 7 to 9 are deterministic in that the thickness of the metal film was measured and monitored (Fig. 5) for each test. Extension of these analyses to those based on statistical inverse analysis is readily apparent in that each of the surface degradation response curves can be assumed to be a member of a sample space corresponding to a distribution of thicknesses or surface states, e.g., levels of roughness. Reinterpretation of each pair $(\Delta t_1,\Delta t_2)$ as $(\langle\Delta t_1\rangle,\langle\Delta t_2\rangle)$ follows directly from Eq 3.

An analogous methodology has been developed for analysis of biofilm growth (Ref 5). For this methodology, the detected signal to be processed assumes exactly the same signature profile as the detected signals considered for the present analyses. This methodology considers, however, intensity loss due to reduction of transmitted intensity through a thin film. As the film thickness increases from zero to some value corresponding to zero transmission, the detected signal assumes the characteristic signature profiles described in Fig. 2.

4. Summary of Concepts Underlying Inverse Analysis of Surface Degradation Using Optical Fibers

The following observations concerning the inverse-problem approach and methodology for analysis of surface degradation using optical fibers have been discussed and illustrated by prototype analyses presented here.

Fiber optic based sensors are well posed for data acquisition for purposes of inverse analyses due to their inherent ability to generate large data sets based on distributed sampling.

Typically, parameterizations that are used for signal analysis of fiber-optic sensors are based on the direct problem approach and are therefore not structured for data-driven analyses that require large data sets based on distributed sampling. That is to say, these parameterizations do not take advantage of the inherent nature of fiber optic based sensing.

Fiber-optic sensor response to surface degradation is characterized by a unique signature profile that is composed of two dominant features. These two features may be adopted for a parameterization of system response that is optimal for inverse analysis.

The general methodology for inverse analysis is based on the feature variables Δt_1 and Δt_2 defined above. Depending on the level of a priori knowledge concerning the system, these feature variables can be adopted as either system parameters (deterministic inverse analysis) or elements of a sample space for the determination of the parameters defined by Eq 3 (nondeterministic or statistical inverse analysis).

In principle, inverse analysis using optical fibers based on the feature variables Δt_1 and Δt_2 does not depend on fiber-optic sensor geometry. The dependence of the detected signal on sensor geometry, i.e., the factor $I_B(D,\theta_c)$ in Eq 2, represents an aspect of this methodology for optimizing the strength of the detected signal.

4.1 Remark

The methodology is potentially extendable by considering changes in the basis intensity functions $I_B(D,\theta_c)$ due to external influence. This requires a parameterization of $I_B(D,\theta_c)$ according to a given sensor-tip geometry.

The methodology for inverse analysis is such that parameter sensitivity is determined according to changes in detected signal that are relative to a zero signal, rather than according to a specified fractional change in signal.

In principle, the degradation trend observed during the period Δt_2 can be correlated with surface processes occurring on an atomic scale.

In practice, the methodology should tend to minimize the need for extensive surface preparation or calibration of surface states with sensor response when Δt_1 and Δt_2 are adopted as elements of a sample space according to Eq 3.

5. Potential Applications and Extensions of Prototype System

The prototype fiber-optic sensor system presented here can be adapted for a wide range of marine and maintenance applications, including on-board embedded sensing of surface corrosion within structures and electronic devices and corrosion detection within fuel storage tanks. This sensor system can be adopted for the inverse analysis of corrosion/oxidation resistant coating materials, including paints. Further, this system can be adopted for analysis of the relative effectiveness of corrosion inhibitors for protection of metal surfaces exposed to various types of environments (Ref 15). Other applications include corrosion detection of inside linings of nuclear or non-nuclear waste storage tanks, and corrosion and crack detection within skin layers of aircraft structures using embedded fiber-optic sensors.

The prototype fiber-optic sensor system can be easily fabricated using existing off-the-shelf technology, such as LED photon sources and optometers. This system is based on a detection scheme that is independent of any particular type of fiber-optic tip geometry or signal analysis methodology for post processing of detected signals. In principle, all types of metals (nickel, iron, zinc, etc.), alloys (bronze, nichrome, stainless steel, etc.), and surface coatings can be adopted as the test surface whose degradation characteristics are to be inverse-analyzed relative to a given environment. In addition, this system can be adopted for inverse chemical engineering, including optimization of corrosion inhibitors relative to field-performance criteria and constituent chemical components.

Some obvious variations of the prototype sensor system are replacement of the LED photon source by a laser and replacement of the glass component (Fig. 3 and 4) by a corrosion-resistant transparent polymer (e.g., polycarbonate, styrene acrylonitrile, polymethyl pentene) or a composite (e.g., fiber glass, polymethyl methacrylate). Finally, the Teflon mount component, as well as all Teflon parts comprising the system, can be replaced by relatively less expensive polycarbonate counterparts (Fig. 4).

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