A National Forum on The Future of Automated Materials Processing in U.S. Industry The Role of Sensors

Report of Workshop I.

December 1985

Edited by:

H. Thomas Yolken
Robert Mehrabian

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Sponsored by:

Industrial Research Institute
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Committee on Materials, Working Group
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In Cooperation with:

University of California at Santa Barbara
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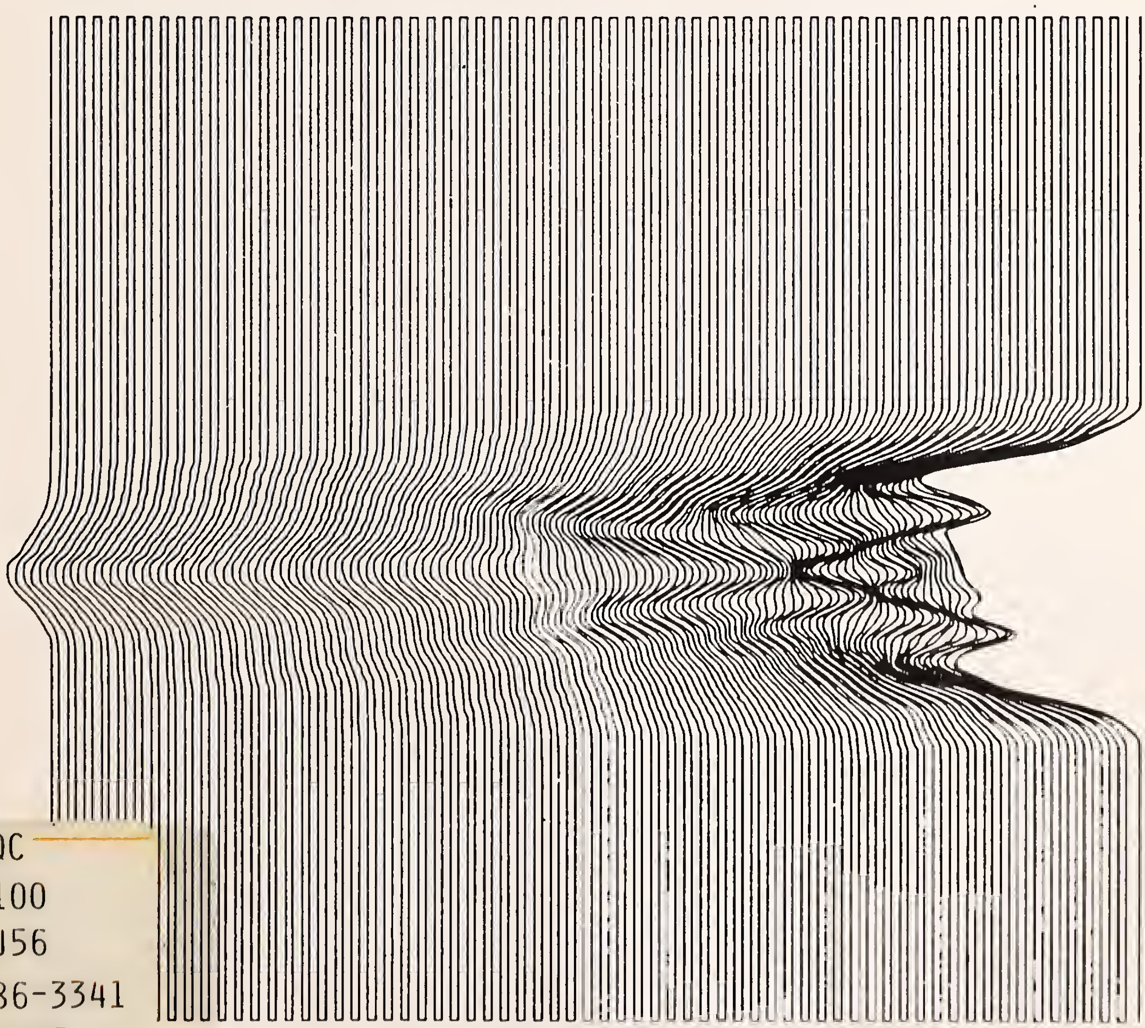

Cover: An analog representation of an intensity field pattern of a 10 MHz ultrasonic transducer.

A NATIONAL FORUM ON THE FUTURE OF AUTOMATED MATERIALS PROCESSING IN U.S. INDUSTRY

. . .THE ROLE OF SENSORS. . .

Report of Workshop

UNIVERSITY OF CALIFORNIA AT SANTA BARBARA
SANTA BARBARA, CALIFORNIA

December 16 - 17, 1985

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INTRODUCTION

This workshop, "A National Forum on the Future of Automated Materials Processing in U.S. Industry - The Role of Sensors," was the first of two workshops to be sponsored by the Industrial Research Institute and the White House Office of Science and Technology Policy, Committee on Materials, Working Group on Automation of Materials Processing.* The second workshop will address the other two key components required for automated materials processing, process models and artificial intelligence coupled with computer integration of the system.

The objective of these workshops is to identify and assess important issues affecting the competitive position of U.S. industry related to its ability to automate production processes for basic and advanced materials and to develop approaches for improved capability through cooperative R&D and associated efforts. These workshops will form the basis for developing information and recommendations for national direction.

This report is the proceedings from the discussion group portion of the meeting. A draft of the proceedings, based on written summaries provided by the discussion leaders, was forwarded to the discussion leaders, the three closing summary speakers, the Program Committee members and the COMAT Ad Hoc Working Group. The suggestions received are incorporated in this final report.

Over the last twenty-five years, and especially during the last decade, major worldwide changes have taken place that are challenging U.S. industrial competitiveness. Conventional structural materials such as steel, cement, and aluminum have, to a substantial degree, become commodity-type materials. Effective and efficient manufacturing processes are urgently required to compete in this world market. Although the technology embodied in more advanced engineering materials will most likely slow the spread of this type of capability to other countries, U.S. competitiveness in advanced materials will nonetheless also depend on manufacturing effectiveness and efficiency.

New advanced engineering materials, if they can be manufactured efficiently, hold the promise of profound beneficial effects on many engineered systems. They can enable the manufacture of new, innovative, and more efficient configurations of existing products. For example, metal matrix composites could provide very substantial gains in stiffness and strength over conventional metal alloys. Utilization of advanced materials can also result in product modifications that enable easier, more economical production methods to be used. The near-net-shape capability embodied in materials processing of advanced metal and ceramic powders can lead to greatly reduced machining costs.

* See pages v and vi, respectively, for the lists of members of the Ad Hoc Working Group and the Program Committee for this workshop.

Another benefit to be derived from using these advanced materials and processes is the savings resulting from the substitution of costly strategic materials. This savings can be illustrated by the examples of metal surface modification by laser glazing or alloying and by ion implantation. Advanced materials can also facilitate the development of entirely new products. For example, objects made of shape memory alloys are able to "remember" their original shapes after being deformed. Potential applications include mechanical activators and mechanical coupling devices.

Unfortunately, advanced materials require complex microstructures to yield the desired advanced properties and these complex microstructures are proving difficult to reproduce. This is the case because process models, or the relationship between process variables and resulting microstructure, is not well understood and adequate process control schemes are often lacking. Products made from advanced materials, therefore, often lack reproducibility and this in turn requires that products be overdesigned. Lack of reproducibility thereby causes a substantial loss of the full potential of advanced materials. In addition, current production of advanced materials is often labor intensive and requires costly post-processing inspection. Reject rates are often high with the rejects typically not identified until late in the production process thereby resulting in major loss. Systems based on high rejection rates and extensive inspections are bound to produce some system failures with accompanying loss of consumer confidence.

In the current state of materials processing, the processing path is determined by research and development in a controlled laboratory environment. Theoretical and empirical process models, often incomplete, are used along with sophisticated analysis of properties. Production processes are then set up with process control usually limited to some extrinsic parameters and other parameters such as temperature, pressure, etc. Intrinsic properties of the materials and other key parameters are usually not monitored during the process to provide closed-loop feedback control. This appears to be a major flaw in current processing methodology. NDE sensors are only used after production in an attempt to "inspect in" quality. What is needed is "built in" quality through automated intelligent materials processing utilizing a system consisting of process control models, on-line NDE sensors, feedback controls, and artificial intelligence or expert systems.

These two workshops were planned because of our recognition that input, involvement, and possibly cooperative programs involving university, industry, and government are essential to achieve a timely wide-scale exploitation of this technology.

The first day of this two-day workshop on sensors dealt with sensor requirements for various processing technologies. The morning plenary sessions involved a series of resource speakers while the afternoon sessions consisted of a parallel series of discussion groups. In a plenary session at the end of the day, the discussion leaders then summarized the conclusions and recommendations that emanated from the discussions.

The second day of the workshop dealt with sensor capabilities. The format was the same as for the first day, with resource speakers in morning plenary sessions and afternoon parallel discussion groups. The discussion leaders then reported the findings in a plenary session. A final plenary panel discussion was held at the conclusion of the workshop.

This introduction and the first three sections of the report were written by the workshop co-chairmen. The first section is a list of major conclusions that are based both on the written material provided by discussion leaders and summary speakers and on the oral information exchanged at the workshop. The next two sections consist of conclusions from each of the discussion groups. These discussion group conclusions were abstracted from the written summaries (contained in Appendix A) that were prepared by each of the discussion leaders. Appendix B contains written remarks by the three closing plenary summary speakers, Appendix C contains a summary of conclusions raised at the last session, Appendix D is a copy of the workshop program, and Appendix E is a list of attendees.

The workshop had 106 participants with 68 from industry, 21 from academia, and 17 from government.

WORKSHOP CONCLUSIONS

1. A clear consensus emerged concerning the formidable benefits to be derived from automating materials processes, and sensors were identified as one of the key ingredients in automated materials processing systems.

2. Several generic sensing problems were identified that cut across broad classes of materials. The sensing problems include: characterizing small flowing powders, determining internal temperature profiles in solids, measuring liquid/solid interface position and interface topography and characterizing solid/solid interfaces.

3. A large number of sensing problems were identified that are applications driven and appear to require somewhat unique solutions.

4. In order to completely define sensor requirements for a specific process an adequate process model must be developed.

5. There is a need for cooperative research on sensors between related industries, universities, and government. This is so because in many cases the required sensor systems will require a multidisciplinary research and development effort. In addition limited applications for each sensor will constrain cost recovery through the sale of sensors.

H. Thomas Yolken
Robert Mehrabian

SENSOR NEEDS FOR ELECTRONIC MATERIALS

Discussion Leader: L. Eric Cross, Pennsylvania State University

The participants confined their consideration to several of the most important electronic materials (Si, GaAs, and CdTe). They reached a number of specific and useful conclusions.

1. What parameters or properties require sensors for monitoring and controlling bulk crystal growth?

    - Three dimensional temperature distribution in real time.
    - Three dimensional flow distribution.
    - Character of interface morphology.
    - Direct (on-line) diagnosis of defect structure during growth.
    - Indirect (off-line) wafer characterization of microscopic and macroscopic defects as to location and electrical activity.

2. Is characterization of sub-micron particles important in very large scale integrated (VLSI) electronic technology?

    - Yes, to monitor and control the environment, raw material chemicals, and the product.

3. What key items require monitoring and control in thin film deposition?

    - Suitability of the substrate and continuous monitoring of composition and structure, with initial stages of deposition most critical.
    - In gas phase deposition (CVD) and plasma methods, three dimensional mapping of gas phase composition is required.

4. What needs to be sensed during materials removal processes?

    - Plasma etching requires determination of local electric fields.
    - All removal methods require enhanced end point determination and residual surface analysis.

See Appendix A, page 23, for discussion leader's summary.

SENSOR NEEDS FOR OPTICAL MATERIALS

Discussion Leader: David H. Smithgall, AT&T Bell Laboratories

This group limited their discussion to optical material as defined by "that which is associated with the transmission, guiding, storage or generation of light energy, e.g., wavelength of 0.2 - 10 μm." They reached a number of specific and useful conclusions.

1. What are the important optical properties that have to be considered and controlled during processing?

   - For conventional optics: image and surface quality, aspheric shape and refractional index gradients.

   - For waveguide optics: geometry, refractive index profiles, attenuation, dispersion and nonlinear effects at high power levels.

   - For electro-optical devices and optical storage devices: geometry, refractive indices, birefringence and the nonlinear effects of elasto-optic and magneto-optic coefficients.

   - Process control for the fabrication of light guide fibers and electro-optical devices required similar accuracies.

   - The fabrication of multiple quantum well structures requires evaluation and control with resolutions on the order of 10 angstroms.

2. What are the future directions in optical materials?

   - Large scale optics where the fabrication requirements are those of conventional optics, scaled to large sizes coupled with the control aspects of adaptive optics.

   - Another future direction is very small scale optical structures, driven by integrated optics and semiconductor VLSI programs.

   - The geometry requirements for very small scale components include measurement of deposited layer thickness, device feature dimensions, and in the case of soot processes, particle size.

   - Materials composition concerns for very small scale comprise refractive index profiles and homogeneity.

   - Process parameters required for very small scale: gas flow rates, concentrations and temperatures of precursors.

See Appendix A, page 25, for discussion leader's summary.

SENSOR NEEDS FOR METALS

Discussion Leader: Phillip Parrish, Defense Advanced Research Projects Agency

The discussion group selected two model systems, ingot melting and heat treatment, to illustrate key sensor needs. They identified a number of important sensor needs that are generic to wide segments of the metal processing industry.

1. What are the broad classes of metal processing?

   - Melt processing (atomization, ingot, castings/single crystals).
   - Solid state transformation processing (heat treatment, diffusion bonding).
   - Thermomechanical processing (hot isostatic pressing, ingot conversion, forging, extrusion).

2. Having selected two basic types of metal processes, ingot melting and heat treatment as model systems, what are their important sensor requirements?

Generic Sensor Requirements	Type of Process
• Ingot Melt Processing	
Melt temperature	VAR } ingot methods
Interfacial (solid/liquid) temperature distribution	E-beam } ingot methods
	Plasma } ingot methods
Interface location and shape (3-D)	Ingot, castings
Melt chemistry (and distribution)	Ingot, castings
Melt inclusions (from unmelted refractory metals, ceramic contaminants)	Ingot, castings
Melt vapor chemistry	E-beam, plasma hearth melting;(also, coatings)
• Heat Treatment	
Inspection of primary phases	Heat treatment for conditioning prior to deformation processing.
Grain size and growth	
Recrystallization	
Features of second phases	Heat treatment for precipitation hardening.
Size	
Distribution	
Volume fraction	
Nature, e.g., coherent or incoherent	
State of residual stress	Final heat treatment

See Appendix A, page 27, for discussion leader's summary.

SENSOR NEEDS FOR CERAMICS

Discussion Leader: Fred F. Lange, Rockwell International Science Center

This group limited their discussion to powder processing methods which generally included the following major steps: powder manufacture, preparation of powder for consolidation, consolidation (making shape), sintering (densification and microstructural development), and post-densification treatments (machining, heat treatments, etc.). The group selected several important areas of need for sensor applications in ceramic processing.

1. What is the current status of sensor applications for ceramic processing?

   - Difficult to judge due to proprietary nature.

   - In-line sensors are used to a higher degree in the manufacture of ceramics for electronic packaging.

   - Powders are characterized only occasionally on a batch to batch basis.

2. What are the important areas of sensor needs for ceramic processing?

   - Content, size and homogeneity of phases in powders.

   - Rheology (viscosity, shear rate sensitivity, etc.) of slurries and deformable powder/polymer mixtures during consolidation/forming.

   - Monitoring organic extraction.

   - Void phase in consolidated powder compacts (average density of compact, density distribution).

   - Adherence of ceramic coatings on metals and other ceramics.

   - Thermal profiling of the furnace and the powder compacts during sintering is desirable.

   - Monitoring tool wear, surface damage, and grinding forces during machining of densified ceramics would be desirable.

See Appendix A, page 29, for discussion leader's summary.

SENSOR NEEDS FOR POLYMERS

Discussion Leader: Witold Brostow, Drexel University

This group discussed a large array of general topics which included sensor techniques; polymerization; processing with real time on-line control computer modeling and simulation; and processors, computers, and expert systems. The group reached some general conclusions.

1. Which type of sensor has the highest potential for control of polymerization?

   - Fiber optic based sensors.

2. For polymer processing which sensor should be given priority?

   - Reflective spectroscopy.

See Appendix A, page 33, for discussion leader's summary.

SENSOR NEEDS FOR BASIC MATERIALS

Discussion Leader: William Dennis, American Iron and Steel Institute

This discussion group took a broad view of sensor needs for basic materials processing rather than focus on actual sensor requirements and reached several conclusions: (1) the development of process control sensors that the industry could afford to use is highly desirable, (2) since sensors for basic industries tend to be more difficult to develop and resources more limited, collaborative approaches to R&D are mandatory, and (3) the desirability of the National Bureau of Standards expanding its role already developed for steel and aluminum to facilitate systematic surveys of domestic needs and overseas sensor technology.

See Appendix A, page 35, for discussion leader's summary.

SENSOR NEEDS FOR COMPOSITES

Discussion Leader: Richard S. Williams, United Technologies Research Center

Initial discussions centered on broad issues concerning intelligent materials processing. The conclusion reached was that the R&D approach to automated materials processing must be truly interdisciplinary including materials and process modeling, sensors and measurement science, artificial intelligence and process control, and engineering design. The group also come to some important and specific conclusions concerning sensor needs for composites.

1. What are the sensor requirements for assembly and lay-up of polymer matrix composites?

   - Measurement of incoming constituent material properties: tackiness of prepreg, extent of aging of the matrix, impurities, composition, voids/inclusions/defects.
   - Tactile sensing for automated lay-up and assembly.
   - Metrology to control positioning accuracy.
   - Fiber orientation.
   - Fiber volume fraction in the prepreg.

2. What are the sensor requirements for composite processing during constituent consolidation?

	Priority for Development		
Need to Sense	Polymer Matrix	Ceramic Matrix	Metal Matrix
Porosity/voids/inclusions	high	high	high
Interfacial bonding	medium	high	high
Matrix properties (Tg, viscosity, etc.)	high	medium	high
Residual stress	low	medium	medium
Fiber geometry	low	medium	medium
Microstructure (fiber and matrix)	low/high*	medium	high

*NOTE: Low for thermosetting polymers and high for thermoplastic polymers.

See Appendix A, page 37, for discussion leader's summary.

SENSOR METHODOLOGIES FOR PROCESS PARAMETERS

Discussion Leader: Robert H. Bullis, United Technologies Research Center

The discussion group made a number of general observations. The sensor community, in general, is not aware of the needs of the advanced materials processing community while the materials community lacks a good appreciation of the most recent sensor advances that can favorably impact process automation. Process modeling is viewed as the key factor which should govern both the overall automation strategy and sensor selection. Specific applications of established sensing and measuring techniques are required rather than a significant number of new inventions. The discussion group also identified several important sensor requirements.

1. What key sensor methodologies are required to determine process parameters for metals and semiconductors?

   - The most important problems are temperature distributions in the melt, location and shape of the liquid/solid interface, flow distributions, melt chemistry, and effluent gas composition.

   - The most promising approaches are acoustics and optical techniques such as CARS, laser induced fluorescence, and Raman scattering.

   - The question of fluid flow distributions in metals and semiconductors remains an open issue.

2. What are the other key sensor methodologies that look promising for process parameters?

   - Miniaturized microelectronic and fiber optic sensors for the measurement of pressure, temperature, fluid flow and gas composition process parameters and for the measurement of cure conditions in composites.

   - Ultrasonics for mechanical properties and grain size determinations.

   - The scanning tunneling microscope for nucleation, wetting, and film growth thickness in electronic materials.

   - Developing techniques on fluid flow analysis for application to crystal growth and electroplating.

   - Many approaches offer potential for thickness measurements of metal coatings including acoustics, x-ray backscattering and electrostatics.

See Appendix A, page 39, for discussion leader's summary.

SENSOR METHODOLOGIES FOR DIMENSIONAL METROLOGY

Discussion Leader: E. Clayton Teague, National Bureau of Standards

The group discussed the broad range of dimensional metrology applications in advanced materials processing within the industries related to conventional structural materials and materials removal processes such as machining, ceramics processing, and semiconductor processing. Scales of measurement range from nanometers to tens of meters; environments range from superb laboratory conditions of the semiconductor class 10 and class 1 clean rooms to the hostile manufacturing conditions of a steel rolling mill; times allowed for a measurement range from the micro and milliseconds for an adaptive control sensor to the static times required for a precise determination of the dimensions of a mold for composite material aerospace components. Participants in this session selected from this broad range of applications those areas of dimensional metrology which they saw as being most important and generic for national needs.

1. What are examples of important national needs for dimensionally-based measurements to achieve adaptive control of process parameters?

   - Date reductions techniques are required to reduce the large quantities of information obtained with modern sensor and computer technology to the relatively small amount of digested information needed for controlling processes.

   - Dimensional measurements in support of adaptive control of other quantities.

   - Fast and remote measurements of part displacements and part dimensions in all ranges of dimensional measurements from small to large scale.

   - The semiconductor industry needs to be able to achieve mechanical manipulation without introducing particulate contamination into the processing environment.

2. What is the major need for dimensionally-based measurements to achieve adaptive control of part properties?

   - Small dimensional measurements for the semiconductor industry involving profiling for features whose dimensions are small compared to visible light wavelengths.

3. What are examples of important needs for dimensionally-based measurements to provide process diagnostics?

   - Control of particulates in semiconductor processing environments and in all materials used in fabrication processes.

4. What are some possible technical solutions to developing the needed sensor methodologies?

   - Modulated scanning laser systems, holography, phase-conjugate optics, adaptive optics, active optics, acoustic and laser ranging, combined nonlinear and active optics appear to hold promise.

   - Techniques which rely upon differential information, i.e., those sensitive to anomalies and defects, the scanning tunneling microscope, scanning optical microscopy relying upon sensitivity to depth of focus, interferometry, etc., also look promising.

5. What work is needed to develop and apply the new methods in the near future?

   - Adapt and adjust available and new sensors to industrial environments.

   - Develop new techniques for very high accuracy time interval measurements to improve capabilities of ranging and pulse caliper-type dimensional measurements.

   - Adapt measurement approaches to select desired information, incorporate as much preprocessing of incoming raw data as possible.

See Appendix A, page 43, for discussion leader's summary.

SENSOR METHODOLOGIES FOR MATERIALS CHARACTERIZATION (NDE)

Discussion Leader: Bernard R. Tittmann, Rockwell International Science Center

The discussion group selected and discussed five broad generic sensor needs for materials characterization during processing. The sensor areas or parameters were selected so as to have as much commonality as possible for the processes discussed for a wide variety of materials. The group reached a number of important conclusions.

1. What are the generic sensor requirements for broad classes of materials processing and what sensor devices look promising?

    - Two and three-D temperature profile utilizing ultrasonic velocity and infrared radiation.

    - Shape of solid liquid interface utilizing ultrasonic backscattering, x-ray tomography, and magnetic flux.

    - Microstructure of primary and secondary phases utilizing ultrasonic attenuation, thermal waves, radiography, eddy currents, and NMR imaging.

    - Rheology including viscosity and shear rate dependence utilizing shear and longitudinal ultrasonic waves and dielectric techniques.

    - Three-D macro-residual stress (not discussed in detail).

2. Is one sensor technique likely to be sufficient to meet these generic sensor needs?

    - No, each sensor methodology should make use of more than one device for a particular process parameter or material property so that the concept of a "multi-component sensor" methodology was developed (e.g., ultrasonics plus eddy currents).

    - Since multisensor methodology requires an interdisciplinary approach, more interdisciplinary graduate training at universities and a deeper interaction between universities and industry is recommended.

See Appendix A, page 47, for discussion leader's summary.

SENSOR METHODOLOGIES FOR SURFACE PROPERTIES

Discussion Leader: L. Duane Dunlap, Aluminum Company of America

The discussion was divided into two principal categories: (1) the detection, processing, and classification of surface defects; and (2) the measurement of surface characteristics critical to process control. In each category interest was expressed solely for non-contacting forms of measurement. Several important sensor needs were identified.

1. Progress is being made in the development of on-line sensor systems to detect defects on the surface of materials moving at high speeds. However, much work remains to develop image processing algorithms and techniques to identify and categorize defects for statistical control of the process.

2. What are the key surface characteristics that need to be determined by accurate, real-time, non-contacting measurement?

    - Temperature.

    - Residual stress.

    - Surface roughness (topography) and flatness.

    - Thin film thickness.

    - Surface chemistry.

3. Why can't measurements of surface properties be made accurately today?

    - There is a lack of understanding of the many surface parameters and their inter-relationships and of the effect upon sensor response.

4. What steps can be taken to improve the accuracy and functioning of remote sensors for surface properties?

    - Actively promote programs that increase fundamental understanding of critical surface parameters and rally key universities, technical societies, and industries around this effort.

    - Develop mathematical models relating variables such as electromagnetic reflectivity, surface roughness and topography, emissivity, etc.

See Appendix A, page 51, for discussion leader's summary.

SENSOR METHODOLOGIES FOR ADHESION AND INTERFACES

Discussion Leader: Haydn N. G. Wadley, National Bureau of Standards

The group developed working definitions of adhesion and interface properties, established a priority order list of sensor needs, and reviewed the present status of sensor R&D.

1. What adhesion and interface properties should be measured?

   - The work to separate an interface less the energy of the two surfaces is a measure of interface adhesion.

   - The adhesion and physical and chemical properties of interfaces need to be measured together with the characterization of phases and defects that may be present in the interface region.

   - Measurements ideally should be capable of being made on a single interface (e.g., weld or adhesive bond), distributed interfaces (e.g., matrix-reinforcement interfaces in composites, grain boundaries and second phase-matrix interfaces in metals), and spatially delocalized interfaces (e.g., liquid-solid interface of alloys with broad "mushy" zones).

2. Are adhesion and interfaces important during materials processing? If so, what systems are most important? How are they presently measured?

   - Adhesion and interface properties are vital components in determining the performance of a material. It is essential that sensors be developed for their measurement during materials processing.

   - Reinforcement-matrix interface and adhesive bond strength are two very important systems where sensors are needed.

   - Sensors are also needed to measure properties in other important systems including solidification interfaces and grain boundaries.

   - Very few techniques exist today for these measurements and none are in the form of process control sensors.

3. What physical phenomena might be available to form the basis of sensor measurement methodologies?

   - Ultrasound can be used to observe quantities such as modulus, density, and temperature (at low frequencies).

   - At higher frequencies, ultrasonic scattering from grain and elastic inhomogeneities promises nondestructive microstructure characterization.

- Interface elastic waves appear promising for characterizing interfaces.

- X-rays, dielectric measurements, NMR, eddy currents, etc. also hold promise.

- A premium is to be attached to techniques that provide spatially resolved information via tomography, synthetic aperture, etc.

- Three-dimensional mapping of internal friction might be used to characterize interfaces.

- Embedded fiber optics can be applied to interfaces.

- Fluorescent dyes, dielectric properties, and shear modulus can monitor epoxy cure for adhesion and composites.

4. In priority order, what are the sensor needs?

   - We really do not know the answer yet!

   - Adhesion might be related to physical mapping of surface condition, contamination, curing (molecular properties), adhesive thickness, porosity, and disbonds.

   - Interfaces might be related to topology, temperature distribution, modules (bulk and local), and residual stress.

See Appendix A, page 53, for discussion leader's summary.

APPENDIX A

WORKSHOP REPORTS

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: ELECTRONIC MATERIALS

L. Eric Cross
Pennsylvania State University

1. Consideration was confined to semiconductor materials, silicon, GaAs, CdTe, etc.

2. Bulk crystal growth.

All techniques which go from liquid to solid state need sensors for:

a) Three dimensional temperature distribution in real time possibly optical or ultrasonic methods.
b) Three dimensional fluid flow distribution possibly using ultrasonic techniques.
c) Techniques for the direct determination of interface morphology.

No direct method appears to exist for diagnosis of defect structure during growth.

Indirect characterization of wafers is currently essential.

Measurements needed are of microscopic and macroscopic defects, dislocation, etc., giving both location and electrical activity.

A rapid nondestructive evaluation is required such as IR imaging or recombination measurement. Currently, these techniques are used in the laboratory but not in production facilities.

3. With decreasing scales imposed by VLSI, techniques are required for characterizing sub-micron particles both in the environment and as contaminants in raw material chemicals.

Light scattering offers a possible technique but probably multisensor approaches will be required to cover the dimensions of interest.

4. For all thin film deposition methods, the initial stages of deposition appear most critical. It is important to be able to define the suitability of the substrate for deposition and to be able to monitor continually at low coverage.

Optical methods and scanning differential microscopy offer possibilities for monitoring surfaces and deposition.

Composition and structure must also be determined and LEED together with surface enhanced optical methods can be used for this purpose.

In gas phase deposition (CVD) and plasma methods, composition in the gas phase as a function of position (spacial coordinates) is required.

5. For material removal, plasma etching requires measurement of local electric fields. All methods would benefit from enhanced end-point determination and residual surface analysis as is possible in the laboratory using laser interferometric techniques.

General Observations

1. Sensing is only one part of measurement science and in general needs reinforcement.

2. The approach to automated materials processing requires interdisciplinary skills and there is need of interaction of university and industry to make university faculty aware of the problems.

3. As a Nation, America appears particularly strong in individual initiative enterprise and innovation, but weak in quick collective exploitation of this advantage in its application to manufacturing.

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: OPTICAL MATERIALS

D. H. Smithgall
AT&T Bell Laboratories

Optical material is defined as that which is associated with the transmission, guiding, storage or generation of light energy, e.g., wavelengths of 0.2 - 10 µm. Typical examples are amorphous (glass) materials such as oxides, fluorides, calcogenides and polymers, and crystalline materials such as sapphire, lithium niobate, and gallium arsenide.

For conventional optics, the properties of image and surface quality, aspheric shape and refractive index gradients are important. For waveguide optics, the geometry, refractive index profiles, attenuation, dispersion and certain nonlinear effects at high power levels are important. For electro-optic devices and optical storage devices, the important factors include geometry, refractive indices, birefringence and the nonlinear effects of elasto-optic, magneto-optic, and electro-optic coefficients.

The process for the fabrication of lightguide fibers was discussed as an example of the fabrication of one class of these materials. The accuracies and tolerances typical of this technology also were representative of those required for the fabrication of electro-optic devices. Process control requires nondestructive, non-contact, high speed and robust sensors. Discussion then shifted to the requirements for electro-optic devices and, in particular, the fabrication of multiple quantum well structures. Evaluation of these structures required resolutions on the order of 10 angstroms.

As a result of the group's discussion, it was determined that there are two directions for future work in optical materials. The first is towards the fabrication of very large scale optics, driven by the SDI program and other astronomical programs. While radar systems employ wavelengths in the millimeter range, many of the fabrication techniques for producing large reflecting surfaces are similar to those for materials used at optical wavelengths. The fabrication requirements are those of conventional optics, scaled to large sizes, coupled with the control aspects of adaptive optics.

The second direction is towards very small scale optical structures, driven by integrated optics and semiconductor VLSI programs. Within this arena, there are two general areas which require measurement: geometry and materials composition.

The geometry requirements include measurement of deposited layer thickness, device feature dimensions and, in the case of soot processes, particle size.

In the extreme of monolayer deposition for quantum well structures, measurement resolutions on the order of 1 - 2 atomic layers are desired. For feature measurements, resolutions of 0.01 µm - 0.1 µm will suffice.

Materials composition concerns comprise refractive index profiles and homogeneity with resolutions on the order of .001% - .1%.

A related concern is the measurement of process parameters, in particular, accurate measurement (.01% - .1%) of gas flow rates, concentrations and temperatures of precursors, and of the process environment. In addition, the purity of the precursors is an important concern.

Finally, it is necessary to know what macroscopic measurements of any quantity adequately predict the average microscopic properties of the final product. This means, for instance, that the measurement of precursor reactant chemical concentration can result, under the proper processing conditions, in the uniformity of characteristics in the final product.

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: METALS

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Goal

Identify some key sensor needs relevant to the control of metals processing.

Approach taken

Broad categorization of classes of metals processes; determination of key intrinsic and extrinsic features which require sensors.

A. Classes of Metals Processing

Class I: Melt Processing
- Atomization
- Ingot
  - VIM
  - VAR
  - E-beam } special hearth methods
  - Plasma } requiring additional control
- Castings/single crystals

Class II: Solid State Transformation Processing
- Heat treatment
- Diffusion bonding

Class III: Thermomechanical Processing
- Hot isostatic pressing
- Ingot conversion
- Forging
- Extrusion

In order to derive the specific sensors required to monitor processes and offer opportunities for active control of processes based upon sensor input and process models, one must determine the critical intrinsic features of the materials being processed, which can be related to desired properties. Thus, sensor readings to be attained can be related to property limit ranges which are acceptable for the finished material. Through the process model, these sensor readings can be related to extrinsic processing parameters which are utilized for control (temperature, pressure, feed rate, draw ratio, etc.).

B. Process Sensor Requirements

The group attempted, in the short period available, to determine several important sensor requirements for two basic types of metals processes, ingot melting and heat treatment. The results are tabulated as follows:

Ingot Melt Processing

Generic Sensor Requirements	Type of Process
Melt temperature	VAR } ingot methods
Interfacial (solid/liquid) temperature distribution	E-beam } ingot methods
	Plasma } ingot methods
Interface location and shape (3-D)	Ingot castings
Melt chemistry (and distribution)	Ingot, castings
Melt inclusions (from unmelted refractory metals, ceramic contaminants)	Ingot, castings
Melt vapor chemistry	Important for E-beam, plasma hearth melting; (also, coatings)

Heat Treatment

Generic Sensor Requirements	Type of Process
Inspection of primary phases Grain size and growth Recrystallization	Heat treatment for conditioning prior to deformation processing.
Features of second phases Size Distribution Volume fraction Nature, e.g., coherent or incoherent	Heat treatment for precipitation hardening.
State of stress Residual	Heat treatment after machining.

In a similar fashion, it is possible to develop sensor requirements for any of the other classes of metals processing.

It is important to realize the iterative nature of sensor--process model--control needs. As new sensors become available, process models may be tested and improved, which will lead to new sensor requirements. The control system will evolve and become more sophisticated both as computational capabilities improve and as sensors and models become more quantitative in their description of the desired process.

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: CERAMICS

Fred F. Lange
Rockwell International Science Center

Discussion included the major topics: current status (where are we?), priorities for sensor needs, and forum for cooperation.

Commonality of Ceramic Processing

A majority of ceramics made for electronics, wear, and structural applications are processed from powders that are consolidated into shapes and densified at elevated temperatures to eliminate voids and to develop the desired property controlling microstructure. Therefore, discussion was limited to powder processing methods which generally include the following major steps:

- Powder manufacture
- Preparation of powder for consolidation
- Consolidation (making shape)
- Sintering (densification and microstructural development)
- Post-densification treatments (machining, heat treatments, etc.)

The appendix lists sub-steps and major characteristics/parameters that require control.

Current Status

The current use of sensors for on-line processing is difficult to judge due to its proprietary nature. It is generally accepted that on-line sensors are used to a higher degree in the manufacture of ceramics for electronic packaging (substrates, IC carriers, multilayer circuit boards, etc.); but it was also stated that powders, which initiate the processing, are only characterized on occasional batch to batch basis.

It was generally agreed that the concept of sensors and process control is less viable without correct control of starting powders. In the United States few ceramic manufacturers make their own powders, i.e., with the exception of several manufactures of silicon carbide and silicon nitride products, powder manufacture is not an integral part of ceramic processing. Powders are generally bought from the chemical or basic materials industry (e.g., alumina from aluminum manufacturers). In recent years, foreign chemical manufacturers, driven to diversify by higher raw materials costs and rising third world competition, have become powder suppliers for advanced ceramics. At the same time, they are developing strong capabilities to manufacture advanced ceramic components. It is not unreasonable to suspect that with the need to control all processing steps to achieve reliability, advanced ceramics can become a branch of the chemical industry.

It was also concluded that our stronger foreign competitors have spent a greater effort in developing empirical process models, a key parameter in their competitive edge that could be overwhelming if they adapt greater in-line control of their empirical models.

Sensor Needs

The discussion group suggested seven areas where sensors could make an impact coupled with known process models.

1. Content, Size, and Homogeneity of Phases: Powders prepared for consolidation can be a mixture of different powders (inorganic additives for densification and second phases used to develop microstructure and properties) and different organics (added to impart flow properties for consolidation). Reasons for knowing the content of constituent phases are self evident. Knowledge of particle (crystallite and agglomerate) size of the powder(s) is important for the densification kinetics and control of flaw size population, e.g., strength (where maximum extreme values are critical); organic inclusions (again, extreme values are critical) produce voids during densification. Homogeneity of the inorganic phases is important for densification, microstructure, and properties. Homogeneity of the organic phases is important for the rheology of consolidation.

2. Flaw Characteristics of Slurries and Deformable Powder/Polymer Mixtures: Ceramic powders are consolidated into shapes by different methods. Some of the important consolidation methods involve either slurries (e.g., tape casting of substrates, slip casting, etc.) or deformable powder/polymer mixtures (e.g., injection molding, extrusion, etc.). Rheology (viscosity, shear rate sensitivity, etc.) is critical to these consolidation/forming methods.

3. Monitoring Organic Extraction: Organic binders are involved in almost all consolidation methods. These organics must be slowly removed at low temperatures without disrupting the powder compact. Sensors are required to monitor the extraction of these polymers.

4. Void Phase in Consolidated Powder Compact (Average Density of Compact, Density Distribution): The bulk density of a powder compact controls densification temperature and kinetics (which, in turn, control microstructure and properties). Gradients in bulk density result in a shape change (shrinkage during densification is proportional to initial bulk density). Isolated regions of different bulk density shrink more or less than their surroundings, producing stresses during densification, resulting in the formation of crack-like voids detrimental for both electrical and structural properties.

5. Coating Adherence: Ceramic coatings are applied to both metals (e.g., for thermal protection) and other ceramics (electronic applications) as powder slurries (thick films), metal-organic compounds (thin films), and flame sprayed coating. Defects at the coating/substrate interface which might grow during heat treatment (densification), causing coating separation, should be identified.

6. Thermal Profile: Thermal gradients exist in the furnaces used to densify the powder compacts; these gradients depend on the furnace, the fixtures used to place the compacts, and the mass of the compacts themselves. Thermal gradients in the compacts will lead to differential shrinkage during sintering, stresses that can lead to disruptive processes, and shape changes. Thermal profiling of the furnace and the components themselves would be desirable.

7. Machining Operations: Ceramics for wear and structural applications usually require diamond machining after densification. Monitoring tool wear, surface damage, and grinding forces would be desirable.

Form for Cooperative Utilization of R&D

The pros and cons of a national center for ceramic processing, co-sponsored by government and industry, was the major focus of discussion. It was questioned whether larger, established corporations would take part in such a consortium (proprietary aspects) but agreed that less capitalized companies would, if the center were a well-equipped user facility (different processing technologies and a knowledgeable technical staff). Evaluation of sensor technology would be one aspect of the center.

APPENDIX--Outline of Major Processing Steps

- Powder Manufacture
  - Important Powder Characteristics
    - Crystallite size
    - Agglomerate size
    - Agglomerate strength
    - Impurities, type and amount
    - Inclusions, inorganic and organic
    - Phase distribution
- Preparation for Consolidation
  - Mixing of
    - Surfactant
    - Sintering aid
    - Second phases
    - Organics
  - Spray drying (dry pressing consolidation methods)
- Consolidation/Forming
  - Sub-division of methods:
    - Dry pressing
      - Uniaxial
      - Iso-pressing
    - Slurry
      - Injection molding
      - Tape casting
      - Slip casting
      - Extrusion

Densification
- Important parameters
  - Dimension
  - Density
  - Weight changes
    - Volatile organics
    - Volatile inorganics
  - Phase development (reactions)
  - Void phase
    - Density
    - Pores size, distribution, extreme values
  - Grain size
    - Distribution
    - Extreme values
  - Other microstructural features
    - Second phases-location, size
  - Surface features

WORKSHOP REPORT OF SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: POLYMERS

Witold Brostow
Drexel University

Discussion at the Polymer Workshop covered a large array of topics, including: sensor techniques, available as well as potentially usable in the future; polymerization, in particular, sampling problems; processing with real time on-line control, if possible; computer modeling and simulation, both for processing and for determination of mechanical and thermophysical properties of manufactured materials; processors, computers and expert systems; international information flow; product characterization; and process integration.

The discussion led at least to one new term, that is of a near-to-line determination procedure. In the following Recommendations, 1 and 2 are specific to polymer manufacture, while the remaining ones are general.

Recommendations

1. Control of polymerization requires knowledge of a number of parameters. Fiber optics have high potential as technique for furnishing several, rather than just one, pertinent parameters.

2. Polymer processing involves also controlling a number of parameters. In development of techniques for this area reflective spectroscopy should be given priority.

3. In case of characteristics which inherently cannot be determined, on-line and near-to-line determination procedures have to be developed. We define the latter procedures as providing data in a time so short that feedback to, and substantially affecting, the ongoing process is possible. Scanning of a plastic pipe surface for crazes and cracks during an extrusion is a simple example.

4. We can hardly afford repetitions of cases when developments abroad have taken American engineers and scientists by surprise. In addition to obviously better scanning of and publishing in international literature, we recommend more attention and more funds for international research projects. At the same time, flow of information across our borders, inside as well as outside of such projects, must be precisely controlled by American researchers.

5. Not only a specific process but materials management in the plant, in fact, the entire plant operation, should be optimized first; then optimizing the process, or processes, will produce a much better overall result.

6. General Strategy of Process Control, which in each case should be implemented as close as possible to the following plan.

(a) Develop a model of the process first, using existing theoretical knowledge and/or computer simulations.

(b) From the results of stage (a), define types and locations of necessary sensors. Develop and install the sensors.

(c) From stages (a) and (b), develop an expert system to run the process.

(d) Don't forget to run the process to see whether it is what was wanted.

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: BASIC MATERIALS

William Dennis
American Iron and Steel Institute

1. To what extent have the sensor needs of the basic industries, other than steel, been documented?

With the exception of the aluminum industry, which is currently reviewing its sensor needs with respect to temperature measurements and surface inspection, only the steel industry has completed a detailed survey.

Other basic industries recognize the critical importance of collaborative action in this high cost-high risk area, but appropriate action has been hindered by perceived problems of confidentiality.

To overcome these traditional institutional barriers it was agreed that a questionnaire should be designed and issued by an acceptable "honest broker" and that the National Bureau of Standards might be an appropriate agency for this purpose. To succeed, it was considered that a committee of experts from the basic industries should advise on the documentation and the addresses for this survey.

2. Are any of these "generic needs" found in several processes or industries?

Although specific, sensor designs will be required to meet specific end-use situations. It was agreed that the research and development required to facilitate sensor design would be substantially generic both in regard to different processes and industries.

Here again, the initial step must be a broad survey of sensor needs which can then be analyzed to determine the extent to which the developments required will be generic.

3. What are the key sources required for sensor research and development and how can they more efficiently be harnessed to the task?

Key resources were seen to include: (a) small business entrepreneurs, (b) academic research, (c) national laboratories, and (d) basic industrial science contributing to multidisciplinary programs. To bring these various elements together and to motivate appropriate actions, it was considered necessary to develop an industry (or better still a multi-industry) focus on the primary sensor needs and the nature of the end use and its environment.

Finally, it was agreed that the preparation of case studies on successful and unsuccessful industrial sensor projects could be worthwhile.

4. To what degree is technology transfer in this area being managed efficiently and how might it be improved?

As no one has this responsibility, basic materials technology transfer is somewhat haphazard, especially in respect to overseas technology on sensors.

To accelerate progress and to efficiently utilize the high cost resources required, it was considered that a central clearing house would be desirable. Here again, it was suggested that the National Bureau of Standards might be an appropriate agency.

Conclusion

For the basic material industries to regain their competitive ability in world markets, the development of process control sensors, which they can afford to install, is highly desirable, although there are obviously many other problems, technical and non-technical, which need to be addressed.

As the sensor needs for these mature industries are frequently more difficult to develop than those required for the new material processes, and as the resources available are severely limited, a collaborative approach to the basic research and development becomes mandatory.

To provide a common ground on which these industries can come together to review, analyze, and act on these needs, it is suggested that the National Bureau of Standards might enlarge on the role which it has already developed in respect to steel and aluminum. Facilitating systematic surveys of overseas sensor technology, with multi-industry participation, might be an important part of this role!

WORKSHOP REPORT ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES: COMPOSITES

Richard S. Williams
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The discussion group on Sensor Needs for Composites Processing met Monday, December 16, 1985. Initial discussions centered on global issues concerning "intelligent materials processing" (IMP) and the scope and goals of the forum. The following comments summarize these discussions.

1. There is a growing trend within the U.S. and abroad to integrate inspection, process control, and manufacturing operations. The goals are to increase product quality, productivity, and profitability by making the part right, the first time and every time, and by eliminating separate inspections and rework which add no value to the product. Further, there is an urgent need for increased R&D in manufacturing science to develop this technology.

2. The prestige, relevance, and importance of manufacturing science R&D needs to be raised with industry, government, and academia.

3. A thorough assessment of sensor needs for any given application cannot be accomplished without the knowledge of the processing mechanisms, the approach for control, and the end use of the product. The conclusion reached was that the R&D approach to IMP must be truly interdisciplinary including materials and process modeling, sensors and measurement science, artificial intelligence and process control, and engineering design.

The discussions of the technical requirements for sensors for composites processing was initially quite circumspect. Composite materials, by definition, encompass a wide and diverse range of material constituents and associated processing technologies. The sensor requirements vary from one type of composite materials system to another. Therefore, it was decided by the group to categorize sensor requirements based on the type of matrix materials: polymer, metal, or ceramic. Further, composites manufacturing is usually accomplished via several separate and distinct operations: fabrication and processing of the constituent materials; assembly and lay-up of the constituent materials; and finally, consolidation of the constituent materials. The consensus of the group was not to address constituent materials fabrication and processing; discussion was limited to the assembly and lay-up of the constituent materials in polymer matrix composites; and to the consolidation processing needs for all three matrix categories.

Table I summarizes the sensor requirements for assembly and lay-up of polymer matrix composites. Further, since the properties of the constituents affect these and subsequent operations, these requirements are also listed. The consolidation processing requirements for polymer, ceramic, and metal matrix composites are summarized in Table II. These needs are also listed as high, medium, and low priority.

TABLE I

Sensor Requirements for Assembly and Lay-up of Polymer Matrix Composites

- Measurement of incoming constituent material properties:
  - Tackiness of prepreg
  - Extent of aging of the matrix
  - Impurities
  - Composition
  - Voids/inclusions/defects

- Tactile sensing for automated lay-up and assembly

- Metrology to control positioning accuracy

- Fiber orientation

- Fiber volume fraction in the prepreg

TABLE II

Sensor Requirements for Composite Processing
During Constituent Consolidation

	Priority for Development		
Need to Sense	Polymer Matrix	Ceramic Matrix	Metal Matrix
Porosity/voids/inclusions	high	high	high
Interfacial bonding	medium	high	high
Matrix properties (Tg, viscosity, etc.)	high	medium	high
Residual stress	low	medium	medium
Fiber geometry	low	medium	medium
Microstructure (fiber and matrix)	low/high*	medium	high

NOTE: Low for thermosetting polymers and high for thermoplastic polymers.

WORKSHOP REPORT ON SENSOR METHODOLOGIES: PROCESS PARAMETERS

Robert H. Bullis
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General Observations

From the presentations and workshop at the Forum, the technical challenges associated with developing automated materials processing techniques are formidable. Equally significant are the rewards to be achieved on a national scale. It is clear the traditional approach of relying on scientific meetings to stimulate developments in this area is not providing the level of interchange required to ensure a successful program. The sensor community, in general, is not aware of the needs of the advanced materials processing community. On the other hand, the materials community lacks a good appreciation of the most recent sensor advances that can favorably impact process automation. Since future national security is at issue, it is important on a national level to provide the stimulus to clearly focus industry and academia on the key technical issues.

It is the general feeling of the technical community at the Process Parameters Workshop that all too often too much emphasis is placed on the development of novel sensors and/or measurement approaches without a clear appreciation of the key parameters governing a specific process. Process modeling is viewed as the key factor which should govern both the overall automation strategy and sensor selection. The development of process models must be viewed as an iterative process which is continually upgraded, redefined, and expanded as new information becomes available. A very significant point made at the Forum was that some processes as they are presently constituted may not lend themselves to a high level of automation. In this situation modeling activities can potentially reveal new directions and approaches to achieve desired objectives. A second observation which is universally true is that the key parameters of the process should be measured directly, if possible, rather than be inferred from a collection of secondary measurements. Lastly, broad or system level solutions must be developed. In this context, the sensor should only be viewed as a tool to achieve the necessary end.

A host of very elegant measuring techniques are continually being developed in the laboratory. The real key to being able to take advantage of these developments is to be able to reduce laboratory concepts to simple real time measurements providing data of high reliability. Lack of real time data acquisition severely, if not completely, reduces the value of any measuring technique, in general, and most profoundly in any automated industrial controls application. Secondly, in a host of process applications non-intrusive measurements are highly desirable if not imperative. Additionally, the measuring technique must be simple and user friendly as well as being both cost and process effective.

Enabling Sensor Technologies

Developments in microelectronics, fiber optics, and optical techniques (near IR, far IR, and laser analysis and spectroscopy) over the past decade have been significant. Today, with miniaturized microelectronic sensors, it is possible to measure pressure, temperature, flow, acceleration, humidity, chemical composition, and cure condition (charge flow transistor) to extremely high accuracies. Spurring the development of these devices have been military and aerospace applications which are just coming to fruition. This same technology can be applied in selected areas of materials process automation. The potential of microelectronic sensor technology is clearly demonstrated by the fact that accuracies achieved with many of the latest generation devices approach levels, heretofore, attainable only with laboratory standards. More importantly, these new sensors are so cost effective that many throw-away applications have been developed. Similar advantages are also achieved with fiber optic and optical sensors. The most promising fiber optic sensors are completely electrically passive at the measurement location, thereby permitting operation in extremely hostile environments with high immunity from electrical interference. The fundamental limitation of many of these devices is determined only by the materials properties of the optical conduit. A further advantage in many applications is that the fiber conduit can be buried or embedded internally in the environment to be measured such as in a composite material. Small fiber size provides still further advantages. Today, temperature, chemistry and composition, strain and deformation, fluid level and flow, foam and bubble detectors, and acoustic and ultrasonic sensors are available in a multitude of optical configurations. As with microelectronic sensors a host of these devices have become highly developed for military and aerospace applications. Lastly, a revolution is also occurring in optical measuring techniques for gas composition, species concentration, and temperature measurements. Most promising of these techniques are coherent antistokes Raman spectroscopy (CARS), laser induced fluorescence and Raman scattering. Developments in this field have been significant from a practical application standpoint. For example, CARS measurements in the past five years have moved from the laboratory into the field with portable systems now being employed to measure jet engine exhaust gas temperature profiles.

A general recommendation is that more emphasis needs to be placed on the new sensor technologies available today. Specific applications of these established sensing and measuring techniques are required rather than a significant number of new inventions. The basic advanced sensing tools are available. It is a question of applying these tools to advanced automation requirements. Only through a direct dialogue between the sensor development engineer and the materials processing engineer can this be achieved.

Areas To Be Addressed

Metals and Semiconductors: The problems deemed most important are temperature distributions in the melt, location and shape of the liquid/solid interface, flow distributions, and the chemistry and effluent gas composition. The most promising approaches to receive first consideration should be acoustics and optical techniques such as CARS, laser induced fluorescence and Raman scattering. The questions of fluid flow distributions in metals and semiconductors remain an open issue.

Mechanical Properties and Grain Size: The most promising approach in this area appears to be ultrasonics.

Nucleation--Wetting--Film Growth Thickness: Most exciting was the IBM report at the Forum on their most recent work with the scanning tunneling microscope (STM). This is a technology, the potential of which remains yet to be fully realized.

Dislocation Density--Point Defects: No approach has been identified.

Crystal Growth and Electroplating: New techniques on fluid flow analysis being developed at MIT appear to hold promise for further advances in this area.

Thickness--Metal Coatings: A host of approaches appear to offer potential in this area including acoustics, x-ray backscattering and electrostatics.

Finally, one area noteworthy of consideration was the whole question of machine monitoring as it applies to process control. This again raises the initial question of the importance of process modeling to develop the most cost effective, practical approach to materials process automation.

Summary

Viewed as the key requirement for achieving significant advances in the automated materials processing arena is the necessity to break the "business as usual" syndrome between U.S. industry, academia, and government. From the results of just this Forum, it is clear that significant progress can be made. The first ingredient is a suitable forum for technical discussion of problems and potential solutions. Secondly, a focused effort is required with a true partnership relationship between industry, academia, and government to establish priorities and objectives. Lastly, a highly cooperative venture with regard to funds, people, and facilities is then required to achieve success on a national scale.

WORKSHOP REPORT ON SENSOR METHODOLOGIES: DIMENSIONAL METROLOGY

E. Clayton Teague
National Bureau of Standards

There is a broad range of dimensional metrology applications in advanced materials processing within the industries related to conventional structural materials and material removal processes such as machining, ceramics processing, and semiconductor processing. Scales of measurement range from nanometers to tens of meters; environments range from superb laboratory conditions of the semiconductor class 10 and class 1 clean rooms to the hostile manufacturing conditions of a steel rolling mill; times allowed for a measurement range from the micro and milliseconds for an adaptive control sensor to the static times required for a precise determination of the dimensions of a mold for composite materials aerospace components. Participants in this session were asked to select from this broad range of applications those areas of dimensional metrology which they saw as being most important and generic for national needs. Some of the questions addressed and conclusions reached by the participants follows:

1. What are examples of important national needs for dimensionally-based measurements to achieve adaptive control of process parameters?

Four general areas were highlighted by the discussions of this topic. (1) A great need to explore and evaluate new systems or other techniques, which would enable one to achieve an appropriate balance between the large quantities of information, which can now be obtained with modern sensor and computer technology and that relatively small amount of digested information which is needed for controlling processes. (2) Dimensional measurements in support of adaptive control of other quantities. An example of this need is that of determining the thickness of steel plates so that time measurements can be used to deduce the temperature profile within the plates via the equation, $t = D/v_{avg}$, where D = plate thickness, v_{avg} = average speed of ultrasound propagation, and t = total propagational time through the plate. In turn, one has $v_{avg} = 1/D \int_0^D v(z)dz$. (3) A need for fast and remote measurements of part displacements and part dimensions was also highlighted in all ranges of dimensional measurements from small to large scale. (4) Several participants from the semiconductor industry strongly expressed the opinion that a major need of this industry's processing facilities was to achieve mechanical manipulation without introducing particulate contamination into the processing environment.

2. What are examples of important national needs for dimensionally-based measurements to achieve adaptive control of part properties?

While the group discussed very briefly the needs of other industries, such as the metal-cutting industries, the major need identified by the group here was in small dimensional measurements for the semiconductor industry. Here the need is for profiling, i.e., obtaining z(x) or z(x,y), for features whose dimensions are small compared to visible light wavelengths. In this dimensional range, there are now no proven techniques available.

3. What are examples of important national needs for dimensionally-based measurements to provide process diagnostics?

Here, the needs of the semiconductor industries seemed most pressing. As the dimensions of features and device elements have dropped below 1.0 micrometer, the need to control particulates in the process environment and in all materials used in the fabrication processes has become critically important for the industry to obtain reasonable yields. For particles with diameters less than 1.0 micrometer, many new phenomena concerning their behavior have been observed. Another requirement is for a reliable means to calibrate instrumentation. The recent availability of a series of polystyrene sphere standards from the NBS Office of Standard Reference Materials was noted. Sphere diameters now available are 0.3, 1.0, 3.0, and 10.0 micrometers.

4. What are some possible technical solutions?

Suggestions from the group were: modulated scanning laser systems, holography, phase-conjugate optics, adaptive optics, active optics, acoustic and laser ranging, combined nonlinear and active optics, techniques which rely upon differential information, i.e., those sensitive to anomalies and defects, the scanning tunneling microscope, scanning optical microscopies relying upon sensitivity to depth of focus, interferometry, etc.

5. What work is needed to develop and apply the new methods in the near future?

(1) Adapt and adjust available and new sensors to be compatible with industrial environments. (2) Develop new techniques which enable very high-accuracy time-interval measurements to improve capabilities of ranging and pulse caliper-type dimensional measurements. (3) Adapt measurement approaches to select desired information and incorporate as much preprocessing of incoming raw data as possible. (4) A question was raised by semiconductor industry representatives as to whether there was any way to eliminate small (less than 1.0 micrometer) particles from the processing materials and environment. Maybe one will just have to deal with or overcome their presence.

A significant portion of the group's discussions centered on the question: Are there issues of National policy or practice which overshadow these technical questions? The following are some of the issues raised in a very lively discussion of this question.

1. Inappropriate competitiveness among associated industries prevents cooperative efforts to attack very real and key problems. The present cooperative program among the steel and aluminum companies for surface defect measurement offered many the hope that U.S. industry could overcome this competitiveness under the right circumstances.

2. Competition and lack of coordination among government agencies both in terms of efforts which are funded externally and undertaken internally.

3. Lack of critical mass in equipment manufacturers for much of the new measurement instrumentation and related process equipment. Particular examples given were manufacturers of clean rooms, submicrometer particle counters, and adaptive control sensors and associated software.

4. Instability of support for subcontractors and suppliers. All members of the group were pleased with and in support of the apparent trend toward more long-term contracts being initiated by both government and private industry.

5. Our National political culture creates fragmentation, adversarial approaches to implementation of new technologies and to solving problems in ongoing technologies, and to overly short-term foci for industrial, governmental and, often, even university efforts.

6. Solutions to many of our technical problems could be in establishing a strong focal point to direct national action. The group, however, did not reach a consensus about whether this focus should more properly lie with government, industry, or university.

7. The conflict between the industrial proprietary interest and the need for universities to have freedom to publish research results continues to create much resistance from industry to fund cooperative centers at universities.

8. Many members of the group said that each industry should follow the example of the steel and aluminum industries and identify their own specific needs which were most pressing and industry wide.

9. The negative impacts of export control was of great concern to many group members.

WORKSHOP REPORT ON SENSOR METHODOLOGIES: NDE FOR MATERIALS CHARACTERIZATION

Bernhard R. Tittmann
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Summary

After the presentation of a prepared statement by B. R. Tittmann of the critical issues for in-process sensing, the Workshop selected five generic sensor concepts with as much commonality as possible for the processes discussed for the following materials: electronic, optical, metallic, ceramic, polymeric, basic and composite materials. The generic process parameters selected were (1) 3-D temperature profile, (2) shape of solid/liquid interface, (3) microstructure of primary and secondary phases, (4) rheology (viscosity, shear rate dependence), and (5) macro-residual stress. See Table I. Next, a 2-D matrix was developed specifying the detailed sensor methodology, corresponding to the process parameters selected. The issues considered were the sensing device, the corresponding measurement technique, the data inversion algorithm, the current status (pay-off in two-five years), and future needs for field application (pay-off in ten years). Time permitted treatment of only the first four sensor technologies. See Table II. A general conclusion emerging from these considerations was that each sensor methodology should make use of more than one device for a particular process parameter so that the concept of a "multi-component sensor" methodology was developed. The integration of several techniques into one sensor methodology requires an interdisciplinary approach. This conclusion logically led to consideration of more interdisciplinary graduate training at universities and the need for a deeper interaction between universities and industry. Two examples of current approaches cited toward these issues were the Ames Center for NDE and the Johns Hopkins University Center for NDE. The conclusions were (1) the importance of recognizing new techniques in NDE, and (2) the need for large DoD programs and the involvement of universities, government laboratories and industrial research laboratories in an integrated, multidisciplinary fashion.

TABLE I: MATERIAL PROCESS STEPS AND GENERIC PROCESS PARAMETERS

PROCESS PARAMETER	MATERIALS PROCESS STEPS						
	ELECTRONIC	OPTICAL	METALLIC	CERAMIC	POLYMERIC	BASIC	COMPOSITE
TEMPERATURE PROFILE 2-D/3-D	SEMICONDUCTOR CRYSTAL GROWTH	MIRROR COATINGS	INGOTS CASTINGS HEAT TREATMENT WELDING	CERAMIC SINTERING	THERMAL SETTING	STEEL PROCESSING	GR/EPOXY CURING OF VARIABLE THICKNESS
SOLID LIQUID INTERFACE SHAPE	CZOCHRALSKI SEMICONDUCTOR BOULE GROWTH		INGOTS CASTINGS WELDING	CONSOLIDATION IN EXTRUSION PROCESS	EXTRUSION OF THERMOPLASTICS	STEEL PROCESSING	AUTOCLAVE CURING OF LARGE COMPOSITES
MICROSTRUCTURE • PRIMARY PHASES • SECONDARY PHASES	CZOCHRALSKI CVD (TWINNING INCLUSIONS, DISLOCATION DENSITY)	CHEMICAL VAPOR DEPOSITION (BUBBLES, INCLUSIONS)	GRAIN SIZE IN CASTINGS (POROSITY INCLUSIONS) 2-PHASE ALLOYS	CONSOLIDATION (HOMOGENEITY, VOID PHASE, ORGANICS)	POLYMERIZATION (GLASS TRANSIT Tg) SOLID PROPELLANTS HIGH EXPLOSIVES	CEMENT HARDENING (POROSITY)	SHORT FIBER COMPOSITES (VOLUME FRACTION, ORIENTATION) INTERFACE BONDING
RHEOLOGY • VISCOSITY • SHEAR RATE DEPENDANCE	MELT VISCOSITY FLOW PROPERTIES		POWDER METALLURGY	SLURRIES (VISCOSITY, SHEAR RATE DEPENDENCE)	PREPREG AGEING INJECTION MOLDING FLOW BEHAVIOR	CEMENT HARDENING	GR/EPOXY CURING (VISCOSITY MINIMUM DETECTION)

TABLE II: GENERIC PROCESS PARAMETERS AND CORRESPONDING SENSOR METHODOLOGY

PROCESS PARAMETER	SENSOR METHODOLOGY: SENSOR DEVICE — TRANSMITTER	SENSOR DEVICE — RECEIVER	SENSOR MEASUREMENT	SENSOR DATA INVERSION	SENSOR CURRENT STATUS (2-5 YEAR PAYOFF)	FUTURE NEEDS FOR FIELD APPLICATION
TEMPERATURE PROFILE 2-D 3-D	• LASER ULTRASONICS • EMAT	• EMAT (METALS) • OPTICAL (NON METALS) • LASER DOPPLER (ROUGH SURFACE	VELOCITY DEPENDENCE ON TEMPERATURE	VELOCITY RAY MODEL	SIMPLE GEOMETRIES HOMOGENEOUS ISOTROPIC MATERIALS	COMPLEX GEOMETRIES COMPLEX MATERIAL PROPERTIES
	INFRARED (IR) THERMAL RADIATION	IR HIGH TEMPERATURE FIBER OPTICS	INTERPRETATION OF IMAGES	NO AUTOMATED INTERPRETATION	FIELD DEVICES IN PLACE NOW	EXPERT SYSTEM INTERPRETATION
SOLID LIQUID INTERFACE SHAPE	• LASER ULTRASONICS • X-RAY TOMOGRAPHY • MAGNETIC FLUX • EMAT	• LASER ULTRASONICS • EMAT • PIEZOELECTRIC	• BACKSCATTER • FREQUENCY DEPENDENCE OF ULTRASONIC BEAM	RAY ANALYSIS	SOME LABORATORY MEASUREMENTS UNDER IDEAL CONDITIONS	TREATMENT OF VARIABLE REFRACTIVE NATURE OF TRANSITION ZONE 2-D INFO
MICROSTRUCTURE • PRIMARY PHASES • SECONDARY PHASES	• LASER ULTRASONICS • RADIOGRAPHY • THERMAL WAVES • EDDY CURRENT • NMR IMAGING	• LASER ULTRASONICS • ACOUSTIC EMISSION	• ULTRASONIC ATTENUATION • IMAGES • THERMAL COND. σ • ELECTRICAL COND. σ	• SCATTERING THEORY • INTERPRETATION OF IMAGES	FORWARD PROBLEM SOLVED AND VERIFIED IN THE LABORATORY	INVERSE ALGORITHMS NEEDED
RHEOLOGY • VISCOSITY • SHEAR RATE DEPENDANCE	ULTRASONIC TECHNIQUES • SHEAR WAVES • LONGITUDINAL WAVES • DIELECTRIC TECHNIQ...		• SHEAR REFLECTIVITY • ATTENUATION • REAL AND IMAGINARY PART OF COMPLEX DIELECTRIC CONSTANT	QUESTIONS OF UNIQUENESS	DEMONSTRATION IN RESEARCH AUTOCLAVE AT 200 C	ADVANCED COMPOSITES NEED HIGHER TEMPERATURE

WORKSHOP REPORT ON SENSOR METHODOLOGIES: SURFACE PROPERTIES

L. Duane Dunlap
Aluminum Company of America

The discussion was directed primarily towards real-time, in-line measurement of surface properties of various materials during the manufacturing process.

The discussion was divided into two principal categories: (1) the detection, processing, and classification of surface defects; (2) the measurement of surface characteristics critical to process control. In each category, interest was expressed solely for non-contacting forms of measurement.

The work presently being done by Westinghouse and sponsored by the AISI for the consortium of steel and aluminum companies was, to our knowledge, the most advanced effort to date in detecting and classifying surface defects. Successful detection of surface defects at speeds approaching 5000 FPM has been accomplished with some success; however, great amounts of work remain to learn how to rapidly process large quantities of data for real-time feedback. Additionally, considerable effort remains in the development of algorithms and material standards for defect classification. The AISI program was considered exemplary and did not need government support to continue. Other industries should note the success of this program and possibly develop similar programs.

Most of our discussion time was directed towards measurement of surface characteristics. Out of these discussions came the need to provide accurate, real-time, non-contacting measurement of the following:

- temperature
- flatness and residual stress
- surface roughness (topography)
- thin film thickness
- surface chemistry

The ensuing discussion developed around the question "Why can't we make these measurements more accurately today?" We answered this question by stating our lack of understanding of the many surface parameters and their interrelationships and knew little of the effect upon sensor performance.

Stated differently, most industries have devoted large amounts of time and money towards greater understanding of surface properties to improve the salability of their product. However, substantially less effort has been devoted towards the understanding of the interaction of physical phenomena with the surface from a sensory standpoint. Rapid growth in the need for highly automated manufacturing facilities and the corresponding need for non-contacting sensors have combined to create escalating requirements for this knowledge.

To improve the accuracy and functionality of remote sensors, our recommendation to COMAT would be--to actively promote programs that increase fundamental understanding of critical surface parameters and rally key universities, technical societies, and industries around this effort. Mathematical models relating variables such as electromagnetic reflectivity, surface roughness and topography, emissivity, etc., are essential to the development and deployment of remote sensors. To our knowledge, no universities and very few industries have active programs in this area. We concluded our discussion by stating that much could be gained from the collaborative efforts of universities, industries, and government and felt this avenue should be diligently pursued.

WORKSHOP REPORT ON SENSOR METHODOLOGIES: ADHESION AND INTERFACES

Haydn N. G. Wadley
National Bureau of Standards

1. What adhesion and interface properties should be measured?

The work to separate an interface less the energy of the two surfaces is a measure of interface adhesion. The adhesion and physical and chemical properties of interfaces need to be measured together with the characterization of phases and defects that may be present in the interface region. These measurements ideally should be capable of being made on a single interface (e.g., weld or adhesive bond), distributed interfaces (e.g., matrix-reinforcement interfaces in composites, grain boundaries and second phase-matrix interfaces in metals), and spatially delocalized interfaces (e.g., liquid/solid interface of alloys with broad "mushy" zones).

2. Are adhesion and interfaces important during materials processing? If so, what systems are most important? How are they presently measured?

Adhesion and interface properties are vital components in determining the performance of a material. It is essential that sensors be developed for their measurement during materials processing. Reinforcement-matrix interface and adhesive bond strength are two very important systems where sensors are needed. Others include solidification interface and grain boundaries (for the control of reversible temper embrittlement in steels for example). Very few techniques exist today for these measurements and none are in the form of process control sensors.

3. What physical phenomena might be available to form the basis of sensor measurement methodologies?

For in situ sensors, any radiation that penetrates a material or is naturally emitted (e.g., acoustic emission) may be the basis of a measurement technique. For example, ultrasound can be used to observe quantities such as modulus, density, and temperature (at low frequencies). At higher frequencies scattering from grains and elastic inhomogenieties promises nondestructive microstructure characterization. Similar applications can be found with electromagnetic radiation. These include x-rays, dielectric measurements, NMR, eddy currents, etc. A premium is to be attached to techniques that provide spatially resolved information via tomography, synthetic aperture, etc.

4. What is the present status of sensor R&D in (a) universities, (b) industry, and (c) government?

University research is scattered and disjointed. Industry has several problem-specific programs. Government is cooperating in several industry programs, notably those associated with steel industry sensor needs.

5. What actions are to be recommended?

More interaction between universities, government labs, and industry are to be encouraged. Generic sensor needs should be identified and addressed through cooperative programs. A single company may find a sensor development uneconomic, but a joint research effort with several companies sharing costs would spread the risk and promote the adoption of automated materials processing throughout the industries' infrastructure. This is a development that will be pivotal in the increasingly intensive competition of the international marketplace.

6. What do we understand by adhesion and interfaces?

Adhesion - A bulk quantity related to the work required to separate an interface. . . . can only be directly measured by a destructive test.

Interfaces - Regions separating materials with different physical and chemical properties.
Examples: Liquid - solid interface
Ceramic - polymer interface
Ceramic - metal interface

7. Are adhesion and interface properties important during (and after) materials processing?

Yes! But we do not have models that relate specific interface properties to bulk behavior (both statically and during extended periods of use).

8. What systems are important?

Composites - Metal matrix composites promise an aerospace revolution; solidification; adhesive bonds.

9. In priority order, what are the sensor needs?

We really do not know the answer yet! However, things of obvious importance are: (a) adhesion - physical mapping of surface condition, contamination, curing (molecular properties), adhesive thickness, porosity, and disbonds and (b) interfaces - topology, temperature distribution, modulus (bulk and local), and residual stress. Numerous indirect measurements will be required with a premium on localized response methodologies, e.g., tomography, synthetic aperture, embedded sensors.

10. What physical phenomena might form basis of sensor measurement methodologies?

Fluorescent dyes, dielectric properties, and shear modulus to follow epoxy cure for adhesion and composites; acoustic emission to characterize proof testing for adhesion; interface elastic waves to characterize interfaces; three-dimensional mapping of internal friction to characterize interfaces; embedded fiber optics for optically integrating interfaces; ultrasonic scattering to probe interfaces; and NMR, x-ray (3-D) to characterize internal structure.

11. What is present status of R&D in (a) universities, (b) industry, and (c) government?

Large, profitable industries are addressing some of their own sensor needs --application driven. Need to involve university--student training issue.

Problem - few generic sensors identified; needs are fragmented.

Solution - cooperative research; AISI a model for this.

12. What actions are recommended?

Urgent need for sensors as tools to measure key variables in research studies of processing--structure--property relations. Workshops need to be convened for in-depth assessments of multidisciplinary issues associated with adhesion and interfaces. Scientists and engineers must collaborate more strongly.

Conclusion

Models do not exist for the relationships between interface properties (including adhesion) and the bulk properties/performance characteristics of components. Thus, it is not clear what must be measured in some systems (particulate, polymer matrix composites).

APPENDIX B

SUMMARY OF CONSENSUS VIEWS

SUMMARY OF CONSENSUS VIEWS: INDUSTRY

Marvin S. Pittler
IBM - T. J. Watson Research Center

The papers and discussions in this Forum demonstrate a diversity of sensing techniques that can be significant in improving productivity and product quality across a range of industries. Sensors are an integral part of process learning, and progressive yield and quality improvement that is essential to the vitality of our competitive industries. The key role of sensors and measurement is to provide rapid feedback to the process on the important parameters influencing yield and quality. For example, in production of memory devices a primary factor in remaining competitive is yield improvement, which is driven by the rapid sensing and eliminating of yield detractors.

Overall, I see an increasing need for industry to apply measurement science to the continuing improvement of processing in specific areas of manufacturing. Competitive pressures will not allow otherwise.

In parallel, I recognize the need for advances in measurement science that provide the underpinnings for new sensors and measurement techniques. University research in the area can be coupled to the more significant opportunities by means of increased awareness of problems facing industry segments. These opportunities go beyond flaw detection, NDE, and sensor transducers to include contamination detection, surface measurement, electrical characterization metrology, and functional properties of materials.

My Specific Observations on This Forum

1. Sensor and measurement requirements should be established by industry, e.g., steel, electronics, chemicals, etc. The quality and defect detection requirements for each are different, and the skills and specific technologies involved are often unique. In addition, the role of measurements in process and quality improvement are different in the various industries.

2. More emphasis is needed on the use of specific measurements to improve the process and on the appropriate trade-offs for sensor requirements. The aim is to simplify the process and improve design margins for manufacturability such that many sensors and measurements become less critical. Tool design and materials selection are a part of the sensor technology.

3. Sensors are used in several fundamentally different ways, each with characteristic requirements:

   a) Process development and modeling.
   b) Prevention and learning (predictability).
   c) Process control and learning.
   d) Detect and prevent the escape of defects.

4. The measurement system should be established and incorporated as part of product development as well as manufacturing.

5. To be effective, the measurement system will include real-time data handling, data reduction and analysis for daily decision making.

Topics and Directions For Future Forums

1. Technology transfer and the role of manufacturing/development.

2. The role of government, universities, and industry in advancing the sciences and technologies that will improve the competitive posture of U.S. industry.

SUMMARY OF CONSENSUS VIEWS: UNIVERSITY

Gordon S. Kino
Stanford University

We have heard from Marvin Pittler the industrial point of view on the problems of introducing manufacturing science to industry. We have similar problems in the university environment. We have been trying to do something about manufacturing technology at Stanford and have been urged by industry to do more. We believe manufacturing science is important, and we would like to contribute more in this field.

After looking at the subject, we do not feel that it is an academic discipline as such. Rather, it would seem more suitable, in the academic environment, to break the subject of manufacturing science into critical components such as sensors, artificial intelligence, and techniques for making semiconductors. This is the direction we are taking at Stanford.

We need, in this country, a critical mass to do a really good job in many of the fields that would contribute to manufacturing science, for example, sensors. This requires cooperation between different industrial firms at the basic science level. Unlike Japan, we have not been doing very much about approaching the problem in this way. There are countless examples, sensors being a good one, where the United States is probably spending far more than Japan on research. There is, however, needless duplication and lack of direction of the overall effort. Therefore, we are not getting as much from our total investment as the Japanese do when they decide to concentrate on a particular problem. We must learn how to set up mechanisms to cooperate with each other better.

There are already some examples of cooperation between between universities and industry; the NSF engineering centers are a recent initiative in this direction. Stanford has its own version of this kind of cooperation, the Center for Integrated Systems. I will describe some aspects of this Center here because it is a good example, and it is the one with which I am most familiar.

The basic idea was to set up a sophisticated sub-micron integrated circuits laboratory with mixed industrial and government financing. As part of this agreement with industry, industrial people come to Stanford for a year or more to work with students, faculty, and each other. The program is at an early stage, but even after a relatively short experience, we find that not only do industrial people interact well with students and faculty, but also their strong interactions with each other have been extremely stimulating for them. The presence of industrial people on campus has been very stimulating for us; some teach us how to organize our research better, others bring know-how, yet others generate new ideas for research. We feel that they learn a different point view at Stanford, particularly with regard to looking at problems more fundamentally. One of the things that we hope we will learn from industrial interaction is how to make small numbers of integrated circuits efficiently. The payoff would be large.

One of the fears expressed by industry about university/industrial cooperation is the possibility of having new developments become more easily available to our competitors. We believe that close cooperation between industries and universities will make the transfer of technology much faster than by dissemination of information in technical papers. In a technical paper, the best results are published, but many of the difficulties are not apparent. It takes much longer to transfer information by the typical publication route, because of the time required for publication and because of the limited amount of information in the paper, than it does when people work together. Therefore, we do not believe that this is a major problem as far as basic research ideas are concerned. It is one way industry can learn to turn research ideas into a product much more quickly than they do at present. The Japanese are much faster than we. Their time from research to production appears to be half that of large-size American industrial firms.

Overall, university/industrial cooperation will help this process. The stimulation and contact with industry is very good for our students, and it is good for industry because it makes students interested in their problems. Along with cooperation in research on sensors and the broader field of manufacturing technology, more publicity is needed. We hope to get bright students for these important problems. We, therefore, need to find ways to excite their interest in the field, and we need long-term financing. Then we can set up the educational programs on sensors and plan for the long term. We should avoid, if we can, turning the spigot on and off when interest in a subject waxes and wanes. We need to develop methodologies and long-term basic research which leads to something useful and gives time to transfer the technology to industry.

I would now like to discuss the subject of sensors in more detail. In an ideal world, sensors would be used during the manufacturing process to give direct feedback so that the process could be controlled directly in real time. We are not yet ready to do that with most manufacturing processes, for the processes are usually not well enough understood to control them, and we do not have adequate sensors or real-time processing available. If we are going to aim at this kind of manufacturing, we will need to redesign some of the processes with feedback in mind, as well as the fact that sensors will be part of it.

We need to take a more conservative approach initially, and not try to run before we can walk. Thus, we need to develop the sensors and apply them to the problems we can solve. For example, we need sensors for metrology in machining processes and for semiconductors. For machining processes, it should be possible, fairly soon, to use the sensors in a feedback system to control the machining processes. It is not easy, however, to try to incorporate sensors at the early stages of the manufacturing process where the temperatures are high and conditions often highly corrosive. Rather, as we develop methodologies on the simpler problems, we should be able to learn from our first results and use them to predict what will happen at the next stage of the process or be able to determine what went wrong at the earlier stages. Thus, in time, as we gain more experience, we will learn how to make sensors for the more difficult stages of the process, which are themselves not yet fully understood.

As far as sensor development is concerned, there are some common problems where a broad thrust may help. Metrology is one of them, as are temperature measurements, but there are other problems which are not universal. For example, the electronics industry needs to measure electronic properties. Other industries' problems are quite different. Where there is a common theme, such as in metrology, we may well be able to develop generic systems which can be made smaller or bigger, as needed. In other cases, we will have to develop appropriate sensors for much more specialized systems.

In conclusion, the development of sensors is fundamental to manufacturing science. We need better quality control; a fundamental approach is to put feedback into the manufacturing process. There is much to be done, and the subject is very important. We must, therefore, put a major development effort into the field.

SUMMARY OF CONSENSUS VIEWS: GOVERNMENT

H. Thomas Yolken
National Bureau of Standards

It is clear from the two days of discussions at this Forum that there is a substantial opportunity in the area of automated materials processing. We have an opportunity to make gains in our industrial competitiveness in areas involving the manufacture of advanced materials by taking advantage of our knowledge base and national lead in materials science and engineering.

Advanced materials utilize complex microstructures to yield the desired advanced properties and these complex microstructures are proving difficult to process. This is so, because process models--the relationships between process variables and resulting microstructure--are not well understood, and adequate process control schemes are often lacking. Products made from advanced materials, therefore, can lack reproducibility and this, in turn, requires that products be overdesigned. Lack of reproducibility, thereby, denies us access to the full potential of advanced materials. In addition, current production of advanced materials is often labor intensive and requires costly post-processing inspection. Reject rates can be substantial with the rejects typically not identified until late in the production process, causing considerable loss.

In order to compete and take advantage of our knowledge-base lead, the U.S. needs to undertake research to develop the scientific understanding for improving process models and to develop automation techniques for advanced materials processing. These automation techniques will be based on advanced on-line process parameter and nondestructive evaluation sensors and expert systems.

I am directing my principal remarks today to sensors and leaving the topic of process models and expert systems for the next workshop. The sensor problems and opportunities that we have reviewed at this workshop are somewhat difficult to categorize. There are several classes of sensor applications that appear to have some generic relationship with each other. A generic class of sensors to characterize and control the production of small powders (metals, ceramics, and polymers) is one example. Another example of generic sensor applications involves determining internal temperature pro files in solids and liquids and determining liquid/solid interface positions in two-phase systems. This is a tractable task for homogeneous mate rials with simple geometry and isotropic properties. However, as with many nondestructive evaluation type sensor problems, the task grows more difficult with complex geometries and inhomogeneous or anisotropic materials.

There is also a wide variety of sensor problems that are applications driven and narrow in scope. These need to be worked on, one at a time, with direct coupling to the specific problem.

For many of the problems that were discussed, there is a basis for a solution that is apparent in some existing sensor techniques. Adapting the measurement technique to the problem offers a reasonable chance for success. But there are some important problems where the basis for a relevant sensor is not yet understood. An outstanding example is the problem of bond strength or adhesion as exemplified in joining and composites.

In order to take advantage of the opportunities that are apparent in sensors for automated materials processing, our R&D efforts must be focused and reach a critical size. I believe that several of the Federal agencies, such as the Defense Advanced Research Projects Agency, the National Science Foundation, the National Bureau of Standards, and the Department of Energy, could take the initiative and select a few model programs to jointly support. These programs would benefit from university, industry, and Federal laboratory involvement. Industry could likewise take the initiative and pursue cooperative research on sensors. In order to promote the formation of cooperative R&D efforts, an industrial organization such as the Industrial Research Institute could serve a valuable and impartial role in facilitating the formation of cooperative R&D efforts for sensors. Providing help in the formation of cooperative R&D efforts on sensors could also provide a model for other cooperative R&D efforts.

APPENDIX C

SUMMARY OF CONCLUSIONS RAISED AT LAST SESSION

SUMMARY OF CONCLUSIONS RAISED AT THE LAST SESSION

by

Charles F. Larson, Executive Director
Industrial Research Institute

CONCLUSIONS

- A credibility gap is apparent between scientists and engineers in the field of sensors.
- A need exists for the transfer of sensor technology from one industry to another.
- Industry interaction and cooperation in the field of sensors is required.
- Equipment manufacturers lack the critical mass needed in sensor technology.
- Support of subcontractors is unstable.
- Short-term focus.
- Focal point needed for national action.
- Strong industry/university collaboration needed.
- Sensors urgently needed as tools for measuring key factors in manufacturing.
- Application of new technology and concept lacking in the U.S.
- A valuable aspect of the conference was learning of the availability of new sensors, thus avoiding the necessity of developing custom sensors for one's own use.

SUMMARIES

Industry Perspective

- It is necessary to divide measurement requirements according to industry because metrology is vastly different in different industries.
- More emphasis is needed on the design of a process to accommodate appropriate sensors.
- Measurement systems must be incorporated into original design for manufacturing.
- Manufacturing should be raised to a level of higher importance in a company's strategic plan.
- Effective collaboration needed among industry, universities, and government.

Academic Perspective

- Agree with necessity to divide sensor requirements by industry.
- Need to make better use of resources through cooperation.
- Interaction through university cooperative programs is fruitful.
- Need stimulation of contact with industry.
- Need more publicity on problems in sensor technology to attract bright students to the field.

Government Perspective

- Cooperative research in this field needs to be examined carefully.
- A champion is needed to provide thrust in creating cooperative mechanisms.
- Need to stimulate application of new technology to commercial products by rewarding persons to do it.
- Discussion groups during workshops needed more time for deliberation.

APPENDIX D

WORKSHOP PROGRAM

CONFERENCE PROGRAM

Sunday, December 15

7:00 p.m. Early registration - mixer with complimentary hors d'oeuvres and cash bar
Sheraton

Monday, December 16

8:00 a.m. Registration
University of California at Santa Barbara
Campus 1104
Coffee/juice/danish

I **OVERVIEW**
Session Chairman:
Robert H. Mehrabian
Dean, College of Engineering
University of California/Santa Barbara

8:30 **Welcome/Introduction**
Announcement Details

8:45 **Conference Goals**
H. Thomas Yolken
Chief, Office of Nondestructive Evaluation
National Bureau of Standards

9:00 **Challenges and Opportunities for Automated Materials Processing**
Robert Mehrabian
Dean, College of Engineering
University of California/Santa Barbara

9:45 Break

II **SENSOR NEEDS FOR PROCESSING TECHNOLOGIES**
Session Chairman:
Peter Bridenbaugh
Vice President, Research & Development
Aluminum Company of America

10:05 **Electronic Materials**
Augustus F. Witt
Department of Materials Science & Engr.
Massachusetts Institute of Technology

10:25 Optical Materials
George H. Sigel
Director, Center for Fiber Optic Materials Research
Rutgers University

10:45 **Metals**
Robert A. Sprague
Manager, Engineering Materials Tech. Labs.
General Electric
Martin Blackburn
Pratt & Whitney, Engineering

11:05 Ceramics
Roy Rice
Director of Materials Research
W. R. Grace and Company

11:25 Polymers
Frank E. Karasz
Professor, Department of Polymer Science and Engineering
University of Massachusetts

11:45 Basic Materials
James R. Cook
Principal Research Engineer
ARMCO Research

12:05 Composites
Bruce Kay
Manager of Composites Design & Develop.
Sikorsky Aircraft

12:25 Lunch

III SIMULTANEOUS WORKSHOPS ON SENSOR NEEDS FOR PROCESSING TECHNOLOGIES

1:30 Electronic Materials
Discussion Leader: L. Eric Cross
Director, Materials Research Laboratory
Pennsylvania State University

Optical Materials
Discussion Leader: Jack McChesney
Bell Telephone Laboratories

Metals
Discussion Leader: Phillip A. Parrish
Program Mgr., Materials Sciences Div.
Defense Advanced Research Projects Agency

Ceramics
Discussion Leader: Fred Lange
Rockwell International Research Center

Polymers
Discussion Leader: Witold Brostow
Professor, Dept. of Materials Engineering
Drexel University

Basic Materials
Discussion Leader: William Dennis
Vice President, Manufacturing & Technology
American Iron & Steel Institute

Composites
Discussion Leader: Richard S. Williams
United Technologies Research Center

3:30 Break

IV WORKSHOP REPORTS ON SENSOR NEEDS
Session Chairman:
Benjamin Wilcox
Asst. Director, Materials Sciences Division
Defense Advanced Research Projects Agency

3:50 Current and future sensor needs
Sensor priorities
Commonalities between processes
Does industry need cooperative mechanisms to meet these needs?
Recommended actions

5:00 Adjourn

6:00 Cash bar and hors d'oeuvres

6:30 Dinner (Faculty Club)

Tuesday, December 16

V SENSOR METHODOLOGIES FOR PROCESS CONTROL
Session Chairman:
Peter Cannon
Vice President, Research & Development
Rockwell International Science Center

8:30 Process Parameters, Temperature, Pressure, Mass Flow, Gas Phase Composition, etc.
Peter F. McCrea
Vice President, Research, Design, Instrumentation, D&E
Foxboro Company

8:50 Dimensional Metrology
H. Kumar Wickramasinghe
IBM - T.J. Watson Research Center

9:10 NDE for Materials Characterization,
Ultrasonic and Eddy Current Techniques
R. Bruce Thompson
Ames Laboratory/Iowa State University

9:30 NDE for Materials Characterization,
Acoustic Emission, Thermal, Optical, and
Other Techniques
Robert E. Green, Jr.
Director, Center for Nondestructive Evaluation
Johns Hopkins University

9:50 NDE for Materials Characterization,
Real-time X-ray Radiography
Robert A. Buchanan
Manager, NDT Technology Laboratory
Lockheed Missiles and Space Co.

10:10 Break

10:30 Surface Properties
Homer B. James
Program Manager
Westinghouse R&D Center

10:50 Adhesion and Interfaces
Edmund G. Henneke, II
Dept. of Engineering Science & Mechanics
Virginia Polytechnic Inst. & State Univ.

VI SIMULTANEOUS WORKSHOPS ON SENSOR METHODOLOGIES

11:10 Process Parameters
Discussion Leader: Robert H. Bullis
Program Director, Sensor Technology
United Technologies Research Center

Dimensional Metrology
Discussion Leader: E. Clayton Teague
Leader, Micro & Optical Metrology Group
National Bureau of Standards

NDE for Materials Characterization
Discussion Leader: Bernhard R. Tittmann
Manager, Materials Characterization
Rockwell International Science Center

Surface Properties
Discussion Leader: L. Duane Dunlap
Manager, Equipment Development Division
Aluminum Company of America

Adhesion and Interfaces
Discussion Leader: Haydn N. G. Wadley
Group Leader, Nondestructive Characterization
National Bureau of Standards

12:10 Lunch

1:15 **Session VI Continues**

2:15 Break

VII WORKSHOP REPORTS ON SENSOR METHODOLOGIES
Session Chairman:
Donald O. Thompson
Principal Scientist
Ames Lab./Iowa State University

2:35 **Status of R&D on sensors**
Status of university education in sensor field
Does industry need cooperative mechanisms?
Recommended actions

VIII SUMMARY OF CONSENSUS VIEWS
Session Chairman:
Jerome H. Schlensker
Vice Pres., Mfg., Planning & Support
Cummins Engine Co., Inc.

3:35 **Panel Discussion by Representatives from:**
Industry
Marvin S. Pittler
Vice President, Manufacturing Research
IBM - T.J. Watson Research Center

University
Gordon S. Kino
Professor of Electrical Engineering
Stanford University

Government
H. Thomas Yolken
Chief, Office of Nondestructive Eval.
National Bureau of Standards

4:20 Adjourn

APPENDIX E

WORKSHOP ATTENDEES

List of Workshop Attendees

A National Forum on the Future of Automated
Materials Processing in U.S. Industry
...The Role of Sensors...

December 16-17, 1986
University of California at Santa Barbara

Ligh Abts, Rexnord
Laszlo Adler, Ohio State University
Ralph P. I. Adler, Army Materials Technology Laboratory
Willialm F. Adler, General Research Corporation
Frederick X. Albrecht, Eastman Kodak Company
George A. Alers, Magnasonics
Marion D. Barker, Lockheed Missiles & Space Co.
George Birnbaum, National Bureau of Standards
Martin J. Blackburn, Pratt & Whitney
Kenneth C. Blaisdell, Johns Hopkins University
Shelly Bodnick, Exxon Research & Engineering Co.
Richard C. Born, Rexnord
Peter R. Bridenbaugh, Aluminum Company of America
Witold Brostow, Drexel University
Robert A. Buchanan, Lockheed Missiles & Space Co.
Robert H. Bullis, United Technologies Research Center
David L. Burk, Allegheny Ludlum Steel Corporation
Robert D. Burnham, Xerox
Heinz H. Busta, Gould Cardiovascular Products Division
Robert J. Calcaterra, Adolph Coors Company
Peter Cannon, Rockwell International Science Center
Kenneth Chen, Whirlpool Corporation
James R. Cook, Armco Inc.
Eric Cross, Pennsylvania State University
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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This is the proceedings of the workshop "A National Forum on the Future of Automated Materials Processing in U.S. Industry - The Role of Sensors." This is the first of two workshops to be sponsored by the Industrial Research Institute and the White House Office of Science and Technology Policy, Committee on Materials Working Group on Automation of Materials Processing. The second workshop will address the other two key components required for automated materials processing, process models and artificial intelligence coupled with computer integration of the system. The objective of these workshops is to identify and assess important issues affecting the competitive position of U.S. industry related to its ability to automate production processes for basic and advanced materials and to develop approaches for improved capability through cooperative R&D and associated efforts.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

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