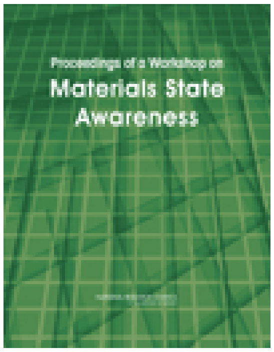

Proceedings of a Workshop on Materials State Awareness

Emily Ann Meyer, Editor, National Research Council

ISBN: 0-309-12166-3, 76 pages, 8 1/2 x 11, (2008)

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Proceedings of a Workshop on Materials State Awareness

Emily Ann Meyer, Editor

National Materials Advisory Board
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This project was supported by Contract No. 07-S508-009-13-C1 between the National Academy of Sciences and Universal Technology Corporation.

International Standard Book Number-13: 978-0-309-12165-1
International Standard Book Number-10: 0-309-12165-5

Available in limited quantities from the
National Materials Advisory Board
500 Fifth Street, N.W.
Washington, DC 20001
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Preface

In order to ensure effective military operations and continued warfighter safety, the functionality and integrity of the equipment used must also be ensured. Currently, effectiveness and safety are achieved by means of physical inspections that are useful in detecting and preventing catastrophic failures but cannot detect the deterioration of parts in real time. This shortcoming leads to higher equipment and materials costs than might be necessary.

For the past several years, the Nondestructive Evaluation Branch at the Air Force Research Laboratory (AFRL) has focused actively on the development of embedded sensing technologies for the real-time monitoring of damage states in aircraft, turbine engines, and aerospace structures. These sensing technologies must be developed for use in environments ranging from the normal to the extreme, confronting researchers with the need to understand issues involving (1) the reliability of and the bonding and attaching of sensors on structures, (2) wireless telemetry over near-system operating conditions, and (3) signal-processing methods for separating structural damage features from extraneous features. Much of this research has resulted in a successful understanding of and progress in developing the physics of the problem.

Additionally, given the unique environments in which these sensors will function, there is a need to develop science and technology that will address the sensing of a material state at the microstructure level, precursor damage at the dislocation level, and fatigue-crack size population. Numerous academic papers have been published on detection of microstructure change in materials, but key areas such as phase changes, recrystallization, nonlinearity development, and other similar topics have not been pursued beyond a theoretical level; many of the reported experiments have been conducted in a controlled laboratory environment and are not easily translatable to components functioning in a real-world environment. Bridging this research-to-practice gap will be of paramount importance to the AFRL if it is to continue to develop the technology for sensing and assessing materials state.

To address these issues, the AFRL asked the National Research Council to convene a workshop (see Appendix A). Following an initial planning meeting, the Materials State Awareness Workshop Organizing Panel developed a comprehensive agenda for the Workshop on Materials State Awareness, which brought together leaders in materials nondestructive evaluation from both industry and research, as well as government officials and other interested parties, on September 25-26, 2007 (see Appendix B). The workshop panelists and speakers (see Appendix C) were asked to give their personal perspectives on technological approaches to understanding materials state and also to describe potential challenges and advances in technology. This proceedings consists primarily of extended abstracts of the workshop speakers' presentations; the abstracts, which reflect the speakers' personal views, convey the nature and scope of the material presented at the workshop.

I would like to express my sincere appreciation to the members of the Materials State Awareness Workshop Organizing Panel for their hard work in preparing for and executing a very valuable workshop. I also thank the speakers, panelists, and participants who attended the workshop for their very important contributions. Finally, I acknowledge the contributions of National Research Council staff members Gary Fischman, Emily Ann Meyer, and Teri Thorowgood for their behind-the-scenes efforts in bringing this workshop together.

Edgar S. Starke, Jr.
Materials State Awareness
Organizing Panel, *Chair*

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dianne Chong, Boeing Corporation,
Boro Djordjevic, Materials Sensors and Technologies,
Glenn Light, Southwest Research Institute, and
Brajendra Mishra, Colorado School of Mines.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the author and the institution.

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APPENDIXES

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* The Missouri Institute of Science and Technology was formerly known as the University of Missouri-Rolla.

Introductory Comments

Kumar V. Jata, Air Force Research Laboratory

U.S. Air Force (USAF) weapons systems use a broad spectrum of materials and components processed through various complex materials processing routes and must be able to operate in a wide range of environments from benign to extreme. Maintenance and prediction of the useful life of these components are technically challenging tasks and are even more daunting when approached from a materials perspective. The future paradigm for maintaining the USAF systems is condition-based maintenance (CBM), which demands rigorous and rapid maintenance, repair, and replacement decisions and accurate prognosis (see Session 1 for a summary of prognosis) at the fleet level. Since the failure or inability of a component to perform its function begins at the material level, successful implementation of CBM hinges on incorporating materials state awareness concepts. The field of CBM is filled with researchers from crosscutting disciplines; besides understanding the science and technology, grasping the terminology itself is often challenging. A number of experts from around the country were invited by the National Materials Advisory Board and a workshop organizing panel chaired by Professor Edgar Starke to discuss issues pertaining to materials state awareness. The following are some of the objectives to which this workshop should contribute: (1) obtain an understanding of the concept of materials state awareness (MSA) in the context of CBM, (2) identify methods to assess MSA, (3) identify issues and challenges associated with the incorporation of MSA into future sustainment and prognosis, and (4) if possible, generate elements of a roadmap that will help with the incorporation of materials science concepts into CBM strategies.

Session I: Key Issues for Materials State Awareness

PROGNOSIS

John Venables, Strategic Analysis, Inc., and
Leo Christodoulou, DARPA/Defense Science Office

Notwithstanding all the improvements made through research on structural materials, damage accumulation through fatigue, creep, or overloads, for example, can lead to highly undesirable engine and/or structure failures in military platforms. For this reason, the Air Force and other branches of the military spend millions each year doing routine inspections and engine tear-downs. In a desire to improve this situation, the Defense Advanced Research Projects Agency (DARPA) has for the last several years sponsored a "Prognosis" program that attempts a new asset management approach based on predicting the remaining useful life (RUL) of aircraft engines, airframes, and helicopter drive trains. To accomplish this, the program focuses on uncertainty management by first exploiting existing sensor technology to define current materials state awareness and then incorporating physics-of-failure models to predict the future evolution of damage accumulation. Such information, along with prior history, measured stresses, etc., are then fed into appropriate reasoners whose RUL estimates are fed to the pilot or mission commander, who in turn can then assess the viability of the platform for the intended mission.

Along with many laboratory tests designed to establish a database of fatigue and creep properties of relevant materials, for example, the program is including numerous spin tests on engine components and low cycle fatigue tests on actual wing panels. By so doing, the physics-of-failure models, state awareness sensors, and state-of-the-art reasoners are combined to test whether the predicted RUL values are consistent with observed lifetimes.

APPLICATION OF MATERIALS STATE AWARENESS TO AIRFRAME STRUCTURES—KEY ISSUES

Donald D. Palmer, Jr., Boeing Phantom Works

In order to gain an understanding of the issues related to materials state awareness as applied to airframe structures, one must understand the range of materials applied, failure modes and mechanisms associated with these materials, and the benefits and drawbacks of the nondestructive evaluation (NDE) sensing modalities used to assess the state. In addition, understanding of the operational environment, combined with the limitations of modeling approaches, is essential in predicting the future state.

From the 1930s through the early 1980s, airframe structures consisted mainly of mechanically fastened aluminum. The key concern was fatigue cracks and the ability to detect them. Although models were developed to predict fatigue crack growth given specific loading spectrums, little attention was paid to the material system other than the presence of the crack. As aging aircraft issues came to the forefront in the 1990s, damage conditions such as corrosion, heat damage, and residual stress received greater attention. With this attention came a greater awareness of the properties of the materials and the impact of the operating environment on material properties.

Composite materials, continuous or discontinuous fibers embedded in a resin matrix, began making their way onto airframe structures in the 1970s as a means to reduce weight while compromising little relative to structural integrity. Today, they make up a significant percentage of military aircraft structures and up to 50 percent of the newest commercial airplanes. Initial concerns centered on delaminations introduced during the manufacturing process or from impact damage. Since then, resin porosity, thermal damage, and ultraviolet degradation prompted studies associated with macro- and micromechanical breakdown of the resin, fiber/resin interfacial properties, and fiber breakage.

Specialty materials, such as ceramic-based thermal protection systems and polymeric-based observable materials, may not be critical to the structural integrity of the airframe; however, they are critical to the mission performance of the vehicles for which their use is intended. Given this, understanding the material state of these nonstructural specialty materials is important.

It is well understood that no one NDE method will tell the entire story about a structure. This is especially true given the wide variety of materials found on airframes today, and is made even more apparent given the range of conditions associated with each material. In some cases, there are no reliable sensing approaches to detect the conditions of interest. In order to fully implement a materials state awareness program, NDE must move from a defect-focused technology area to a properties-based technology area. This creates needs from the sensor development standpoint, especially for cases in which conditions of interest cannot be adequately evaluated.

The desire to continuously monitor the state of a material opens up opportunities for utilizing NDE sensors in a structural health monitoring (SHM) capacity. SHM approaches are desirable from several standpoints, including that of reducing maintenance costs and promoting a greater awareness of the materials state. However, there are some roadblocks in the path to implementation. These include sensor technologies incapable of detecting key properties, weight issues associated with the number of sensors required to provide adequate fidelity, limited efforts relative to data collection methods and signal processing, and a production/maintenance infrastructure that is resistant to change.

A key element of materials state awareness is predicting the future state of the material system. This requires robust models that factor in all key characteristics of the operating environment. Models for fatigue crack growth are well established; however, models to support properties-based assessments are very immature as they relate to impact on a material or structural system.

Successful implementation of a materials state awareness program also requires close collaboration between the physicist developing sensor technology, the materials specialist who understands material properties and their impact on the structure, the structural analyst who can identify failure modes and define acceptable limits, and the NDE specialist who understands the measurement principles and applications and would serve as the technology integrator. Often, each of these disciplines operates in a silo, not fully communicating key information required for seamless transition.

KEY ISSUES IN MATERIALS STATE AWARENESS FOR AVIATION PROPULSION SYSTEMS

Robert Schafrik and Jeffrey Williams, GE Aviation

Nondestructive evaluation encompasses sensing techniques that provide quantitative information regarding materials properties. These techniques would not adversely affect the condition of the material being examined. The scope of NDE encompasses material evaluation, component evaluation, and in situ (on-platform) monitoring. In order to accomplish materials state awareness, appropriate NDE methods must be selected on the basis of required functionality and the ability to perform satisfactorily in the application environment.

Current fleet management capability is constrained by uncertainty in the current state of the individual aircraft engines. The ability to sense or measure the damage state of an individual part is limited at best. Further, specific part operational capability is not captured with the current lifing process; hence many components are not operating to their life entitlement because the life is based on fleet weighted average missions.

Materials in propulsion applications are subjected to severe environments, often at high temperature. Key material degradation modes of interest are fatigue and creep, plus environmental attack from oxidation and hot corrosion. Prime driving forces for incorporating materials state awareness (MSA) into critical propulsion system components include the following:

- *More precisely estimating the remaining useful life of an individual component based on actual usage in the application environment*. The current practice uses a fixed maintenance schedule based on fleetwide statistics and then retires parts based on a hard time limit calculated on the basis of a typical mission profile.
- *Lower risk application of new materials in structural applications without necessitating extensive field experience.*

MSA offers considerable advantages to engine fleet owners and operators:

- *Increasing the sustainability of engine fleets, since maintenance, repair, and replacement decisions are based on the condition of the hardware.* Prognosis requires an on-engine assessment of material condition (that is, MSA) to allow an estimation of the useful remaining life of a component by modeling degradation progression.
- *Facilitating advanced planning of required maintenance actions.* Health management uses the prognostic information on an engine-by-engine basis to make decisions about maintenance and logistics actions to minimize cost and maximize readiness.
- *Minimizing field failures.*

The key to success in MSA involves a basic understanding of the primary material degradation modes for a component in the application environment; using this knowledge, the appropriate material parameters can be evaluated. This level of understanding exists for certain propulsion material applications, but further study is warranted in several areas, particularly for the advanced classes of materials.

The second key to success involves matching sensor and NDE techniques to the MSA requirement in the application of interest. Importantly, a systems approach is needed so that MSA is included as a basic requirement during the product design cycle. During design, a number of considerations for each candidate sensing technique would be taken into account; they include the following:

- Inherent limitations and constraints of the sensing method;
- Speed, accuracy, and repeatability, along with the capability to quantify anomalies;
- Scalability regarding large and small components;
- Development and qualification costs of sensors and associated reasoner software; and
- Cost to incorporate sensors and their network into the propulsion system hardware, plus operations and maintenance costs throughout the lifetime of the engine.

Within the turbine engine, structural components offer a significant opportunity for MSA. These components range from mainshaft engine bearings, to polymer and ceramic matrix composite components, to superalloy turbine airfoils and disks. Initial NDE to characterize the baseline as-manufactured condition of the component is important, followed by methods to monitor in-service condition. In general, during the operation of the engine, the sensor data are analyzed by diagnostic reasoner software to continually evaluate the ability of a component to perform its intended function. This diagnostic system must have a high degree of fault detection and isolation to properly detect material degradation without producing false alarms. As an example, superalloy turbine airfoils that continually operate in a high-stress, high-temperature environment offer a significant opportunity for benefit from MSA; in this case, the degradation modes are dominated by the thermal history of the blade, and hence accurate surface-temperature measurement across the airfoil is particularly critical to MSA success.

Research and development opportunities to advance MSA include the following:

- Furthering the fundamental understanding of material degradation modes, especially those of advanced materials targeted for production applications; historically this work has not been well funded;

- Development of in situ NDE techniques that provide technology options to detect changes in the material state by functionality, for example, temperature measurement;
- Database storage and retrieval capability for large, persistent databases, including images, and analysis algorithms; and
- Secure, reliable network technology, including wireless technology that meets demanding military requirements.

In summary, MSA requires a fundamental knowledge of materials degradation mechanisms in the service environment, although empirical-based models can be useful if extrapolation outside the experience base is not crucial. NDE methods must measure physical changes in a material that in turn can be physically linked to the progress of degradation modes. A systems approach is necessary to selecting sensors, developing reasoner software, and designing hardware that can be suitably interrogated by MSA methods. Sensing and inspection technologies are enabling technologies; importantly, sensors must be highly reliable over a long time period in severe environments. Constraints imposed by computing power, data storage and access, and data transmission are also critically important.

Session II: What Is Materials State Awareness?

AN INTEGRATED VIEW OF MATERIALS STATE AWARENESS

R. Bruce Thompson, Iowa State University

Materials state awareness seeks to estimate the remaining lifetime of individual systems or structures or components, the heart of condition-based maintenance strategies. In principle, such estimates should be based on a knowledge of the initial state, damage or failure processes, operational environment, and nondestructive evaluation (NDE) assessment of state at various points in the lifetime. Achieving this goal requires the integration of information from a variety of disciplines, including the mechanics of materials, materials science, engineering mechanics, and NDE engineering. Data interpretation and analysis will also require a focused effort, relying on the integration of statistical concepts with the engineering functions as well. Included in this overview of some of the issues associated with engineering integration is a discussion of some fundamental differences in the structure of the data that would be obtained in depot and field inspections as opposed to those from onboard sensors, and the need to deal with missing data, uncertainty, and variability in the process of estimating state from field-generated information. It is suggested that Bayesian approaches, which are designed to provide strategies to combine new data with existing knowledge or expertise, provide an appealing framework for this integration by virtue of being able to handle the wide diversity of inputs. Some early efforts in the NDE community to use such approaches are reviewed; at the time (early 1980s) they were considered fairly academic. However, the major advances in simulation tools for NDE and damage processes as well as in computational capability that have occurred in the intervening 25 years suggest that the NDE community should re-examine these approaches.

NONDESTRUCTIVE PHYSICAL PROPERTY MEASUREMENTS TO ESTABLISH MATERIALS STATE AWARENESS

David L. Olson, Colorado School of Mines

The commonality of advanced NDE techniques occurs at the electronic level. All of the NDE techniques assess the electronic structure of materials and perturbations in the structure due to crystallinity, defects, microstructural phases and their features, manufacturing and processing, and service-induced strains. Electronic, magnetic, and elastic properties have all been correlated to the fundamental electronic properties of the material.

The Role of the Electron in Solid State

Hume-Rothery, Darken and Gurry, Gschneider, and Waber,[1] on a diagram, correlated the elemental electronegativity and the atomic radius to the degree of solubility of a solute in a solid solvent. This correlation was the first attempt to introduce the role of the electron to define the material state. Engel[2] and Brewer[3] further developed the methods to predict elemental crystal structures, terminal solubilities, and the phase fields of intermetallic phases. Brewer drew from concepts of spectroscopy and chemical bonding in introducing the electron promotion energy to establish a hybrid elemental electronic structure. This hybrid structure correlates electronic and crystal structures, such as d^ns (*bcc*), d^nsp (*hcp*), d^nsp^2 (*fcc*), *and* d^nsp^3 (*dc*). Miedema and Chelikowsky,[4] by using a model based on the Wigner-Seitz cell, related the enthalpy of formation of a specific phase to the elemental work function and the bulk modulus/molar volume. The work function suggests the role of the electron in property predictions, and the bulk modulus suggests the connection to elastic property measurements. This method is able to predict interfacial properties and behavior.

Mott and Jones and others[5] introduced the wave mechanics concepts allowing for the establishment of the electronic band theory, Fermi energy, and Brillouin zones. The use of the

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[1] W. Hume-Rothery. 1967. Factors Affecting the Stability of Metallic Phases. Pp. 3-23 in Phase Stability of Metals and Alloys. New York: McGraw-Hill; J.T. Waber, K. Gschneider, Jr., A.C. Larson, and M.Y. Prince. 1963. Prediction of Solid Solubility in Metallic Alloys. Transactions of the Metallurgical Society of AIME 227: 717-723; K.A. Gschneider, Jr. 1979. L.S. (Larry) Darken's Contribution to the Theory of Alloy Formation and Where We Are Today. Pp. 1-39 in Theory of Alloy Phase Formation. Warrendale, Pa.: TMS-AIME.

[2] N. Engel. 1964. Metallic Lattice Considered as Electron Concentration Phases. Transactions of ASM 57: 611-619.

[3] L. Brewer. 1994. Calculation of Phase Diagrams of the Actinides. Journal of Alloys and Compounds 213/214: 132-137; L. Brewer. 1970. Thermodynamics and Alloy Behavior of the BCC and FCC Phases of Plutonium and Thorium in Plutonium and Other Actinides. Pp. 650-658 in TMS Nuclear Metallurgy Series, Vol 17. Warrendale, Pa.: TMS-AIME.

[4] A.H. Miedema, R. Boom, and F.R. deBoer. 1975. Simple Rules for Alloying in Crystal Structures and Chemical Bonding in Inorganic Chemistry. The Netherlands: North Holland Publishing; J.R. Chelikowsky. 1979. Solid Solubilities in Divalent Alloys. Physical Review B 19(1): 686.

[5] N.F. Mott and H. Jones. 1936. The Theory of the Properties of Metals and Alloys. London: Oxford University Press; J.M. Ziman. 1963. Electrons in Metals: A Short Guide to the Fermi Surface. London: Taylor and Francis, Ltd; C. Kittel. 1963. Introduction to Solid State Physics. New York: Wiley; R.E. Watson and L.H. Bennett. 1978. Transition Metals: d-band Hybridation, Electronegativities, and Structural Stability of Intermetallic Components. Physical Review B 18(12): 6439-6449; L.H. Bennett and R.E. Watson. 1979. Parameters in Semi-Empirical Theories of Alloy Phase Formation. Proceedings of the AIME International Annual Meeting. New Orleans; R.H. Bube. 1992. Electrons in Solids, 3rd Edition. New York: Academic Press; J.C. Phillips. 1979. From Wigner-Seitz to Miedema to ? Pp. 330-343 in Theory of Alloy Phase Formation, Warrendale, Pa.: TMS-AIME.

free electron model for a metal can be extended to consider electron-lattice potential interactions through the introduction of the effective mass of the electron. The effective mass of the electron, m_e, is derived to be:

$$m_e = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} \tag{1}$$

where $\hbar$ is the Planck constant divided by 2π. The effective mass describes the shape of the Fermi energy surface in situations at the Fermi energy level where the band filling is subject to electron-lattice potential interaction. The second derivative factor allows electronic property measurements to be useful, sensitive NDE microstructure and alloy stability assessment tools. When the Fermi energy surface contacts the Brillouin zone boundary, which represents an energy band gap that exists when the electron energy has a wave vector that will be diffracted, the conditions for a phase transformation occur. After the Fermi energy surface contacts the Brillouin zone boundary, it quickly fills higher energy states during further alloy additions, thus rapidly increasing the effective mass of the electron. The lattice will select a different crystal structure, thus a new Brillouin zone, which can continue filling the electronic states, allowing for lower energy filling. This situation is the electronic explanation for phase transformations.

Recognizing that the phase compositional field on a phase diagram is defined by the chemical potential of a species between two phases, the chemical potential of the electron in one phase is equal to the chemical potential of the electron in the second phase. It is also known that the chemical potential of the electron is defined as the Fermi energy at absolute zero. From the free electron model, the Fermi energy is directly related to the conduction electron concentration. Dooley et al.[6] used these concepts of phase equilibrium with the Brewer values of the e/a for specific phases and calculated the phase diagram for the Pu-Ga system, which has respectable correlation to experimentally determined phase diagrams.[7]

The utility of using the effective mass of the electron, m_e, to understand the state of the microstructure can be seen by considering the total energy, E, of an electron in a solid, based on wave mechanics; then:

$$E = \frac{\hbar^2 k^2}{2m} + V, \tag{2}$$

where k is the electronic wave vector, and V is the potential that the nearly free electron is experiencing from the lattice. If the information of the potential of electron-lattice interactions, V, is incorporated into the factor m, then the total energy of electron in the lattice can be expressed in terms of effective mass m_e as:

$$E = \frac{\hbar^2 k^2}{2m_e}. \tag{3}$$

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[6] D.E. Dooley, D.L. Olson, G.R. Edwards, and F. E.Gibbs. 2001. Development of an Electronic Phase Diagram and the Production of Plutonium Alloy Phase Stability Using Electronic Properties. Journal of Physics-Condensed Matter 13: 8677-8696.

[7] L. Brewer. 1994. Calculation of Phase Diagrams of the Actinides. Journal of Alloys and Compounds 213/214: 132-137; L. Brewer. 1970. Thermodynamics and Alloy Behavior of the BCC and FCC Phases of Plutonium and Thorium. Pp. 650-658 in TMS Nuclear Metallurgy Series, Vol 17. Warrendale, Pa.: TMS-AIME.

These localized potentials represent the structural contributions that disturb the periodic lattice (Block function), such as dislocations, grain boundaries, areas of lattice strain, and phase changes. The m_e concept is very sensitive to changes in alloy composition, lattice strain, and susceptibility of a phase transition allowing for electric conductivity and thermoelectric power (TEP) coefficient measurements as materials state assessment tools.

The TEP coefficient is a measure of the electron configurational entropy in the filling of the electronic bands of the metal or alloy and can be expressed as:

$$S = \left(\pm \frac{k_B}{e}\right)(27.1)\left(r + \frac{3}{2}\right)\left(\frac{m_e}{h^2}\right)\left(k_B T n^{\left(-\frac{2}{3}\right)}\right), \tag{4}$$

where k_B is the Boltzmann's constant.[8] If the lattice experiences compressive or tensile stresses due to solute additions, residual strains, radiation damage, and so forth, then the electronic overlap of *d* and *f* orbitals between lattice atoms will cause both changes in the reciprocal lattice and, thus, the size and shape of the bands. Also, the change in the electronic concentration causes a relocation of the Fermi energy level in the band. The m_e at the Fermi energy is extremely sensitive to changes in the electronic band structures due to the (d^2E/dk^2) factor. Electronic properties, such as TEP coefficients, resistivity, and induced resistivity measurements, have demonstrated correlation to solute and phase content, a potential phase transformation, and even residual strain. Retained austenite in transformation-induced plasticity steels have been accurately determined by using TEP measurements.

Woodyatt et al.[9] developed phase computation (PHACOMP), an analytical practice, with criteria to determine if an alloy is susceptible to sigma phase formation. Sigma phase is a detrimental microconstituent that can form in high-temperature superalloys used in high-performance turbine engines. The electron vacancy (unfilled states of the d-band), N_V, is estimated and used to correlate to the criteria for the formation of sigma phase. If N_V is greater than 2.49, sigma phase is likely to form.

$$\begin{aligned} N_V &= 0.66\,\mathrm{Ni} + 1.71\,\mathrm{Co} + 2.66\,\mathrm{Fe} + 3.66\,\mathrm{Mn} + 4.66(\mathrm{Cr} + \mathrm{Mo} + \mathrm{W}) \\ &+ 5.66(\mathrm{V} + \mathrm{Nb} + \mathrm{Ta}) + 6.66(\mathrm{Si} + \mathrm{Ti}) + 7.66\,\mathrm{Al} \end{aligned} \tag{5}$$

Further efforts have developed a more fundamental-based model, known as New PHACOMP, to predict more accurately the phase boundary for sigma phase formation.[10] This quantum mechanical calculation gives a more specific elemental contribution to the d-band electron filling. If it is possible to calculate whether a specific alloy composition is susceptible for sigma phase formation by an electronic computation and correlation, then it should be possible to measure the electronic property state for the susceptibility of sigma phase formation.

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[8] A. Sommerfeld and H. Bethe. 1933. Elektronentheorie der Metalle. Pp. 333-622 in Handbuch der Physik 24: 2. Berlin: Springer.

[9] L.R. Woodyatt, C.T. Sims, and H.M. Beltram. 1966. Prediction of Sigma-Type Phase Occurrence from Compositions in Austenitic Superalloys. Transactions of the Metallurgical Society of AIME 235(4): 519-527.

[10] M. Morinaga, N. Yukawa, H. Adachi, and H. Ezaki. 1984. New PHACOMP and Its Applications to Alloy Design. Pp. 523-532 in Superalloys. Metals Park, Ohio: ASM; M. Morinaga, N. Yukawa, H. Adachi, and H. Ezaki. 1984. Alloying Effect on the Electronic Structure of Ni3Al(γ′). Journal of the Physical Society of Japan 53(2): 653-663; M.J. Cieslak, G.A. Knorovsky, J.J. Headley, and A.D. Romig, Jr. 1986. The Use of New PHACOMP in Understanding the Solidification Microstructure of Nickel Base Alloy Weld Metal. Metallurgical Transactions 17A(12): 2107-2116.

Available Physical Property Measurements

X-ray fluorescence spectroscopy offers a rapid NDE chemical compositional analysis for elements in the condensed matter. Elastic analysis, in its many forms, is advancing rapidly to reach beyond just the determination of the number, size, and morphology of defects in the solid. Elastic waves perturb the atomic positioning, but also the electron density throughout the perturbed lattice. This electronic-phononic exchange in both directions can be seen with the use of elastic waves generated by either piezoelectric transducers or electromagnetic acoustic transducers (EMATs). The elastic moduli are a function of the electron density of the elements.[11]

Through the use of spaced, properly calibrated EMATs, the speed of sound can assess the temperature in a material. Balashchenkov and Livanov[12] have correlated the elastic behavior to the electronic structure in an expression that connects the speed of sound to the TEP value when performing nondestructive measurements of impurities in solids, indicating the relationship between various physical property measurements.

Magnetic analysis can detect phase changes and even prephase transformations, such as Guinier-Preston zones or γ' ordered-structure formation.[13] Magnetic analysis has been used to assess the hydrogen content in hydrogen storage materials and should also be able to measure residual strain in ferrous alloys.[14]

The Use of Frequency and Amplitude Modulations

By implementing a full range of wave-perturbing frequencies, and with knowledge of the depth factor, wavelengths can be used at all levels of microstructural scale, from nano to millimeter, to assess atomic-to-grain structure, size, and morphology. The interplay between wave perturbations and the matter (and the reverse) will become an even more valuable assessment protocol. Both frequency and amplitude modulation can be applied to this wave analysis. With instrumentation, various combinations of harmonics between the perturbation wave and the analyzed wave may be employed to assist in signal recognition analysis. The use of wave analysis, whether electronic, magnetic, or elastic, offers the new capabilities to assess the material without using a calibration standard.

Magnetic Barkhausen and magnetic acoustic emissions analyses assess the elastic emission resulting from the transporting of the magnetic domain wall through ferromagnetic

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[11] Seung-Am Cho. 1977. Engel-Brewer Theory and Related Physical Properties of Hume-Rothery's Class-I Metals. Acta Metallurgica 25:1085-1094; J.J. Gilman. 2003. Chapter 12, Bulk Modulus. Pp. 110-141 in Electronic Basis of the Strength of Materials. Cambridge, U.K.: Cambridge University Press.

[12] K.D. Balashchenkov and D.V. Livanov. 1997. Effect of Impurities on Thermoelectric Power Due to Phonon Drag. Journal of Experimental and Theoretical Physics 84(6): 1221-1224.

[13] K.A. Lindahl, D.L. Olson, and J.U. Trefny. 1996. Alloy Phase Analysis from Measurements of Bulk Magnetic Properties. Metallurgical and Materials Transactions 27: 2958-2965.

[14] Y.D. Park et al. 2003. Characterization and Prediction of Hydrogen Absorption Behavior for AB5 Type Hydrogen Storage Alloys by Using Electronic Measurement. Pp. 69-75 in Proceedings of the 6th International Conference on New Energy Systems and Conversions, Pusan, Korea; A.N. Lasseigne-Jackson, J.E. Jackson, D.L. Olson, and B. Mishra. 2007. Development of Electromagnetic Techniques for Hydrogen Content Assessment in Coated Linepipe Steel. Pp. 1159-1166 in Review of Quantitative Nondestructive Evaluation, Vol. 26. D.O. Thompson and D.E. Chimenti, eds. Melville, N.Y.: American Institute of Physics.

materials.[15] The elastic emission results from the unpinning events of the block wall from nonperiodic sites in the lattice. By varying the frequency of the eddy current source, which perturbs and oscillates the domain wall, one can identify specific frequencies that are more pronounced in unpinning specific structural lattice irregularities, and these frequencies can be used to identify the microstructural state of the ferrous material. By scanning frequencies, the evolution of the many carbide types in 2¼ Cr–Mo steel resulting from high-temperature services can be assessed, and the results can assist in the determination of remaining service life.

The Need for Multiple Measurements

The significant difficulty of using a single physical measurement to characterize material microstructure, composition, or other properties is that the measurements are dependent on numerous independent variables. Electronic property measurements are dependent on at least three independent electronic properties. For a physical property measurement to assess the material state requires reference to materials standards, requiring calibration measurements to hold most of the physical and compositional variables constant by comparing measured values to this calibrated material's standard.

The necessary advancement in use of physical measurements to assess materials is through the use and correlation of sufficient different physical measurements to experience all of the independent material variables. This case is similar to the algebraic problem of having sufficient equations for the unknowns. The use of a combination of magnetic and elastic property measurements on the same material, and with the same thermomechanical history, offers a practice to achieve sufficient correlatable information to assess the material without the use of materials standards. Also, the use of property measurements, based on wave analysis (electromagnetic and elastic waves), allows measurements to be made at different frequencies that interact with different specific microstructural details. The use of the same physical measurements at different frequencies can offer independent information to allow correlation to the material's independent variables. Likewise, amplitude modulation also allows wave analysis to offer more insight to the determination of material properties, microstructure, and behavior.

The aging kinetics of maraging steels involves precipitation of metastable phases ($Ni_3[Ti,Mo]$) followed by the formation of stable phases ($Fe_2[Mo,Ti]$) and austenite with continued composition changes in the highly alloyed matrix. Also, high residual strains caused by the semicoherent precipitates and reduction in the dislocation and point defect densities have offered a number of investigators a family of alloys providing an opportunity to examine the concept of fully characterizing a material using multiple nondestructive evaluations. The literature describes much nondestructive testing of maraging 250 steels, which includes resistivity, eddy currents, magnetic properties (magnetic saturation and magnetic Barkhausen emission [MBE] remote monitoring systems), ultrasonic wave velocities, TEP, x-ray diffraction (full-width half maximum as an indication of residual strains and phase composition) and x-ray fluorescence (phase composition).[16]

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[15] K.V. Rajkumar, S. Vaidyanathan, A. Kumar, T. Jayakumar, B. Raj, and K.K. Ray. 2007. Characterization of Aging-induced Microstructural Changes in M250 Maraging Steel Using Magnetic Parameters. Journal of Magnetism and Magnetic Materials 312: 359-365; F.G. Caballero, A. García-Junceda, C. Capdevila, and C. García de Andre. 2005. Precipitation of M23C6 Carbides: Thermoelectric Power Measurements. Scripta Materialia 52: 501-505.

[16] M. Morinaga, N. Yukawa, H. Adachi, and H. Ezaki. 1984. Alloying Effect on the Electronic Structure of Ni3Al(γ′). Journal of the Physical Society of Japan 53(2): 653-663; M.J. Cieslak, G.A. Knorovsky, J.J. Headley, and A.D. Romig, Jr. 1986.

The Need for a Microstructural Rule

As with materials phase analysis, the phase rule determines the least number of intrinsic properties, the degrees of freedom (*F*), to define the number of phases. A microstructural rule is needed to determine the specific number of intrinsic property measurements needed to fully characterize a microstructure. The microstructure rule is given as:

$$F = C - P + 2 + M, \tag{6}$$

where *C* is the number of components and *P* is the number of phases, the "2" recognizes pressure and temperature, and an additional *M* term addresses the need for measurements to express microstructural constituents' concentrations, sizes, and morphologies. A microstructural rule is needed to identify the minimum number of intrinsic property measurements required to fully characterize the material. Consider the example of the two-phase, α + Fe_3C, region of the iron-carbon system. This region can be represented by various morphologies such as pearlite, Bainite, or as spherical carbides in a ferrite matrix. All three satisfy the same phase rule count of phases, but additional property measurements are needed to distinguish the specific microstructural features. The effort to establish a quantitative scheme to determine *M* will have to draw on rules from phase equilibrium, phase transformation, metallography, petrology, and topology.

The Use of New PHACOMP in Understanding the Solidification Microstructure of Nickel Base Alloy Weld Metal. Metallurgical Transactions 17A(12): 2107-2116; Seung-Am Cho. 1977. Engel-Brewer Theory and Related Physical Properties of Hume-Rothery's Class-I Metals. Acta Metallurgica 25:1085-1094; J.J. Gilman. 2003. Chapter 12, Bulk Modulus. Pp. 110-141 in Electronic Basis of the Strength of Materials. Cambridge, U.K.: Cambridge University Press; K.D. Balashchenkov and D.V. Livanov. 1997. Effect of Impurities on Thermoelectric Power Due to Phonon Drag. Journal of Experimental and Theoretical Physics 84(6): 1221-1224; K.A. Lindahl, D.L. Olson, and J.U. Trefny. 1996. Alloy Phase Analysis from Measurements of Bulk Magnetic Properties. Metallurgical and Materials Transactions 27: 2958-2965; Y.D. Park et al. 2003. Characterization and Prediction of Hydrogen Absorption Behavior for AB5 Type Hydrogen Storage Alloys by Using Electronic Measurement. Pp. 69-75 in Proceedings of the 6th International Conference on New Energy Systems and Conversions, Pusan, Korea; A.N. Lasseigne-Jackson, J.E. Jackson, D.L. Olson, and B. Mishra. 2007. Development of Electromagnetic Techniques for Hydrogen Content Assessment in Coated Linepipe Steel. Pp. 1159-1166 in Review of Quantitative Nondestructive Evaluation, Vol. 26, D.O. Thompson and D.E. Chimenti, eds. Melville, N.Y.: American Institute of Physics; K.V. Rajkumar, S. Vaidyanathan, A. Kumar, T. Jayakumar, B. Raj, and K.K. Ray. 2007. Characterization of Aging-induced Microstructural Changes in M250 Maraging Steel Using Magnetic Parameters. Journal of Magnetism and Magnetic Materials 312: 359-365; F.G. Caballero, A. García-Junceda, C. Capdevila, and C. García de Andre. 2005. Precipitation of M23C6 Carbides: Thermoelectric Power Measurements. Scripta Materialia 52: 501-505; M.N. Rao. 2006. Progress in Understanding the Metallurgy of 18% Nickel Maraging Steels. International Journal of Materials Research (formely Z. Metallkd.) 97(11): 1594-1607; R. Tewari, S. Mazumder, I.S. Batra, G.K. Dey, and S. Banerjee. 2000. Precipitation in 18 wt% Ni Maraging Steel of Grade 350. Acta Materialia. 48: 1187-1200; K.V. Rajkumar, S. Vaidyanathan, A. Kumar, T. Jayakumar, B. Raj, and K.K. Ray. 2007. Characterization of Aging-Induced Microstructural Changes in M250 Maraging Steel Using Magnetic Parameters. Journal of Magnetism and Magnetic Materials 312: 359-365; K.V. Rajkumar, A. Kumar, T. Jayakumar, B. Raj, and K.K. Ray. 2007. Characterization of Aging Behavior in M250 Grade Maraging Steel Using Ultrasonic Measurements. Metals and Materials Transactions 38A: 236-243; Y. Snir, M. Pinkas, Y. Gelbstein, O. Yeheskel, and A. Landau. 2007. Applying TEP Measurements to Assess the Aging Stage of a Maraging 250 Steel, 34th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE2007), July 23-27, 2007.

The Need for Generation II Materials Science

Processed materials consist of compositional, microstructural, and property gradients that require modifications in the materials science fundamentals to describe the nonuniform materials behavior, such as aging, phase stability, and the defect initiation. This is so especially in materials that depend on nanostructural features. When lattice dimensions in the nano-to-millimeter range are necessary to describe the material, then nonlinear thermodynamics and kinetics need to be used to accurately describe the system.[17] Cahn and Hilliard[18] describe the thermodynamics on the nonuniform systems, Hart[19] has addressed the nonuniform strain issues, and Tu[20] described the need for application of nonlinear terms in the expressions describing the evolution of nanoscale thin films. Advanced composite theory will need to describe the electronic charge gradient across the bonding interfaces based on electronic concepts. These bonding interfaces, which will be considered as junctions with electronic gradients described by the Debye lengths, will use electronic and elastic NDE tools to assess the amount of remaining service life. The expressions for describing lattice behavior and the response of the lattice to perturbations will require additional nonlinear terms. The influence of these nonlinear effects on NDE assessment needs to be investigated, and the analytical materials science practices need to be developed to allow interpretation of the micro (nano)-structural state of many advanced and high-performance materials now being used or that will be used by the United States Air Force.

Outlook

With the use of the proper combination of independent NDE measurements, it is possible to accurately evaluate the microstructure and properties of materials. The fundamental limitations of correlating microstructure and properties to NDE measurements result from both the numerous independent variables that each of these properties has and the number of intrinsic property measurements necessary to characterize the number of phases and the microstructural features. Different electronic, magnetic, and elastic measurement combinations offer complementary insights into materials properties, and practices for their selection need to be developed for the appropriate applications. This advanced integration of physical property and phenomena measurements will result in new opportunities for the NDE community and the development of new analytical measurement equipment and practices.

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[18] J.W. Cahn and J.E. Hilliard. 1958. Free Energy of a Non-Uniform System, I: Interfacial Free Energy. Journal of Chemical Physics 28: 258; J.W. Cahn and J.E. Hilliard. 1959. Free Energy of a Non-Uniform System, II: Thermodynamic Basis. Journal of Chemical Physics 30: 1121-1124; M. Hillert. 1961. A Solid-Solution Model for Inhomogenous System. Acta Metallica 9: 525-535; A. Novick-Cohen and L.A. Segel. 1985. Non-Linear Aspects of the Cahn-Hilliard Equation. Physica D. 10: 277-298.; M.F. Ashby. 1970. The Deformation of Plastically Non-Homogenous Materials. Philosophical Magazine 21(170): 399-424.

[19] E.W. Hart. 1959. Thermodynamics of Inhomogeneous Systems. Physical Review 113: 412-416.

[20] K.N. Tu. 1985. Interdiffusion in Thin Films. Annual Review of Materials Science 15: 147-176.

MODELING AND SENSING MECHANICAL DEGRADATION IN METALS AND COMPOSITES

W.A. Curtin, Brown University

The detection of cracks in structural components poses significant technological challenges as the necessary scale for detection decreases. The detection of precursors to cracks remains largely a long-term goal. Nonetheless, modeling of the material behavior at micro- or nanoscales can provide insight into what the precursors actually are, how they evolve, and what methods of detection might be feasible. Here, recent progress in the modeling of damage evolution in metals and carbon-fiber-reinforced polymer composites is discussed. In metals, discrete dislocation models are being applied to model fatigue crack growth emanating from precracked inclusion particles. While these models show the role of both size and particle type in the growth of micron-sized fatigue cracks and on dislocation distributions around the cracks, such models are still far from providing the information needed for designing detection methodologies. In contrast, in carbon-fiber-reinforced polymer composites the use of electrical resistance changes owing to evolving distributed damage is emerging as a promising approach to couple mechanical degradation and prognosis. Here, a coupled electromechanical model to predict resistance versus applied loading and/or applied cycles is presented, and predictions from both analytical and simulation studies show that electrical resistance changes can (1) be far larger than stiffness changes, (2) provide evidence of internal damage early in life, and (3) be sensitive to anomalous load spikes. While this modeling has yet to be extended fully to evaluate detection methodologies, statistical features, and sensitivity versus probed volume, the results to date represent a firm foundation on which systems for materials state awareness and prognosis can be built.

VIRTUAL TESTS: MAKING THE MOST OF EXPERIMENTAL KNOWLEDGE

Brian Cox, Teledyne Scientific

Taking advantage of major recent advances in computational methods and the conceptual representation of failure mechanisms, the modeling community is building increasingly realistic models of damage evolution in structural composites. The goal of virtual tests, in which most (but not all) real experimental tests can be replaced by high-fidelity computer simulation, appears to be reachable. The payoff in reduced cycle time and costs for designing and certifying composite structures is very attractive; and the possibility also arises of considering material configurations that are too complex to certify by purely empirical methods. However, major challenges remain, the foremost being the formal linking of the many disciplines that must be involved in creating a functioning virtual test. Far more than being merely a computational simulation, a virtual test must be a system of hierarchical models, engineering tests, and specialized laboratory experiments, organized to address the assurance of fidelity by applications of information science, model-based statistical analysis, and decision theory. The virtual test must be structured so that it can function usefully at current levels of knowledge, while continually evolving as new theories and experimental methods enable more refined depictions of damage.

To achieve the first generation of a virtual test system, special attention must be paid to unresolved questions relating to the linking of theory and experiment: how can one ensure that damage models address all important mechanisms, how can the materials properties embedded in the models be calibrated, and what constitutes sufficient validation of model predictions? The virtual test definition must include real tests that are designed in such a way as to be rich in the information needed to inform models and model-based analyses of the tests that are required to mine the information. But to date these compelling issues have been greatly underserved by both the modeling and experimental communities. Model-based analysis of tests has been undertaken only in terms of very simple (linear or continuum) engineering concepts; information-rich tests for more complex damage mechanisms have not been defined; and in fact the information in which experiments need to be rich has not been stated. Specific challenges in designing experiments for informing virtual tests and some promising experimental methods are summarized.

Session III: What Should We Sense for Materials State Awareness and How Should We Look for It?

MATERIALS STATE AWARENESS: A PROPULSION PERSPECTIVE

Kevin Smith, Pratt & Whitney

Materials state awareness is an emerging issue in the propulsion nondestructive evaluation (NDE) community. While the NDE community has had this issue on its long-range plans for some time, only recently has an adequate understanding been developed in the academic community to begin realistically considering the implementation of practical methods to effectively consider material state as part of the overall engine maintenance philosophy. NDE has highly developed technology to address cracking, especially surface-connected low-cycle fatigue cracks. Very sensitive crack detection by means of eddy current has been implemented through automated systems at the original equipment manufacturers and at the military depot for military engines. On-wing and semiautomated crack detection has also been successfully implemented in the commercial fleet as well. Inspection methods, especially in the face of unanticipated durability issues, have provided excellent economic and readiness benefits to the military and commercial aircraft operators. The use of NDE to provide information about the condition of engine hardware both prior to installation and during service has a high value that is appreciated, certainly at Pratt & Whitney and probably at other original equipment manufacturers. Knowledge of the state of the product has been leveraged to apply effectively such damage tolerance philosophies as retirement for cause, engine structural integrity programs, and propulsion system integrity programs—all of which have brought economic, readiness, and safety benefits to the military customer. A greater understanding of the state of the components has allowed the safe and effective use of the material and the design to a much greater extent as the NDE capabilities have developed. The ability to monitor the state of components coming out of production as well as monitoring their condition in the field has moved in lockstep with the continuing push toward improved design life and engine efficiency. NDE technology has been a key contributor in the evolution of aircraft propulsion, from the air-cooled radial engine, which was instrumental in the outcome of World War II, to the current generation of the high-performance military and commercial turbofan engines.

The next quantum step in the development of product knowledge and its application to the fleet is awareness of the material state prior to crack formation. A number of challenges exist in this area that will require the development of enabling technologies to practically implement effective strategies. To the extent that the state of fatigue damage prior to cracking can be understood, it will be possible to more effectively address high cycle fatigue issues in the field. When the grain-size distribution inside individual disks can be understood and these data used to actively control the process such that resultant properties fall within a tighter band than they do today, the design system and subsequent fleet issues will lead to production of lighter, more fuel-efficient designs. Residual stress, its changes over the life of the component, and its influence on NDE are all very significant in the design and fleet management of the engine system. Prognostics is an emerging technology that will benefit from understanding of the materials state. Currently, usage monitoring is being applied to the F135 engine. This technology allows the actual usage and damage accumulation of each serial number engine to be tracked separately, thereby also allowing the maintenance plan to be optimized for each engine. This approach varies radically from the current approach of using a nominal flight mission mix to manage an entire fleet that is not flying the same way. By removing the conservatism of the current approach, the economic, safety, and readiness benefits are obvious. End users will actually be in a position to manage an engine in an optimal manner based on its usage rather than on nominal assumptions.

To practically implement the capabilities mentioned above, the ability to readily access the interior of the engine and to deliver a sensor, as well as the ability to quantify the result of the sensor response, are of paramount importance. The ability to deliver a sensor deep inside the engine reliably—that is, to place the sensor accurately, but also to be able to retrieve the sensor—is a key technology that needs to be developed. To make meaningful use of any nondestructive technique in a design or fleet management scenario, the capability needs to be quantified. Model-assisted probability of detection (MAPOD) has been used successfully by Pratt & Whitney for some years as an effective method of quantifying the effectiveness of nondestructive evaluation techniques. A second generation of these MAPOD techniques that is able to more effectively leverage the modularity of the approach and the data collected from various sources is a key to success. As the need to respond more quickly and efficiently to the demands of the end user continues, the ability to quickly and accurately quantify the capability of conventional and next-generation NDE techniques will become more important. Ultimately, the implementation of technologies that allow for the understanding of the state of the material in a gas turbine engine at new manufacture and during service will provide additional opportunities to extend the economic life of the engine safely and provide additional flexibility to the customer.

INTEGRATED STRUCTURAL HEALTH AND LIFE MANAGEMENT OF AIRFRAME STRUCTURES DEPENDENT ON CHARACTERIZING THE STATE OF THE MATERIAL AS A FUNCTION OF TIME IN SERVICE

J.P. Gallagher, Independent Consultant

Damage characterizes and defines the material state that directly relates to structural health and to remaining life. The aircraft structural integrity program[1] provides the framework and processes associated with the initial and continuing airworthiness certification of USAF airframe structures. Defined in this presentation are the framework and processes used to characterize the state of damage in aircraft structures as a function of time in service. Concepts for multiple methods for characterizing the damage state are presented, including the onboard usage-monitoring method (provided by virtual sensors), the off-board damage-monitoring method (based on maintenance/inspection data collection and storage of damage information), and the onboard damage-monitoring method (provided by damage event sensors).[2] By focusing on the fatigue mechanism and aging issues, several types of damage distributions are identified. The presentation identifies several serious challenges associated with characterizing the current state of damage and its accurate projection into a future state. It identifies one particularly difficult challenge associated with the accurate measurement of damage using existing nondestructive inspection (NDI) capabilities. This well-known existing NDI reliability challenge provides important guidance for those investing in onboard damage-monitoring systems for airframe structures. The presentation provides some guidance on the way ahead.

MATERIALS PROPERTY MEASUREMENT USING NONDESTRUCTIVE EVALUATION METHODS AT GE

Shridhar Nath, Tom Batzinger, Waseem Faidi, Jian Li, Ed Nieters, Harry Ringermacher, and Nilesh Tralshawala, GE Global Research; and Thadd Patton, GE Aviation

General Electric (GE) has a rich history and track record of solving problems with NDE. GE researchers develop new NDE technologies, manufacturer state-of-the-art NDE equipment and systems, and use NDE methodologies in a wide range of businesses. Materials characterization and materials property measurements are the new NDE paradigm, shifting from the traditional defect detection. Fundamental microstructural characteristics such as grain size, porosity, and texture and materials properties related to failure mechanisms such as fatigue and residual stress are of increasing interest to the NDE community.

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[1] Department of Defense. 2005. Standard Practice, Aircraft Structural Integrity Program. MIL-STD-1530C.

[2] J.P. Gallagher. 2007. A Review of Philosophies, Processes, Methods and Approaches that Protect In-Service Aircraft from the Scourge of Fatigue Failures. Proceedings of the 24th ICAF Symposium. Naples, Italy. May; L.M. Butkus et al. 2007. U.S. Air Force Efforts in Understanding and Mitigating the Effects of “NDI Misses.” Proceedings of the 24th ICAF Symposium. Naples, Italy. May; J.P. Gallagher et al. 2007. Demonstrating the Effectiveness of an Inspection System to Detect Cracks in Safety of Flight Structure. Proceedings of the 10th DoD/FAA/NASA Aging Aircraft Conference, Palm Springs, April; J.P. Gallagher. 2007. Damage Tolerant Aircraft Design and Its Relationship to Inspections. Presentation at the G.R. Irwin Memorial Conference. College Park, Maryland. March.

The presentation on which this abstract is based discusses two examples being pursued at GE Global Research: (1) nonlinear ultrasound for characterizing low cycle fatigue and (2) thermoelectric magnetic field measurements for mapping residual stress in titanium. A quick overview of the NDE methods used to study aerospace composite materials is also discussed. Finally, a technology roadmap is presented that lays out a strategy that GE is pursuing in improving the prediction of the remaining life accuracy of engine components.

EXAMPLES OF MATERIALS STATE AWARENESS PROBLEMS AND RESEARCH DIRECTIONS TO SOLVE THEM

S.I. Rokhlin, Ohio State University

Several research programs seem to represent applications of the materials state awareness concepts well: for example, how one can predict the effect of the evolution of the state of a material (including damage) in service and the resulting mechanical state. First, the problem of cold dwell fatigue (CDF) in Ti alloys, used in engine components, is reviewed. CDF results in a significant reduction (debit) of fatigue lifetime compared with continuous cycling fatigue. This debit decreases with increasing temperature. In spite of the importance of the CDF phenomenon for aircraft engine safety, its mechanism and life predictive capabilities have not been sufficiently addressed. There is an urgent need to develop an understanding of dwell-time fatigue–microstructure relations and dwell-time crack initiation: Why does CDF happen? What are the microstructural features that control it? How can the resulting mechanical state be predicted? How can dwell-fatigue-sensitive microstructures be nondestructively sensed? How can dwell fatigue life be prognosticated? This set of problems is addressed by an Ohio State University research program sponsored by the Federal Aviation Administration. The problems are being attacked by an interdisciplinary team: J. Williams and M. Mills (microstructures), S. Ghosh (microstructure-based mechanical modeling), and S.I. Rokhlin (microstructure and damage sensing and NDE). Small dwell fatigue and cycle fatigue crack growth rates have been obtained in experiments in which crack initiation and evolution were monitored by ultrasonics and crack sizing by microradiography. It was found that the rates for small dwell fatigue cracks are one to two orders of magnitude higher than those for small cyclic fatigue cracks. This growth behavior of small cracks differs greatly from that of long cracks, which exhibit identical rates for dwell and cycling fatigue. Thus, the process of crack initiation and small crack growth controls the reduction of dwell fatigue life. A micromechanical predictive model has been developed that incorporates experimental input data of single colonies and single crystals: a matrix of elastic properties (anisotropy) obtained by time-resolved line-focused acoustic microscopy, and microscale plastic properties measured by microscale and nanoscale compressive tests. The key modeling results include an understanding of microstructural effects on crack initiation and small crack growth. The soft phase has less resistance to plastic flow than the hard phase does, and as a result the load redistribution is taken up by the hard phase, and high stress concentration at the interface of the hard and soft phases leads to crack initiation. The issue of how possibly one may sense nondestructively dwell-fatigue-sensitive microstructures is also briefly addressed.

In addition, work at the University of Cincinnati and the AFRL (Nagy, Blodgett) on residual stress sensing to improve engine reliability is very briefly reviewed, as is Boeing (Bossi) work on a laser method of strength assessment of bonded joints, and work on characterization of bonded joints by angle beam ultrasonic spectroscopy (Ohio State University, S.I. Rokhlin, Adler Consultants, Adler).

ISSUES AND IDEAS IN MATERIALS STATE AWARENESS FOR AEROSPACE STRUCTURAL JOINTS

Thomas Farris, Purdue University

Much progress has been made in characterizing materials state awareness in homogeneous materials and structures. There are state awareness issues that are unique to structural joints common in aerospace structures, such as lap joints, blade/disk attachments in engines, and bonded composite joints. The role that the evolution of friction plays in materials state awareness is also shown through the connection between contact stresses in joints and friction. For instance, load transfer will depend on the current coefficient of friction that may evolve over time due to wear of the contacting surfaces. Environmental effects such as temperature will also influence the evolution of friction during the life of the joint. There may also be changes, induced by thermal exposure, to residual stresses generated by manufacture that are important to materials state awareness in joints. The wear itself may lead to a loss of stiffness of the joint that changes the nature of the load transfer. There are measurement techniques, such as infrared thermography, capable of capturing the detailed changes in the behavior in the joints in the laboratory. Some of these techniques are discussed and some successful applications demonstrated. Ideas for future research in state awareness for joints are also discussed.

MATERIALS CORROSION FUNDAMENTALS, PREVENTION, AND DETECTION

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"Corrosion" is normally defined as the unwanted deterioration of a material, especially metals, by chemical or electrochemical reaction with the environment. In most cases this involves the oxidation of a metal or alloy through an electrochemical process. Not all oxidation processes are detrimental; for instance, the oxidation of aluminum in air provides a very thin (~10 nm) layer of aluminum oxide on the surface that protects, or passivates, the underlying aluminum metal from further oxidation under ambient conditions. However, in the presence of halogen compounds, such as chlorine and fluorine, the aluminum oxide is removed and pitting corrosion can occur. Although atomistic in mechanism, the impact of corrosion on the U.S. economy is enormous, estimated at $300 billion annually.[4] Corrosion and metal wastage arising from oxidation as caused by exposure to the elements and reactivity between dissimilar materials cost the U.S. military about $20 billion each year.[5] Both the U.S. Air Force and U.S. Navy spend

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[3] The Missouri Institute of Science and Technology was formerly known as the University of Missouri-Rolla.

[4] Corrosion Costs and Preventative Strategies in the United States, DoD Report Number FHWA-RD-01-156, CC Technologies, Inc. Houston, Tex.

[5] Corrosion Costs and Preventative Strategies in the United States, DoD Report Number FHWA-RD-01-156, CC Technologies, Inc. Houston, Tex.

almost $1 billion annually[6] on corrosion-related efforts for aircraft, with the majority of the costs related to inspection for corrosion that involves removing and reapplying corrosion-inhibiting coatings. Improvements in corrosion prevention, detection, and remediation have the potential to make a significant impact on military force readiness and life-cycle costs.

Fundamentals

At the most fundamental level, corrosion occurs due to the formation of an electrochemical cell. Every electrochemical cell consists of four parts: an anode in which oxidation, or electron loss, occurs; a cathode in which reduction, or electron gain, occurs; a first-class conductor, such as metals, to transport electrons from the anode to the cathode; and a second-class conductor, an electrolyte, which allows the movement of ions in the cell. The most common electrolyte is water. These same four components are present in every electrochemical cell, including batteries, electroplating operations, and corrosion, but in some cases the reaction is spontaneous (i.e., batteries, corrosion), while in other cases it is nonspontaneous (i.e., electroplating that requires an external power supply). Differences in the electromotive force (emf) potential of materials provide the thermodynamic factor to cause a reaction, but the kinetics, or speed, of the reaction cannot normally be predicted a priori. In the case of corrosion, the electron loss at the anode is often associated with dissolution of the material (metal) into the electrolyte, resulting in a loss of mass, or in oxidation of the metal. While all corrosion cells have the same components and nominally result in the same deterioration of the material, there are different types of corrosion as determined by the mechanism or appearance of the degradation. Although there are a number of ways to categorize corrosion, eight forms of corrosion are often described: galvanic, uniform, erosion, crevice, pitting, intergranular, selective leaching, and stress corrosion cracking. Each has similarities and differences, with each corrosion product unique to that system or form, but all result in the degradation of material through chemical and electrochemical attack. It should be noted that corrosion is almost always a localized event due to the atomistic nature of the reactions.

Prevention

Methods to prevent each of the forms of corrosion vary widely, but in all cases corrosion is inhibited by isolating or removing one or more of the four components of an electrochemical cell, essentially creating an open circuit that prevents electron flow. Anodic inhibitors, cathodic inhibitors, barriers, insulators, and so on are all viable methods to prevent or minimize corrosion. Identifying what controls the corrosion is a key component in determining how to prevent the reaction. While proper materials selection and compatibility can often minimize corrosion, it is often not the main priority for designers more concerned with other properties, such as mechanical strength, that are needed for the intended application. Therefore, in many instances corrosion is addressed as a postassembly issue, and methods to mitigate corrosion have to be compatible with the overall product. Since almost all corrosion events start at the surface of the

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[6] Corrosion Costs and Preventative Strategies in the United States, DoD Report Number FHWA-RD-01-156, CC Technologies, Inc. Houston, Tex.

material and work inward, coatings and surface treatments are frequently used to prevent the onset of unwanted electrochemical reactions. The most common corrosion coatings employ inhibitors that preferentially and electrochemically protect or passivate the surface of the underlying substrate. Examples include Zn and Cd on steel, hexavalent chromate (Cr[VI]) compounds on aluminum alloys, and polymeric sealants on any number of materials. Each inhibitor prevents corrosion in a certain way, such as barriers that prevent the ingress of moisture and thus eliminate the electrolyte, but the overall effect is to stop or slow the deterioration process. However, many of the coatings that have been very effective for many decades must now be replaced owing to other constraints, such as environmental and health issues related to Cd and Cr(VI). This need to replace traditional coatings impacts not only the corrosion community but also other technical areas, such as nondestructive inspection, as new materials and processes that must comply with all requirements may not behave or respond in a manner similar to that of the corrosion inhibitors that have been used in the past and provide the baseline for performance and inspection requirements.

Detection

As is the case in many health-related matters, early detection of corrosion is a key aspect to maintaining the integrity and performance of the material subject to corrosion. Historically, visual examination and inspection have been used as the main detection method for corrosion. While very effective in assessing visible corrosion, in many ways these constitute an “after event” method that relies on a deteriorated condition to signal the occurrence of an undesirable or unacceptable event. In addition, it is left to the experience and judgment of the inspector to assess the extent and severity of the damage and how that impacts the mission. There are a number of technical challenges that could improve corrosion detection methods and assessment, including the following:

- Characterizing and categorizing the response and sensitivity of the known types of corrosion for various materials systems using a variety of approaches and techniques.
- Developing methods to profile systems over the entire life cycle, including before use, so as to predict the timing and extent of corrosion events that occur during deployment.
- Resolving discontinuities at smaller dimensional feature sizes, even down to nanometer lengths if possible, to determine not only the presence and extent of the damage but also providing information that can be used to determine the source of the degradation.
- Integrating sensors and inspection data to develop circuit models that simulate electrochemical cells and reactions that lead to kinetic rate models which predict the time-dependent degradation process and enable managing of the corrosion process through preventive maintenance.
- Developing procedures and methods to assess accurately the status of materials in “blind” areas that are often inaccessible after final assembly and often have an unknown status during service and operation.

- Investigating materials and processes to provide other means of detection, such as optical or electrical property changes as a result of corrosion, to supplement the nondestructive inspection methods.

Collectively these challenges are quite formidable, but by addressing each in a systematic and coordinated manner, significant progress can be made in the detection, prevention, and management of materials corrosion.

MICROWAVE AND MILLIMETER-WAVE NONDESTRUCTIVE TESTING AND EVALUATION TECHNIQUES AND APPLICATIONS: A COMPREHENSIVE OVERVIEW

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Microwave and millimeter-wave signals occupy the specific frequency bands of ~300 MHz to 30 GHz and 30 GHz to 300 GHz, corresponding to the wavelengths of 1,000 mm to 10 mm and 10 mm to 1 mm, respectively. These waves possess certain advantageous attributes, which make them suitable for nondestructive testing and evaluation (NDT&E) of a wide array of materials and structures. Microwave and millimeter-wave signals can easily penetrate inside dielectric materials and composites and interact with their inner structures. This interaction may be at the molecular level making them suitable for materials characterization, or it may take the form of reflections from undesired boundaries produced as a result of inferior manufacturing or in-service stresses such as disbonds and delaminations. These signals do not penetrate inside electrically conducting materials, such as metals and multidirectional graphite composites. However, they can very effectively interact with critical surface flaws, including surface-breaking fatigue cracks, impact damage, corrosion precursor pitting, and so forth. The relatively small wavelengths and wide bandwidths associated with these signals enable the production of high-spatial-resolution images of materials and structures. These signals can be launched and received using a wide variety of probes (particularly when inspecting a material in their near fields), each with own unique characteristics that can significantly influence measurement accuracy and robustness. Signals at these frequencies can be launched and received using different "wave polarizations" (i.e., relative orientation of electric field vector). The proper choice of signal polarization can result in better detection of targets whose preferred orientation coincides with the wave polarization and more effective detection of small flaws near structural features that have a preferred orientation. Inspection systems at these frequencies are usually small, handled, portable, battery-operated, robust, rapid, online, real-time, and require no operator knowledge in the field of microwave and millimeter-wave engineering. The following is a list and brief description of applications for which microwave and millimeter-wave NDT&E techniques have provided capable and robust, and in some cases unique, NDT&E solutions.

Materials Characterization

Once exposed to an electric field, dielectric materials become polarized (“material polarization”). The degree to which this material polarization takes place is a function of the frequency of the electric field and molecular makeup of the material (e.g., its physical and chemical states). Material polarization is macroscopically manifested through a parameter called (relative to free space) complex dielectric properties (or constant) denoted by ($\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$). The real part, known as the relative permittivity, indicates the ability of the material to store microwave energy, and its imaginary part, known as the relative loss factor, indicates the ability of the material to absorb microwave energy. Therefore, the study of the dielectric properties of a material as a function of frequency can yield valuable information about the state and properties of the material. The dielectric properties of materials undergoing chemical changes such as curing (e.g., resins, special coatings, and so forth) change as a function of cure state, which can be detected and monitored to evaluate the state of cure. The dielectric properties of materials composed of several different constituents are a function of the dielectric properties and volume fraction of each constituent. Therefore, material changes, such as an addition of porosity due to microcracking during in-service conditions in thermal barrier coatings, can be detected and comprehensively evaluated.

Stratified Composite Evaluation

Microwave and millimeter-wave signals are sensitive to the presence of boundaries within a structure as they propagate through it. This is due to the fact that these signals partially reflect and transmit through boundaries of materials with dissimilar dielectric properties. Consequently, the presence of voids, disbonds, delaminations, and so forth can be easily and effectively detected. The thickness and location of such flaws within the structure can also be evaluated, resulting in critical information about their relative severity and impact on the in-service operation of a composite structure. In addition to the above applications, there are numerous structures and applications that may fall under this category of inspection: namely, detection and evaluation of corrosion under paint and/or dielectric composite laminates, accurate thickness evaluation of special coatings and paints, and thick composite inspection. Since the overwhelming majority of these inspections are conducted in the near field of a microwave probe, measurement accuracies in the range of a few micrometers are easily achievable at frequencies around 10 GHz (corresponding to a wavelength of 30,000 micrometers). Moreover, when operating in the near field, the frequency of operation, standoff distance, and the type of probe used provide for multiple degrees of freedom in choosing the most effective set of measurement parameters.

Surface Crack and Corrosion Precursor Pitting Detection

Microwave and millimeter-wave signals do not penetrate inside highly conducting materials such as metals. However, these signals induce a surface current density in metals. Therefore, when operating in the near field, the reflection properties of the metal surface *markedly* change as a result of the presence of a surface-breaking fatigue crack. Evaluating the changes in the reflection properties of the metal surface not only renders a tight crack detected but also provides information about its dimensions (width and depth) and crack ends (critical for repair purposes). This technique is metal-independent and applies to crack detection under coatings (i.e., no need to remove paint) and filled cracks. Moreover, different probes can offer experimental features that may be uniquely useful for particular applications. Tiny corrosion precursor pitting can also be effectively detected while exposed or under paint. Information about the presence of such pitting can offer maintenance personnel critical information about the onset of corrosion, and because the dimensions of such pitting may also be effectively provided with these techniques, proper decisions with respect to resource-consuming repair activities can also be made.

High-Resolution Imaging

Whether a structure is in the near field of a microwave and millimeter-wave probe or in its far field, a number of imaging techniques are available for producing high-spatial-resolution images of various structures. When operating in the near field of a probe, spatial resolution is no longer a function of wavelength and is a function of the probe dimensions, geometry and the electric field distribution. Since there are various available probes that may be strategically used, one may produce direct raster scan (C-scan) images of objects under inspection. Antennas focus these waves and produce small inspection footprints on an object. These antennas may be in the form of small horns or lenses which, when combined with high frequencies (i.e., 150 GHz), can provide footprints on the order of a couple of millimeters. Imaging methods such as synthetic aperture, holographical, and a multitude of back-propagation techniques can be used to produce high-resolution images in all three dimensions. Some of the current research activities in this area involve the development of portable, on-shot, and real-time imaging systems (e.g., microwave and millimeter-wave “cameras”).

Microwave and millimeter-wave NDT&E techniques are not known as “standard” methods by the community, in particular in their early stages of development more than two decades ago. However, much has been gained since then, which has culminated in bringing these viable techniques to the forefront and serious consideration by NDT&E practitioners, users, and engineers. Much of what has been accomplished has been corroborated and improved using complex analytical and numerical electromagnetic modeling. This has been an important issue reaffirming the intricate science on which these techniques are founded. The advent and increased utility of dielectric-based composite structures have necessitated new and innovative inspection methodologies, since many of the “standard” methods are not capable of inspecting these structures. Most of the microwave and millimeter-wave hardware and systems developed for NDT&E purposes were custom-designed for a specific purpose, and there were not many off-the-shelf systems available. The telecommunications bonanza has significantly helped microwave and millimeter-wave NDT&E in that many of the required components are readily available at very high frequencies, are made to be compact, and are relatively inexpensive. Among other factors, this will aid in the availability of more inspection systems in the future. The fusion of data from other inspection modalities with those from microwave and millimeter-wave sensors is also expected to help bring these methods to the forefront. High-resolution imaging techniques at these frequencies are currently receiving significant attention and are expected to flourish even more in the near future. More companies are looking to expand their product lines into new areas, and these techniques certainly are at the top of the list. In conclusion, microwave and millimeter-wave NDT&E methods are finding more applications and are being increasingly considered for many critical inspection applications.

WE FIND WHAT WE SEEK

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Selecting an appropriate method for materials condition assessment involves three fundamental considerations: identifying imperfections of interest, identifying the requirements of the assessment procedure, and recognizing constraints imposed by the application. All of this must be done in the context of the engineering design and with careful attention to scale.

Selecting an appropriate strategy, measurement method, and procedure for implementation for awareness of material state involves careful consideration of design for inspectability and design for detectability, as well as materials condition assessment.

If one considers, for purposes of discussion, a solid composed of a collection of similar aluminum atoms, it is observed that these atoms organize themselves in a distinctive, face-centered cubic array. Depending on the scale of the engineering design, the associated collection might be organized with a similar characteristic array, but atoms might be missing (voids) or regions might be aligned differently (grains), other atoms might be present (impurities or alloy additions), alignment deviations (dislocations) might exist, regions might have slightly different spacing due to residual or thermal stresses, and near the surface the atoms might be bonded to oxide atoms with a form of bonding that is different from the bonding in the bulk material. Also, atoms at the surface are not completely surrounded by other atoms as in the bulk.

If this collection of atoms was formed by casting, or forging, or rolling, or sintering, or some combination of these, the organization might be different. If one were to assess the condition of such a collection of atoms, the assessment would depend in part on the environment within which the collection of atoms exists: the temperature, the pressure, the chemical potentials at the surface, the electric and magnetic fields, and so forth.

If the condition of the collection of atoms is determined at a particular instant, that condition might in fact be changing, so that if it was reassessed at another time it would be different. If the change is undesirable, it would be associated with degradation of the material. The purpose of the assessment of the condition might be to provide data for the overall assessment of the condition of a structure or system that contains the collection of atoms. However, it might be used as input to a more demanding evaluation as regards the future implications of the present condition on the performance of the system: a prognosis of future performance.

In either case, it is recognized that if the condition is changing, then assessing the rate at which it is changing is perhaps even more important. Often, however, the rate of materials degradation depends directly on the environment; if the environment changes, the rate of degredation is also likely to change. So a material that at present is experiencing very little degradation might degrade rapidly if the environment changes (thermal, mechanical, chemical, radiation, and so forth). This fact suggests that monitoring the environment might offer an earlier indication of impending materials state changes than what is provided by knowledge of the instantaneous condition.

However, in general, the nature of materials degradation is such that localization is more problematic than more extensive overall degradation. For example, corrosion resulting in a pit might be more problematic than uniform metal loss due to stress concentration caused by the localized loss of metal in the pit.

Efforts of the author and others to develop methods to detect and track material degradation preceding detectable crack formation, as well as variations in material condition associated with precipitation hardening, include early work to monitor the influence of mobile dislocation populations on ultrasonic attenuation; efforts to use continuous monitoring of changes in ultrasonic attenuation to detect degradation preceding crack formation during cyclic loading of 7075 Al; combined continuous monitoring of changes in ultrasonic attenuation and acoustic emission for the early detection of life-limiting fatigue damage; continuous monitoring of ultrasonic plate waves to track damage development in fiber-reinforced laminated composite materials; and practical limitations with using nonlinear ultrasonic response to monitor precursor fatigue damage in metal alloys. The issue of measurement scale and critical flaw size is discussed in this context.

In addition, the potential of electromagnetic, mechanical, and thermal assessment of surface and near-surface condition is discussed with regard to point and multipoint (array) measurements for assessing work hardening, alloy variation, nonuniform cyclic, residual stress mapping, and alloy variation.

Finally, the notion of developing components from sensible material “particles” that facilitate state awareness polling or reporting is proposed as a way to overcome practical physical measurement limitations on the atomic scale. The importance of sustainable design in this context is emphasized.

Session IV: Materials State Awareness Application Issues

ISSUES AND IDEAS IN STATE AWARENESS FOR REALISTIC MATERIALS AND STRUCTURES

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Structural state awareness is a process through which loading, damage, and performance in structural material components are identified through a combination of offline nondestructive testing and online monitoring. The basic building blocks and premise of structural state awareness are first reviewed. The position taken here is that key research issues have been revealed as structural state awareness technologies are implemented. Some of the key barriers to implementing structural state awareness methods are then described using specific applications in military ground vehicles, composite weapons systems, and rotorcraft. It is believed that many of these barriers to implementation involve materials state awareness solutions. One possible method for classifying research topics in materials state awareness is then derived using modern systems theory as a catalyst. This classification method is organized according to material, component, model, measurement, environment, and data analysis issues. After providing a list of key challenges in materials state awareness, two noncompeting visions are articulated for short-term and long-term research, respectively, in materials state awareness.

COUPLING MATERIALS STATE AWARENESS WITH STRUCTURAL HEALTH MONITORING AND DAMAGE PROGNOSIS

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The process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long-term SHM, the output of this process is periodically updated information regarding the ability of the structure to continue to perform its intended function in light of the inevitable aging and degradation resulting from the operational environments. Under an extreme event, such as an earthquake or unanticipated blast loading, SHM is used for rapid condition screening. This screening is intended to provide, in near real time, reliable information about system performance during such extreme events and the subsequent integrity of the system. Once damage is detected, damage prognosis (DP) is employed to predict the remaining useful life of a system, given some estimate of the future loading conditions that the system will experience. Currently, for most complex engineering systems accurate DP is not feasible with existing engineering capabilities. To date, SHM and DP studies have for the most part been carried out independent of the materials science community.

It is the author's speculation that damage detection, as determined by changes in the dynamic response of systems, has been practiced in a qualitative manner, using acoustic techniques (e.g., tap tests on train wheels), since modern humans have used tools. More recently, this subject has received considerable attention in the technical literature. However, with the exception of condition monitoring of rotating machinery, there are very few instances in which SHM technology has made the transition from research to practice.

A review of the literature reveals several outstanding challenges for transitioning SHM technology from research to practice. These challenges include the following:

- *Structural monitoring versus structural health monitoring*. Many sensor systems currently being deployed on real-world structures are actually structural monitoring systems, as opposed to SHM systems. They are simply sparse arrays of sensors deployed with no a priori definition of the damage to be detected and no definition of the methods for feature extraction and statistical classification that will be used to identify damage.
- *Local versus global damage detection*. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the global response of a structure that is normally measured during operation.
- *Defining damage a priori*. The success of any damage detection technique will be directly related to the ability to define the damage that is to be detected in as much detail as possible and in as quantifiable terms as possible.
- *Defining the requisite sensing system properties*. A significant challenge for SHM is to develop the capability to define the required sensing system properties before field deployment and, if possible, to demonstrate that the sensor system itself will not be damaged when deployed in the field.

- *Accounting for operation and environmental variability*. When deployed on a structure outside of a controlled laboratory setting, the damage detection process will have to deal with structures that experience changing operational and environmental conditions.
- *Need for long-term proof-of-concept studies*. There are very few long-term SHM studies ongoing on real-world structures. Theses studies are difficult to perform because of costs. However, such studies are needed before structure owners and regulators will accept SHM as an acceptable means of condition-based maintenance.
- *Lack of data from damaged systems*. Few system owners will allow engineers to damage their structure in an effort to validate a damage detection approach. Even if such studies were allowed, in almost all cases damage is introduced in an artificial manner and it is questionable if such "damage" is truly indicative of the actual damage that will be encountered in the field.
- *Time scales associated with damage evolution*. Damage can accumulate over widely varying time scales, which poses significant challenges for the validation of SHM sensing systems in the field.
- *Nontechnical issues*. In addition to the challenges described above, there are other nontechnical issues that must be addressed before SHM technology can make the transition from a research topic to actual practice. These issues include convincing system owners that the SHM technology provides an economic benefit over their current maintenance approaches of using quantified benefit-cost analyses, and convincing regulatory agencies that this technology provides a significant life-safety benefit. Also, universities have to overcome inherent barriers to multidisciplinary research. Tenure and promotion at U.S. universities still primarily reward the individual investigator, and SHM is too multidisciplinary for most individual investigators. Master's and doctoral students still need focused research topics for their theses and dissertations, and so they tend to be trained as specialists. If a group of graduate students with different backgrounds work collaboratively on a project, one must be the technology integrator, and this role often does not help these individuals toward the completion of a dissertation. Finally, the U.S. university education system is not evolving to train more multidisciplinary technology integrators and leaders for the future. Such training must always be balanced with the continued need for the technology specialist. These barriers and conflicting goals have led to a state in which the SHM research community is divided into two distinct subdisciplines: (1) those developing data analysis procedures and (2) those developing sensing technology. However, to develop effective SHM solutions these technologies need to be developed in a coupled manner. These issues are coupled with many industries' short research time horizons that are on the order of a 12- to 18-month time to market.

The materials science community can contribute significantly to the further development of effective SHM/DP technology in three general areas: (1) developing new materials for sensing, (2) developing better fundamental understanding of damage mechanisms and the associated changes in materials properties that are indicators of damage, and (3) developing more robust multiphysics damage evolution models. Significant future developments of SHM/DP technology will need to come by way of multidisciplinary research efforts in which fundamental materials science is coupled with mechanical and electrical engineering to systematically address the issues listed above.

STATISTICAL ISSUES RELATED TO MATERIALS STATE AWARENESS

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Emerging technologies are changing the way that engineers view reliability and system health for purposes of planning and effecting maintenance, repair, and replacement. Today we have an increasing ability to measure critical parameters and gather and process large amounts of data. This, along with advances in scientific modeling of degradation processes, is providing the potential for obtaining better information more quickly for the purposes of making better decisions.

Historically, reliability data consisted of time-to-failure information and predictions based on empirical models that are used to estimate lifetime distributions. Estimation is based on the use of data either from field experience or accelerated laboratory life tests, in the case of new materials or components. In the case of high-reliability components, it may be impossible (or undesirable) to observe relevant failures in the field or in the laboratory. In such cases it is sometimes possible to obtain degradation data (actual physical or chemical degradation, performance degradation, or other kinds of degradation surrogates) that are useful for predicting failure, even for individual units. Examples include light output of lasers, vibration in a motor, and chemical change in a coating. An important advantage of degradation data is that they provide a much richer basis for developing chemical and physical models of failure.

If there is enough fundamental knowledge about a particular failure mode so that one can develop an adequate model for incremental damage as a function of environmental variables, then it is possible to predict the time to failure for a given environmental profile. One example relates to work done at the National Institute of Standards and Technology (NIST). NIST scientists conducted careful indoor experiments designed to obtain fundamental understanding of the degradation processes of a model epoxy coating as a function of environmental conditions (temperature, humidity, and ultraviolet intensity and spectrum). This information and the experimental results were used to develop a response surface model to predict incremental damage as a function of the environmental conditions at a point in time. The resulting model, when used with actual outdoor environmental data, can be used to predict cumulative damage. For model verification, the predictions were compared with actual observed damage in units exposed to input environment.

In general, the task of predicting the failure of individual units offers both challenges and opportunities. The ability to make such predictions hinges on the ability to develop a useful model to predict degradation and/or the ability to sense relevant changes in the state of the system (component or material) of interest. Models for both the physical state of the system and for sensor data will require appropriate stochastic elements in addition to the usual deterministic structure. The detailed characteristics of these models will have to be obtained from extensive experimentation or other data-gathering methods.

An important component of any failure-prediction methodology is the determination of a decision criterion: Which variable or variables (empirical, physical/chemical model output, or a combination) should be used to make a call that a failure is eminent or that there is too high a safety risk? Consider a traditional nondestructive evaluation (NDE) system as an analogy. For a simple scalar criterion (such as the amplitude of a reflection from a crack in an ultrasonic transducer at inspection), modeling the variable and determination of a threshold are relatively straightforward. In the more complicated multizone ultrasonic transducer system, a bivariate response (signal amplitude and signal-to-noise ratio) is used for the decision criterion. Such bivariate data require a more advanced statistical model for the decision criterion. In more complicated situations (e.g., system state and/or environmental monitoring from an array of sensors), data could be highly multivariate, and some means of dimension reduction will almost certainly be needed. Such dimension reductions could be done through a physical and chemical model for incremental damage as a function of environmental conditions or through empirical modeling.

The other element of choosing a decision criterion is the determination of a decision threshold (which will have the same dimension as the decision variable[s]). Generally this is done through the quantification and assessment of the trade-off between quantities analogous to probability of detection (POD) and probability of a false alarm (PFA). In continuous monitoring, however, the concepts of POD and PFA are more complicated than they are in periodic inspection. In particular, POD is usually replaced by something like "average run length," giving the amount of time that it will take to detect a subtle change in the system state when data are contaminated with noise. There has been much previous work in the area of statistical process monitoring (also known as statistical process control or change-point detection), particularly methods developed for the chemical process industries. Such methods have the potential to provide useful tools for materials state awareness.

A final practical concern for a failure prediction methodology running in real time is the reliability of the sensors themselves. It is easy to imagine how faulty sensors could lead to either false alarms or failure to predict.

Session V: What Is the Future of Materials State Awareness?

AN OVERVIEW OF DATA FUSION METHODS AND APPLICATIONS

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Fusion of information sources or data fusion is becoming increasingly employed to merge information obtained from individual or multiple sensors and associated databases to improve decision-making, analytical, or inference-making capability. Humans often use multiple information sources such as sight, smell, touch, taste, and personal experiences to evaluate the quality of their dining experiences. From a system development perspective, data fusion involves the usage of tools, techniques, and/or methods for information merging. Techniques for individual, multisensor, and/or database-related data fusion are obtained from a wide range of areas including image and signal processing, control theory, numerical methods, artificial intelligence, fuzzy systems, neural networks, evolutionary computation, pattern recognition, statistical estimation, and other areas. The selection of techniques depends on the type, availability, and dynamic nature of data available for the system or application. Fusing multiple information sources is ideally intended to improve the accuracy with which an entity or entities of interest can be observed and characterized over a single information source.

There are numerous applications to which data fusion has been applied. Some military application examples of data fusion are (1) detection and tracking of targets of interest using air-, ground-, or ocean-based surveillance; (2) land mine or minefield detection using individual or multiple sensors in airborne-, vehicle-, or handheld-based systems; and (3) nondestructive evaluation (NDE) for assessing the structural health of aircraft and ships. A few examples of nonmilitary applications include (1) medical patient diagnosis or assessment based on integrating information from diagnostic tests, vital signs, patient symptoms, and so forth; (2) weather forecasting using ground-, aircraft-, subsurface-, and satellite-based sensors; and (3) robot navigation using map and visualization sources. There are several issues that need to be addressed in the design and development of a data fusion-based system, including: (1) the number and type of information sources, (2) what information from each source is to be used to get the most from the data fusion process, (3) the operating conditions of the system for which data fusion will foster enhanced system operation, (4) the system architecture to provide for where and how the data from different sources are to be fused, (5) the algorithm type and choice that are appropriate for the data sources and the application, (6) the target level of performance of the data fusion process, and (7) the ability of the system to adapt in a dynamic environment.

Data fusion can be used to translate between observed values from one or more sources for an entity and a decision or inference related to the entity at different levels of complexity. Data fusion can be used for data alignment or registration from multiple sensors such as a robotic unit determining positional information from a mounted camera and the Global Positioning System. Data fusion can also be used for enhancing classification tasks, where individual or multiple modalities and/or sensors can be merged at the raw data, feature, or decision level for contributing to classification decisions. For performing raw data fusion, there is typically some common domain to integrate raw data from multiple sources. For example, ultrasound and radiographic images of an aircraft panel may be fused at the pixel level based on mapping or registering the corresponding pixel locations from the two image sources. Approaches for performing raw data fusion commonly involve standard detection, estimation, and registration methods. Feature-level fusion typically involves extracting representative attributes from objects or entities of interest from the source data. Using the aircraft example, if the ultrasound and radiographic images for a panel are used separately, attributes related to size and shape may be determined from objects that may be potential areas of corrosion. The attributes or features from the ultrasound and radiographic images for each object may be combined into a single-feature vector for describing the object. The generated feature vectors are input into classification algorithms such as template matching, clustering methods, or neural networks. Decision-level fusion can involve combining source information after a preliminary decision or confidence has been determined for each source related to an entity's detection, position, presence of a specific feature, or identity. Decision-level fusion may also involve combining single-source information based on multiple approaches for generating preliminary decisions or confidence values related to the entity. Techniques for performing decision-level fusion include voting and weighting schemes and other computational intelligence methods. An important consideration for performing raw data, feature, or decision-level fusion is data normalization. Data normalization is often necessary to allow data collected from different sources to be directly compared or combined. For example, in collecting an ultrasound and a radiograph image of the same aircraft panel, the sensor values will typically have different value ranges. In order to perform raw data fusion, part of the fusion process is to standardize the values from the ultrasound and radiograph images for combining the values to generate a single fused image.

The utilization of data fusion-based systems is becoming more prevalent as the need increases for systems with enhanced decision- and inference-making capability. Accordingly, future considerations in the development of data fusion-based systems would appear to include the development of technology that will allow data fusion capability to be transparently integrated into the system development and manufacturing processes for a wide range of applications. Some potential future directions for data fusion-based systems may include (1) the development and large-scale manufacturing of specialized hardware integrated circuits that implement standard multisensor data fusion methods, (2) parallel architectures for real-time implementation of multisensor or information source fusion systems, (3) methods for dynamic source selection for adaptive system design and development for source and modality integration, (4) validation methods for source uncertainty models and the development of robust approaches to estimate model parameters, (5) improved sensor design for usage in real-time systems, and (6) the development of multisensor systems providing the capability to acquired co-registered data.

MODEL-BASED SYSTEM DESIGN AND SIGNAL PROCESSING FOR MATERIALS STATE AWARENESS

Wm. Garth Frazier, Miltec Corporation

In the field of systems health monitoring, there are many researchers working on various aspects of the problem: for example, sensor development, mathematical modeling, and signal-processing algorithms. However, there is still no overarching philosophy to help focus research contributions. As the field evolves away from merely detecting damage to estimating the entire material state, this overarching philosophy should address how systems health monitoring and traditional nondestructive evaluation are different and how they will complement each other in the new goal of materials state awareness. There is also a need for systematic methods for designing these systems to meet the new end user goals. A “systematic design method” is defined here to mean a method that can be applied to a very broad class of problems by changing the particulars of the application of interest and the desired outcome without changing the steps of the method. An attempt is made to identify a materials state awareness philosophy along with some of the scientific knowledge components and technological capabilities that are needed to develop systematic design methods and how they can be used by these methods to achieve specified outcomes. This naturally leads to the question of how these desired outcomes can be specified in a quantitative way to achieve materials state awareness. As defined here, material state is that set of quantitative information about a material system that, when known at an instant of time, along with the value of all current and future independent influences on its behavior, is sufficient to know that same set of quantitative information for all future time. A simple example is that knowing the velocity and density distributions (the state) in a flow field along with the nonsteady (time-varying) boundary conditions is sufficient to know these distributions for all future time. This is so because we know from mechanics that the equation of continuity and the equation of momentum balance must hold. In addition, we have models of the material constitutive relations.

Drawing on the now-well-developed (and successful) fields of automatic control system design and signal processing as examples, it is proposed that the most essential scientific knowledge component required to perform successful designs using a systematic methodology is the availability of mathematical models (usually nonsteady, nonlinear differential equations), of sufficient fidelity, that are able to predict the evolution of the states that are desired to be estimated over the range of anticipated conditions. To achieve materials state awareness as a goal, in addition to mechanical (continuum) state awareness, an aggressive approach to the identification of the appropriate material states and development of quantitative models of their evolution in their operating environments is needed. Moreover, it is anticipated that these models will need to include a stochastic component in order to provide a satisfactory description. For most industrial-scale problems, these models will have to be analyzed and simulated using numerical methods, for example, dynamic finite-element techniques.

For practical systems there will be a need for adequate monitoring (passive sensing) and interrogation (active sensing) capabilities in order reduce the effect of imperfect modeling and uncontrolled, unmeasured influences on the system's state evolution. In this context, adequate monitoring or interrogation does not imply that direct or instantaneous measurement of the state is required. It does mean, however, that the ability to obtain stable estimates of the state as time passes by using the available data is required. This can be achieved even when the system is nonsteady and nonlinear by using the well-established signal processing technique traditionally referred to as a model-based observer. Therefore, the essential technological capability that is needed is a sufficient variety of actuating and sensing technologies from which a designer can choose, or better yet, from which a systematic design methodology can choose. Needless to say, models of how these sensors and actuators interact with the structure and material system are required.

The need for satisfactory models, as well as adequate actuating and sensing technologies, is not a surprise to anyone involved in the field of NDE. But a method for formally quantifying and achieving what is meant by adequate and sufficient when trying to achieve complex design goals for a wide variety of materials state awareness applications might be less obvious, especially when the goals are not limited to a single traditional measure of performance. When trying to achieve several figures-of-merit such as false call rate, cost per inspection, and so forth for a design, in addition to the commonly used one-time interrogation probability of detection, a systematic, mathematically based design optimization method is likely to be the only feasible way to achieve consistent design results that are not prejudiced by a human designer's preconceived notions. This is not because human designers are always biased, but it is because in order to make a highly complex problem with many decision variables tractable, the human designer needs to fix some decision variables in advance to keep the size of the decision space manageable. This can easily lead to a suboptimal solution. Therefore, the synthesizing element for materials state awareness system design is the use of model-based engineering design algorithms, of which there are many good ones such as the classical methods of mathematical programming, pattern search algorithms, genetic algorithms, simulated annealing, and particle swarm optimization (a recent area of research interest in the field of design algorithms). The most appropriate algorithm to use will depend on the mathematical structure of the particular problem, but frequently this choice does not affect the outcome, but instead only the time it takes to find a solution. In addition, it is very important to realize at this stage of the development of these research areas that the resulting optimal solution to a particular problem may prescribe the use of integrated sensors and signal processing, which provide only course estimates of the material state that trigger the use of higher-fidelity interrogation methods to reduce the state uncertainty to a satisfactory level. In other words, a mix of global and local methods for obtaining state awareness should not be disregarded in advance as a good design solution.

In summary, it is proposed that the problem of designing a materials state awareness system for a component, multiple components, or as part of a larger system, in a systematic way is more closely related to the problem of designing a quantitative state estimation system than a damage detection system. It requires at a minimum (1) the availability of mathematical models (likely stochastic) that describe the evolution of the states under all expected environments and a method to analyze these models numerically; (2) monitoring and interrogation technologies that provide a means to periodically estimate either directly, or indirectly by using model-based observers, the values of the states as time passes; (3) a mathematical description of design criteria for the particular application, that is, objectives, constraints, and decision variables; and (4) an algorithm that uses items 1 through 3 to manipulate the decision variables to find a solution or multiple solutions that achieve the design criteria. In light of this, it is proposed that the weakest link is the availability of the definition and models for the evolution of material state—that is, our understanding of the relevant physics. This is followed by the potential lack of availability of appropriate sensors and actuators for particular applications—for example, environmentally extreme environments.

SYSTEM STATE AWARENESS: AN INTEGRATED PERSPECTIVE

Thomas Cruse, Vanderbilt University, Emeritus

Materials state awareness (MSA) goes beyond traditional NDE in its challenge to characterize the current state of material damage long before the onset of macro-damage such as cracks. MSA must link nontraditional and innovative NDE with advances in microstructurally based damage progression modeling. Such modeling is tied to the variability in material microstructure, microstress, and processing history. System state awareness refers to the global application of this proposed integrated damage modeling for the entire life cycle of any structural system. System state awareness requires the integration of three critical technologies: (1) high-fidelity life-prediction models that include processing and usage history, (2) high-fidelity characterization of the mechanical and environmental "loading" history, and (3) the ability to provide real-time MSA. Such an approach to system state awareness requires advances in all three technologies, but the primary advance has to be in new approaches and capabilities in NDE for MSA.

Appendixes

Appendix A
Materials State Awareness Workshop Statement of Task

A workshop will be convened to consider scientific and technical issues pertinent to developing an understanding of materials, structural, and system-state awareness through nondestructive evaluation (NDE)-based sensing in military aerospace systems. The workshop's agenda will focus primarily on the materials science associated with the mechanisms of material damage state assessment and its correlation to the structural and lifetime condition of the system. The discussion will (1) cover a wide variety of material systems, computational techniques, and virtual NDE methods and (2) identify possible future directions for NDE research and development. The invited speakers will be asked to focus on the progress that industry, academia, and government laboratories have made in recent years so that the attendees might develop a vision for future material state awareness technologies for aerospace applications to indirect observations of material and damage states.

This workshop will bring together government, industrial, and academic specialists with expertise surrounding the use and understanding of sensors as a tool for the nondestructive evaluation of the useful lifetime of materials within equipment. The workshop activity will result in a proceedings report that will not contain any conclusions or recommendations from the organizing panel.

Appendix B
Workshop Agenda and List of Attendees

AGENDA

Woods Hole, Massachusetts, September 25-26, 2007

September 25, 2007

8:15 a.m.	Welcome and Call to Order	Edgar Starke, Organizing Panel Chair University of Virginia
8:30 a.m.	Setting the Stage: Introduction from the Sponsor	Kumar Jata Air Force Research Laboratory
9:00 a.m.	Q&A Session	Edgar Starke, Organizing Panel Chair University of Virginia

SESSION I: KEY ISSUES FOR MATERIALS STATE AWARENESS

9:45 a.m.	Prognosis	John Venables Strategic Analysis, Inc.
10:15 a.m.	Materials State Awareness Application to Airframe Structures—Key Issues	Donald Palmer Boeing Phantom Works

September 25, 2007 (cont.)

10:45 a.m.	Key Issues in Materials State Awareness for Aviation Propulsion Systems	Robert Schafrik GE Aviation
11:15 a.m.	Panel Q&A	Thomas Farris, Organizing Panel Member Purdue University
11:45 p.m.	LUNCH BREAK	

SESSION II: WHAT IS MATERIALS STATE AWARENESS?

12:45 p.m.	An Integrated View of Materials State Awareness	Bruce Thompson Iowa State University
1:15 p.m.	Nondestructive Physical Property Measurements to Establish Materials State Awareness	David Olson Colorado School of Mines
1:45 p.m.	Modeling and Sensing Mechanical Degradation in Metals and Composites	William Curtin Brown University
2:15 p.m.	Virtual Tests: Making the Most of Experimental Knowledge	Brian Cox Teledyne Scientific
2:45 p.m.	Panel Q&A	Robert Latiff, Organizing Panel Member Science Applications International Corporation

SESSION III: WHAT SHOULD WE SENSE FOR MATERIALS STATE AWARENESS AND HOW SHOULD WE LOOK FOR IT?

3:30 p.m.	Material State Awareness—A Propulsion Perspective	Kevin Smith Pratt & Whitney
4:00 p.m.	The Integrated Structural Health/Life Management of Airframe Structures Depends on Characterizing the State of the Material as a Function of Time in Service	Joseph Gallagher Independent Consultant
4:30 p.m.	Material Property Measurement using NDE methods at GE	Shridhar Nath GE Global Research Laboratory
5:00 p.m.	Examples of Material-State Awareness Problems and Research Directions to Solve Them	Stanislav Rokhlin Ohio State University
5:30 p.m.	Panel Q&A	Jiangang Sun, Organizing Panel Member Argonne National Laboratory

September 26, 2007

8:00 a.m.	Welcome and Call to Order	Edgar Starke, Organizing Panel Chair University of Virginia

SESSION III (Cont'd): WHAT SHOULD WE SENSE FOR MATERIALS STATE AWARENESS AND HOW SHOULD WE LOOK FOR IT?

8:15 a.m.	Issues and Ideas in State Awareness for Aerospace Structural Joints	Thomas Farris Purdue University
8:45 a.m.	Materials Corrosion Fundamentals, Prevention, and Detection	Matthew O'Keefe Missouri Institute of Science and Technology
9:15 a.m.	Microwave and Millimeter-Wave Nondestructive Testing and Evaluation Techniques and Applications—A Comprehensive Overview	Reza Zoughi Missouri Institute of Science and Technology
9:45 a.m.	We Find What We Seek	John Duke Virginia Polytechnic Institute and State University
10:15 a.m.	Panel Q&A	Jiangang Sun, Organizing Panel Member Argonne National Laboratory

SESSION IV: MATERIALS STATE AWARENESS APPLICATION ISSUES

10:45 a.m.	Issues and Ideas in State Awareness for Realistic Materials and Structures	Douglas Adams Purdue University
11:15 a.m.	Coupling Material State Awareness with Structural Health Monitoring and Damage Prognosis	Charles Farrar Los Alamos National Laboratory
11:45 a.m.	Statistical Issues Related to Materials State Awareness	William Meeker Iowa State University
12:15 a.m.	Panel Q&A	Richard Bossi, Organizing Panel Member Boeing Corporation
12:45 a.m.	LUNCH BREAK	

SESSION V: WHAT IS THE FUTURE OF MATERIALS STATE AWARENESS?

1:45 a.m.	An Overview of Data Fusion Methods and Applications	Joseph Stanley Missouri Institute of Science and Technology

September 26, 2007 (cont.)

2:15 p.m.	Model-Based System Design and Signal Processing for Materials State Awareness	Garth Frazier Miltec Corporation
2:45 p.m.	System State Awareness—An Integrated Perspective	Thomas Cruse Vanderbilt University, Emeritus
3:15 p.m.	Panel Q&A	Bruce Thompson, Organizing Panel Member Iowa State University
3:45 p.m.	Open Discussion	Edgar Starke, Organizing Panel Chair University of Virginia
5:00 p.m.	Adjourn	

ATTENDEES

Douglas Adams, Purdue University
James Blackshire, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Mark Blodgett, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Richard Bossi, Boeing Phantom Works
Lisa Brasche, Iowa State Center for Nondestructive Evaluation
Charles Buynak, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Brian Cox, Teledyne Scientific
Thomas Cruse, Vanderbilt University (retired)
William Curtin, Brown University
Boro Djordjevic, Materials and Sensor Technologies, Inc.
John Duke, Virginia Polytechnic Institute and State University
Charles Farrar, Los Alamos National Laboratory
Thomas Farris, Purdue University
Gary Fischman, National Materials Advisory Board
Garth Frazier, Miltec Corporation
Joe Gallagher, Consultant
Victor Giurgiutiu, Air Force Office of Scientific Research
Kumar Jata, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Reji John, Air Force Research Laboratory Materials and Manufacturing Directorate
Warren Johnson, Universal Technology Corporation
Ronald Kerans, Air Force Research Laboratory Manufacturing Technology Division
Jeremy Knopp, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Bernd Köhler, Fraunhofer Institute for Non-Destructive Testing
Robert Latiff, Science Applications International Corporation

Eric Lindgren, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
James Malas, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Robert Marshall, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Steven Martin, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Siamack Mazdiyasni, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Steve McKnight, Army Research Laboratory
Enrique Medina, Radiance Technologies
William Meeker, Iowa State University
Emily Ann Meyer, National Materials Advisory Board
Brajendra Mishra, Colorado School of Mines
Michael Moloney, National Materials Advisory Board
Stephen Mott, Air Force Research Laboratory, Sensors Research Directorate
Shridhar Nath, GE Global Research Center
Craig Neslen, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Matt O'Keefe, Missouri Institute of Science and Technology
David Olson, Colorado School of Mines
Donald Palmer, Boeing Phantom Works
DannyParker, Miltec Corporation
Robert Rapson, Air Force Research Laboratory Materials and Manufacturing Directorate
Stanislav Rokhlin, Ohio State University
Shamachary Sathish, University of Dayton Research Institute
Robert Schafrik, GE Aviation
Kevin Smith, Pratt & Whitney
R. Joe Stanley, Missouri Institute of Science and Technology
Edgar Starke, University of Virginia
Jiangang Sun, Argonne National Laboratory
Bruce Thompson, Iowa State University
Teri Thorowgood, National Materials Advisory Board
John Venables, Consultant to Defense Advanced Research Projects Agency/Defense Science Office
Charles Ward, Air Force Research Laboratory Materials and Manufacturing Directorate's Nondestructive Evaluation Branch
Joe Wells, JMW Associates
Reza Zoughi, Missouri Institute of Science and Technology

Appendix C
Speaker and Panelist Biographies

Douglas E. Adams conducts fundamental and applied research in structural state awareness for aerospace and automotive systems. He has graduated 17 Ph.D. and M.S. students, published more than 130 papers, authored or edited several book chapters, and delivered 15 short courses and more than 50 invited seminars and keynote addresses. He has also recently published a textbook on health monitoring of structural materials and components for John Wiley and Sons. He has received 13 research and teaching awards, including a Presidential Early Career Award for Scientists and Engineers from President George W. Bush and the 2003 Structural Health Monitoring Person of the Year Award; he has recently been named a Purdue University Faculty Scholar. Dr. Adams has also been inducted as a fellow in the Purdue Teaching Academy. Many of his research discoveries have been developed and fielded for use by industry and defense agencies; for example, he has recently deployed 22 crack-detection kits for the U.S. Army for condition-based maintenance of a ground vehicle wheel assembly. He has also developed a load-monitoring system for the next-generation composite precision attack missile and is working to develop damage identification methods for the next-generation heavy-lift helicopter.

Richard H. Bossi is a senior technical fellow for NDE on the physics staff of Boeing Phantom Works, Seattle, Washington. He received his B.S. degree from Seattle University in 1971 and his Ph.D. from Oregon State University in 1977. Dr. Bossi has more than 30 years of experience in the field of nondestructive evaluation (NDE). Following graduate school he spent 1 year at Centre d'Etudes Nucléaires in Grenoble, France, 5 years at Lawrence Livermore National Laboratory, and 4 years at Sigma Research before joining the Boeing Company in 1988. He has worked on a variety of programs dealing with material characterization using NDE technology, including radiography, computed tomography, ultrasonics, and data fusion. Dr.

Bossi also served as the quality assurance team leader for the Composite Affordability Initiative program, developing methods for bonded joint characterization. He chairs the annual Boeing NDE Technical Forum meeting, is a fellow of the American Society for Nondestructive Testing, and serves as an associate technical editor for *Materials Evaluation* and as a contributor to and technical editor for ASNT handbooks.

Lisa J.H. Brasche is an associate director for CNDE and a program manager for the Federal Aviation Administration Center for Aviation Systems Reliability and for Engine Titanium Consortium, as well as the director of the Airworthiness Assurance Center of Excellence program at Iowa State University. She received her B.S. in materials science and engineering from North Carolina State University and her M.S. in metallurgy from Iowa State University. Prior to her graduate career, Ms. Brasche served as an intern at Duke Power Company in its NDT and Nuclear Maintenance Division. Her research efforts include evaluation of materials properties and detection of detrimental mechanical conditions using nondestructive techniques in ferrous and nonferrous alloys, improving the effectiveness of fluorescent penetrant inspection, practical uses of inspection simulation, and probability-of-detection studies. Ms. Brasche has authored over more than 30 publications and holds one patent.

Brian Cox received his Ph.D. in theoretical physics from Monash University, Australia, and has worked at Teledyne Scientific (formerly Rockwell Scientific and Rockwell Science Center) for 25 years. His current interests include materials design and modeling materials failure.

Thomas Cruse is the former chief of technologies at the Air Force Research Laboratory (AFRL) and a professor emeritus at Vanderbilt University. He has also worked at the Southwest Research Institute as the program director for reliability, and prior to that, as director of the Engineering Mechanics Department. Dr. Cruse has also held positions at Pratt and Whitney Aircraft, Carnegie Mellon University, and the Boeing Company. He holds a Ph.D. in engineering mechanics from the University of Washington and M.S. and B.S. degrees in engineering mechanics and mechanical engineering, respectively, from Stanford University. Dr. Cruse is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), the American Society of Mechanical Engineers (ASME, for which he chaired the Applied Mechanics Division), the American Academy of Mechanics, and the U.S. Association for Computational Mechanics. He is the past president and founder of the International Association for Boundary Element Methods.

W.A. Curtin received a combined 4-year Sc.B./Sc.M. degree in physics from Brown University in 1981 and a Ph.D. in theoretical physics from Cornell University in 1986, working on the optical properties of metal nanoparticles and on statistical mechanics theories of freezing. Professor Curtin then joined the Applied Physics Group at the British Petroleum Research Laboratories (formerly SOHIO) in Clevelend, Ohio, where he worked on hydrogen storage in amorphous metal alloys, the statistical mechanics of crystal/melt interfaces, and the mechanics of ceramic and composites. In 1993, he joined the faculty at the Virginia Polytechnic Institute and State University with a joint appointment in materials science and engineering and engineering science and mechanics. In 1998, Professor Curtin returned to Brown University as a faculty member in the Solid Mechanics Group of the Division of Engineering and was appointed the Elisha Benjamin Andrews Professor in 2006. A current overall theme of Professor Curtin's research is multiscale modeling of the mechanical behavior of materials, with specific applications to atomistic/continuum models of plasticity and fracture, solute hardening in aluminum alloys, fiber composites, and impurity/defect diffusion. Other current work includes experiments and modeling of carbon-nanotube-based ceramic composites, electrical sensing of damage in polymer composites, and mechanics of complex microstructures. Professor Curtin is director of the Center for Advanced Research Materials at Brown University and director of the National Science Foundation (NSF) Materials Research Science and Engineering Center at Brown. He was appointed as a Guggenheim Fellow in 2006, has published more than 125 technical papers, and has presented many invited talks at national and international venues.

John C. Duke, Jr., is a professor and director of the Nondestructive Evaluation Development Laboratory at Virginia Polytechnic Institute and State University. He holds Ph.D., M.S.E., and B.E.S. degrees in mechanics and materials science from the Johns Hopkins University. Dr. Duke's interests are in nondestructive measurement science, testing, and evaluation; experimental mechanics; materials behavior, micromechanical materials characterization; evaluation of advanced materials and bonded joints; civil infrastructure assessment; nondestructive evaluation of electronic components; and packaging for process manufacturing.

Charles R. Farrar has 25 years of experience as a technical staff member, project leader, and team leader at the Los Alamos National Laboratory (LANL). He is currently the director of the Engineering Institute at LANL. While at Los Alamos, he earned a Ph.D. in civil engineering from the University of New Mexico in 1988. The first 10 years of his career at LANL focused on performing experimental and analytical structural dynamics studies for a wide variety of systems, including nuclear power plant structures subject to seismic loading and weapons components subject to various portions of their stockpile-to-target loading environments. Currently, his research interests focus on developing integrated hardware and software solutions to structural health monitoring problems and the development of damage prognosis technology. The results of this research have been documented in more than 280 publications, as well as in numerous keynote lectures at international conferences. In 2000 Dr. Farrar founded the Los Alamos Dynamics Summer School. His work has recently been recognized at Los Alamos through his reception of the inaugural Los Alamos Fellows Prize for Technical Leadership and by the Structural Health Monitoring community through the reception of the inaugural Lifetime Achievement Award in Structural Health Monitoring. He is currently working jointly with engineering faculty at the University of California, San Diego (UCSD) to develop the LANL/UCSD Engineering Institute with a research focus on damage prognosis. This initiative is also developing a formal, degree-granting educational program in the closely related areas of validated simulations and structural health monitoring. Dr. Farrar's additional professional activities include his current appointments to associate editor positions for the *International Journal of Structural Health Monitoring* and *Earthquake Engineering and Structural Dynamics*, and the development of a short course entitled "Structural Health Monitoring: A Statistical Pattern Recognition Approach" that has been offered more than 15 times to industry and government agencies in Asia, Australia, Europe, and the United States. In 2007, Dr. Farrar was elected to the position of fellow in the American Society of Mechanical Engineers.

Thomas Farris is professor and head of the Purdue University School of Aeronautics and Astronautics. He received a B.S.M.E. in 1982 from Rice University and a Ph.D. in applied mechanics from Northwestern University in 1986, at which time he joined Purdue. His teaching and research interests are in tribology, manufacturing processes, and the fatigue and fracture of aerospace structures. He has supervised more than 40 M.S. and Ph.D. theses, authored or co-authored more than 100 archival publications, and has one patent. He has been acknowledged for research by an NSF Presidential Young Investigator Award, a fellowship from the Japan Society for the Promotion of Science, ASME's Burt L. Newkirk Award, the ASME/Boeing Structures and Materials Award, and the Journal of Strain Analysis P.E. Publishing Award. He is currently a member the executive committee of the Applied Mechanics Division of ASME, of which he is a fellow, and he is a consultant to the Army Science Board.

Wm. Garth Frazier received his B.S. and M.S. degrees from Mississippi State University and his Ph.D. from Ohio University. All of his degrees are in electrical engineering, with emphases on dynamical systems theory, automatic control, and signal processing. After completing his Ph.D., Dr. Frazier worked at the Materials and Manufacturing Directorate, Air Force Research Laboratory, as an onsite contractor and as a government civilian employee. His research there focused on the application of dynamical systems theory and optimal control to the design of thermomechanical materials processes. In 1999 he was selected as an Outstanding Young Manufacturing Engineer by the Society of Manufacturing Engineers (SME) for his work in that area. Also in 1999, he was selected to participate in the National Academy of Engineering's Frontiers of Engineering Program. In 2000, Dr. Frazier accepted a position in industry in which he led the development of acoustic signal processing and multiple-target tracking algorithms for a large U.S. Army battlefield acoustics research program. Since 2002 he has helped to develop two research programs managed by the Materials and Manufacturing Directorate, AFRL, that are directed toward the development and demonstration of dynamical systems theory techniques applied to structural health monitoring applications. In particular, Dr. Frazier is interested in the development of systematic, model-based engineering design methods. He currently works as an independent consultant supporting research and development in battlefield acoustics and in structural health monitoring.

J.P. Gallagher retired as the USAF Technical Advisor for Aircraft Structural Integrity, Engineering Directorate, Aeronautical Systems Center, Wright-Patterson Air Force Base, Ohio, on July 31, 2007. He is a recognized authority in aircraft structural integrity; in that capacity he provided technical oversight, advice, and guidance to the highest Air Force and government officials and to numerous national aerospace weapons system programs. Starting in October 2002 as technical advisor for aircraft structural integrity, he led the Air Force structures community by establishing a clearly defined Aircraft Structural Integrity Program (ASIP) that is now documented by a Department of Defense (DOD) standard (MIL-STD-1530C), which provides the framework for managing the structural integrity of aircraft weapons systems. His efforts corrected key problems associated with policy, technical approaches, and oversight of this critical integrity program. Dr. Gallagher also led numerous independent review teams that forged solutions to critical structural safety-related problems affecting the safety, availability, and cost of maintaining the A-10, F-22, F-16, C-130, KC-135, and C-5 aircraft. Recommendations from these efforts were implemented and have ensured the continuing safety and performance of these critical Air Force aircraft. Before assuming the position as USAF technical advisor for aircraft structural integrity, Dr. Gallagher held various positions at the University of Dayton and the University of Dayton Research Institute (UDRI) between 1978 and 2002. When he retired from the university after about 25 years of service, he held a joint appointment with UDRI and as a professor who taught in the graduate materials program in the School of Engineering. Within UDRI, he held multiple positions, including those of Sustainment Center director, head of a division, group leader, and principal investigator. Dr. Gallagher received his bachelor of science degree in civil engineering from Drexel University and his master of science and doctor of philosophy degrees in theoretical and applied mechanics from the University of Illinois.

Kumar V. Jata is a research scientist at the Air Force Research Laboratory Materials and Manufacturing Directorate's Metals, Ceramics, and Nondestructive Evaluation Division. Basic research conceived and performed by Dr. Jata has had a significant impact on the Air Force's aircraft and space materials programs. Aircraft and space launch companies are using the scientific concepts and findings generated in his research for the design of Al-Li metal cryotanks for access to space and for the improvement of the structural performance of fielded aircraft and space systems. His research on friction stir joining and processing is already having a significant impact on the manufacture of metal cryogenic tanks for space access, new ways to manufacture future aerospace structures, and replacement of fasteners in fielded aircraft. Dr. Jata's science and technology leadership in this area is evidenced in a number of research and development collaborations with industry, government laboratories, and universities. He has been an invited colloquium speaker on this subject at various universities and conferences at Drexel University, the University of Utah, the University of Virginia, and Ohio State University; Light Materials for Transportation (Korea); the International Conference on Aluminium Alloys (Virginia); and NATO Structural Metallic Materials with High Efficiency (Kiev, Ukraine). Dr. Jata is the lead editor of the *Friction Stir Joining and Processing Conference Proceedings*, which accompanies a conference held by TMS every 2 years. Between 2000 and 2003, Dr. Jata published six refereed journal articles in *Metallurgical and Materials Transactions*, *Scripta Materiala*, and *International Journal of Fatigue*. Twenty-two conference papers and presentations have also evolved from his work during this time period. Dr. Jata holds a doctorate degree in materials science from the University of Minnesota. He was elected as a fellow of the ASM International in 1998. He is also an adjunct professor at the Wright State University and a mentor for younger engineers and scientists.

Robert H. Latiff is vice president, chief engineer and technology officer in Science Applications International Corporation's Space and Geospatial Intelligence Business Unit. He is recently retired from the U.S. Air Force as a major general, with his last assignments at the National Reconnaissance Office as the director for Systems Engineering and as the director of Advanced Systems and Technology. General Latiff was a career acquisition officer, managing large complex systems such as the Cheyenne Mountain Complex, the Air Force's airspace management and landing systems, and the Joint Strategic Target Attack Radar System (JSTARS). Dr Latiff holds a M.S. and a Ph.D. in materials science and a B.S. in physics from the University of Notre Dame.

William Q. Meeker is a professor of statistics and Distinguished Professor of Liberal Arts and Sciences at Iowa State University. He is a fellow of the American Statistical Association, an elected member of the International Statistical Institute, and a past editor of *Technometrics*. He is co-author of the books *Statistical Methods for Reliability Data* with Luis Escobar (1998) and *Statistical Intervals: A Guide for Practitioners* with Gerald Hahn (1991); of four book chapters; and of numerous publications in the engineering and statistical literature. He and his co-authors have won the American Society for Quality (ASQ) Youden Prize four times and the ASQ Wilcoxon Prize three times. In 2001, he and his co-author were recognized by the American Statistical Association with the Best Practical Application Award. He has consulted extensively on problems in reliability data analysis, reliability test planning, accelerated testing, nondestructive evaluation, and statistical computing.

Shridhar Nath joined GE Global Research (GE-GR) in March 1997 and has been the manager of the Nondestructive Technologies Laboratory since November 2001. The team is involved in several nondestructive evaluation (NDE) modalities, including radiography, ultrasound, electromagnetics, and infrared imaging. At GE-GR, the team supports all of the GE businesses, including aviation, energy, oil and gas, inspection technologies, and others. Research includes materials characterization, numerical modeling, and transducer and system development for both metals and composite materials. Before joining GE, Dr. Nath worked at a small start-up company (AMTAK, Inc.) developing and implementing eddy current NDE systems for various applications. As a contractor for the NASA Langley Research Center, Dr. Nath was involved primarily in numerical modeling (finite element method and boundary element method) of electromagnetic phenomena. Dr. Nath received his B.S. in electrical engineering from Bombay University, India, and his M.S. and Ph.D. in electrical engineering from Colorado State University and Iowa State University, respectively. He holds 10 U.S. patents and is a member of ASNT and the Institute of Electrical and Electronics Engineers.

Matthew J. O'Keefe received a B.S. degree from the University of Missouri-Rolla (UMR) and a Ph.D. from the University of Illinois, both in metallurgical engineering. He previously worked for AT&T Microelectronics, AT&T Bell Laboratories, and the Air Force Research Laboratory. He is currently a professor in the Department of Materials Science and Engineering and director of the Graduate Center for Materials Research at UMR, specializing in the deposition, characterization, and industrial use of thin films, coatings, and environmentally friendly materials and processes for corrosion, wear, and microelectronic applications.

David L. Olson received a B.S. in physical metallurgy from Washington State University and a Ph.D. in materials science from Cornell University. After a short tour at Texas Instruments and postdoctoral studies at Ohio State University, Dr. Olson joined the Colorado School of Mines (CSM) in 1972 and was appointed professor of metallurgical engineering in 1978. In 1979 he was a visiting senior scientist at the Norwegian Institute of Technology. In 1981 he became head of the CSM Center for Welding Research. From 1986 to 1989 he served as vice president for research and development and dean of research. In 1997 he was named the John H. Moore Distinguished Professor of Physical Metallurgy. Dr. Olson is a professional engineer (Colorado). His research is in welding metallurgy, reactive metals, hydrogen in materials and nondestructive assessment of materials. He has authored and edited more than 17 books, 497 technical papers, and 152 archived reports, and he holds six patents. As a thesis advisor, he has completed 36 Ph.D. and 65 M.Sci. theses. He has been recognized with more than 20 international awards, including the CSM AMOCO Foundation Teaching Award (1982), Burlington Northern Foundation Faculty Achievement Award (1990), and the Dean's Excellence Award (1994). He is a fellow of ASM and AWS and a foreign member of the National Academy of Science of Ukraine. He won the 2001 International Institute of Welding Arata Medal and Prize and was elected to Theta Tau, Sigma Xi, Tau Beta Pi, Alpha Sigma Mu, and Blue Key. Professor Olson has chaired and served on ASM, American Welding Society, and TMS committees, and he chaired the Materials Advisory Group for the Committee on Marine Structures (NAE). He has served as a DOD focus officer on an international research project on hydrogen management of steel welds. For this effort he was awarded the 1999 DOD Technical Cooperation Program Achievement Award. He has served as a U.S. delegate to the International Ship Structure Congress, on the National Science Foundation U.S.–Argentinean Study Group on Cracking in Nuclear Fuel Rods, on the U.S.–Indian Welding Research Program (PL 480 funds), and as key reader for *Metal Materials Transactions* and *The Welding Journal*. He has been a Materials Program visitor to Ben Gurion University and a member of the U.S. Army–Defense Advanced Research Projects Agency visiting team to Russian shock research and welding research centers.

Professor Olson is a university affiliate at Los Alamos National Laboratory and has been associated with the Albuquerque Project for 33 years. He has traveled extensively.

Donald D. Palmer, Jr., received his B.S. degree in physics and his M.S. degree in materials science and engineering from Iowa State University in 1985 and 1987, respectively. He received a doctorate in materials science and engineering from Washington University in St. Louis in 2004. Beginning in 1985, Dr. Palmer worked as a research assistant at the Center for Nondestructive Evaluation at Iowa State University, focusing his research on the ultrasonic characterization of diffusion bonds. In 1987, he joined McDonnell Douglas Corporation (later Boeing) as a nondestructive evaluation specialist, supporting both production and advanced aircraft programs. During this period, he developed several microwave testing processes for quality assurance of low-observable materials and structures. He also developed an ultrasonic scattering model to support the design of stiffened composite structure. In 1997, he became the team leader of the NDE group at Boeing in St. Louis, Missouri, leading research and development activities directed at both manufacturing and support applications of NDE. This responsibility included leading the development and implementation of the Mobile Automated Scanner (MAUS) system, a portable, multimodal inspection system currently used to support production and depot maintenance processes. He was elected to the Boeing Technical Fellowship Program as an associate fellow in 2001 and a fellow in 2005. He currently leads a Boeing enterprisewide team developing NDE processes for composite materials and structures directed at both military and commercial applications. Dr. Palmer holds three patents and has more than 40 publications in technical journals and conference proceedings. He has organized and chaired sessions at a number of technical conferences and served as co-chair of the Nondestructive Testing Information Analysis Center Conference on NDE for Process Control. Dr. Palmer has also represented the aerospace industry on a NASA peer review committee and served on a panel focused on reducing the inspection burden at the USAF ASIP Conference. He has served on the Research Council of the American Society for Nondestructive Testing (ASNT) and is currently chair of the St. Louis Section of ASNT. He is also a member of ASM International.

S.I. Rokhlin is a professor in the Department of Industrial, Welding and Systems Engineering at Ohio State University (OSU). He joined the faculty of OSU in 1985. His research interests are in the experimental and modeling areas of ultrasonic wave propagation; in the characterization and imaging of inhomogeneous and anisotropic materials, including composites and bonded materials; and in interphase mechanics and environmental degradation and failure. He is also active in imaging with high-resolution microfocal x-ray radiography and tomography. His more resent research interests include nanoindentation, nanomanufacturing, and molecular dynamic simulations of nanoparticle interaction. He has several patents, has authored more than 300 publications, and has given numerous presentations. Dr. Rokhlin received the Charles H. Jennings Memorial Medal Award from AWS in 1986; the Alcoa Foundation Award in 1988 and 1989; the A.F. Davis Silver Medal Award from AWS in 1991; the Faculty Research Award in 1990, 1994, and 1998 from OSU; the NASA Technical Recognition Award in 1996; and the ASNT Outstanding Paper Award in 1998. He received the 2004 Lumley Individual Research Award and the 2004 and also the 2006 Lumley Interdisciplinary Research Award, all from the Ohio State University College of Engineering, “in recognition of outstanding research accomplishments.” Dr. Rokhlin is a member of ASNT, AWS, and ASME and has served on several committees for these societies; he is a fellow of the American Statistical Association. He is an associate editor of *Materials Evaluation* and is on the editorial boards of *Research in NDE* and *Journal of NDE*. He has served as guest editor for several special issues on NDE topics for different journals and has been the organizer of several professional meetings. He has also served on the ASNT board of directors and has been on the editorial board of the *Journal of Adhesion Science and Technology*.

Robert Schafrik is currently the general manager of the Materials and Process Engineering Department at GE Aviation. He is responsible for developing advanced materials and processes used in GE's aeronautical turbine engines and their marine and industrial derivatives. He oversees materials application engineering activities supporting GE Aviation's global design engineering, manufacturing, and field-support activities. He also operates a state-of-the-art in-house laboratory for advanced materials development, characterization, and failure analysis. Dr. Schafrik also heads the GE Infrastructure Materials Council, which includes GE Energy, GE Transportation, and GE Water. Before joining GE in November 1997, he served in two concurrent positions within the National Research Council, which he joined in 1991: as director of the National Materials Advisory Board and as director of the Board on Manufacturing and Engineering Design. Under his direction, 33 final reports for studies were issued that addressed significant national issues in materials and manufacturing. Dr. Schafrik also served in the U.S. Air Force in a variety of research and development (R&D) and system acquisition capacities; he retired as a lieutenant colonel. He has a Ph.D. in metallurgical engineering from Ohio State University, an M.S. in information systems from George Mason University, an M.S. in aerospace engineering from the Air Force Institute of Technology, and a B.S. in metallurgy from Case Western Reserve University.

Kevin Smith earned his B.S. degree in mechanical engineering, with honors, from the University of Texas in 1980. Since that time he has been employed at Pratt & Whitney Aircraft Engines, a division of United Technologies, and has advanced through a series of positions. From 1980 to 1995, he was with the Materials Engineering Nondestructive Evaluation Group of the Military Aircraft Division in West Palm Beach, ultimately supervising a team of 12 technicians and engineers. In 1995, Mr. Smith became the manager of Advanced NDE and Process Sensing, which includes responsibility for support of both commercial and military engine programs. Development, application, and implementation of advanced NDE and sensors to address design, production, and in-service needs in a cost-effective manner are the primary goals of his efforts. Mr. Smith’s experience includes all NDE modalities, with particular expertise in focal plane instrument, ultrasonic transducer, eddy current, and radiography in R&D as well as practical implementation in manufacturing and overhaul environments. He has received the Hamilton Standard President's Award for work in response to a highly visible propeller failure, the Titanium Matrix Composite Technology Consortium (TMCTECC)-Leadership Award, and the Special Award-F119 Inertia Bonded Compressor Rotor, as well as participating on numerous task forces that guided many major corporate efforts. More recently he was the recipient of the 2003 William G. Chamberlain Customer Service Award for Pratt and Whitney and in 2004 of the ASME Distinguished Engineer of the Year Award. Mr. Smith has been a strong champion for moving inspection technology from an empirical art to a science-based engineering discipline and has raised the visibility and importance of this activity significantly within the company.

R. Joseph Stanley is an associate professor in the Department of Electrical and Computer Engineering at the Missouri Institute of Science and Technology (formerly the University of Missouri-Rolla). His research interests include data fusion, signal and image processing, and pattern recognition and automation. He is a senior member of the IEEE and a member of the North American Fuzzy Information Processing Society. He received B.S.E.E. and

M.S.E.E. degrees in electrical engineering and a Ph.D. degree in computer engineering and computer science from the University of Missouri-Columbia. As a graduate student at the University of Missouri-Columbia, he worked under training grants from the National Library of Medicine and the National Cancer Institute. Upon completing his doctoral study, he served as a principal investigator for the Image Recognition Program at Systems and Electronics, Inc., in St. Louis, Missouri.

Edgar A. Starke has served on the faculty of the University of Virginia since 1983, during which time he served as dean of the School of Engineering and Applied Science. He has published more than 250 technical articles and holds three patents on aluminum alloys. Dr. Starke received the Metal Award of the Nonferrous Division of the Wire Association and has twice served as an Alpha Sigma Mu lecturer. He served as a member of NATO's Structures and Materials Panel, the Advisory Group for Aerospace Research and Development, NASA’s Aeronautics Advisory Committee, and the Government and Public Affairs Committee of the American Society for Materials International. He served on and chaired the National Materials Advisory Board of the National Research Council. Recently NASA awarded him the Public Service Medal, the highest honor given to a nongovernment employee. Dr. Starke also received the Innovations in Real Materials Award from the International Union of Materials Research Societies in 1998. He is a fellow in ASM International, a fellow in the Materials Society of AIME, and a member of the National Academy of Engineering. Dr. Starke's research interests include the mechanical behavior of materials and alloy development, with an emphasis on the relationships among primary processing, microstructure development, and mechanical properties. His current research focuses on monolithic aluminum alloys, aluminum-matrix composites, and titanium alloys.

J.G. Sun is a mechanical engineer in the Energy Technology Division of Argonne National Laboratory. His expertise is in the areas of nondestructive evaluation and life cycle prediction. He has captured the power of a wide range of technologies in order to assess materials stress and fatigue, including confocol microscopy, thermal imaging, and x-ray backscatter. Dr. Sun’s research is widely published in such journals as *International Nanomanufacturing*, *Journal of Applied Ceramic Technology,* and *Infrared Physics and Technology*. Dr. Sun has also been a presenter at multiple conferences on nondestructive evaluation and materials science. With his colleagues at Argonne National Laboratory Dr. Sun holds multiple patents for nondestructive evaluation methods and technology.

R. Bruce Thompson is the director of the Center for Nondestructive Evaluation, director of the Ames Laboratory Applied Nondestructive Evaluation Program, and a Distinguished Professor in the Department of Materials Science and Engineering and in the Department of Aerospace Engineering and Engineering Mechanics at Iowa State University. He received his B.A. in physics from Rice University, his M.S. in physics from Stanford University, and his Ph.D. in applied physics from Stanford University. From 1970 to 1980, he served as a member of the technical staff and as group leader of ultrasonic applications at the Rockwell International Center before joining Iowa State University. Dr. Thompson's research interests fall in the area of ultrasonic nondestructive evaluation. His specialties include the analysis and development of noncontact sensors, in particular, electromagnetic acoustic transducers; modeling the effects of measurement geometry on ultrasonic inspection; studying the uses of ultrasound to characterize a variety of microstructural and material properties such as stress, texture, porosity, grain size, and anisotropy and partially contacting interfaces; and uses of physics-based simulation tools to assist in the determination of probability of detection. Dr. Thompson is the author of six major invited review articles in the field of nondestructive evaluation, more 90 articles in archival journals, and more 323 papers in edited conference proceedings. He has been awarded 24 U.S. patents and currently serves as the editor-in-chief of the *Journal of Nondestructive Evaluation*. Dr. Thompson is a member of the National Academy of Engineering.

John Venables received his Ph.D. in physics from the University of Warwick, England, and, until his retirement he served as associate director and chief scientist at Martin Marietta Laboratories in Baltimore, Maryland. He has served on numerous study committees of the National Research Council and was a member of the Board on Army Science and Technology. He is a co-author of an entry in the *Encyclopedia Britannica*, “Materials Science,” and is currently a consultant for DARPA/Defense Sciences Office through Strategic Analysis, Inc.

Reza Zoughi received his B.S.E.E, M.S.E.E, and Ph.D. degrees in electrical engineering from the University of Kansas. Currently he is the Schlumberger Distinguished Professor of Electrical and Computer Engineering at the Missouri Institute of Science and Technology (formerly the University of Missouri-Rolla [UMR]). Prior to joining UMR Dr. Zoughi was with the Electrical and Computer Engineering Department at Colorado State University (CSU), where he was a professor. He also established UMR’s Applied Microwave Nondestructive Testing Laboratory (amntl). His current areas of research include developing new nondestructive techniques (NDT) for microwave and millimeter-wave inspection and testing of materials, developing new electromagnetic probes to measure characteristic properties of material at microwave frequencies, and developing embedded modulated scattering techniques for NDT purposes, in particular, for complex composite structures. Dr. Zoughi held the position of Business Challenge Endowed Professor of Electrical and Computer Engineering while at CSU. He has more than 290 journal publications, conference presentations and proceedings, technical reports, and overview articles in the fields of radar remote sensing and microwave nondestructive evaluation. He is also the author of a graduate textbook entitled *Microwave Nondestructive Testing and Evaluation Principles* (Kluwer, 2000), and the co-author with A. Bahr and N. Qaddoumi of a chapter on microwave techniques in an undergraduate introductory textbook entitled *Nondestructive Evaluation: Theory, Techniques, and Applications,* edited by P.J. Shull (Marcel and Dekker, 2002). Dr. Zoughi received the College of Engineering Abell Faculty Teaching Award in 1995. He is the 1996 recipient of the Colorado State Board of Agriculture’s Excellence in Undergraduate Teaching Award and was recognized as an honored researcher for 7 years by the Colorado State University Research Foundation. He has six patents, all in the field of microwave nondestructive testing and evaluation, and has given numerous invited talks on the subject of microwave nondestructive testing and evaluation. He is a senior member of IEEE and a member of Sigma Xi, Eta Kappa Nu, and the American Society for Nondestructive Testing.

Appendix D
Acronyms

AFRL	Air Force Research Laboratory
CBM	condition-based maintenance
CDF	cold dwell fatigue
CFRP	carbon-fiber-reinforced polymer
DARPA	Defense Advanced Research Projects Agency
DP	damage prognosis
DSO	Defense Science Office
EMAT	electromagnetic acoustic transducer
FWHM	full-width half maximum
MAPOD	model-assisted probability of detection
MBE	magnetic Barkhausen emission
MSA	materials state awareness
NDE	nondestructive evaluation
NDI	nondestructive inspection
NDT&E	nondestructive testing and evaluation
PFA	probability of false alarm
PHACOMP	phase computation
POD	probability of detection

RUL	remaining useful life
SHM	structural health monitoring
TEP	thermoelectric power
USAF	United States Air Force