Sensors for Intelligent Processing of Materials

Haydn N.G. Wadley

INTRODUCTION

A sensor is a device that detects and measures some physical/chemical quantity and outputs it as an electrical signal. A common example is a piezoelectric transducer which detects a mechanical vibration and outputs an electrical signal which can be used to characterize the vibration. Numerous types of sensors are routinely used to measure quantities such as temperature, pressure, flow rate, pH, etc. For example, sensors are extensively applied in automobiles to control pollution, enhance fuel economy, implement anti-lock braking, activate safety measures during collisions, etc. In chemical engineering plants, sensors control processes. Emerging devices promise to expand sensor use in the chemical industry by allowing measurement of flow rates, particle distributions, and so on. Sensors are also enhancing robotic vision and tactile sensitivity.

The entire field of sensors is presently poised for major advances as a result of recent developments in non-evasive sensing technologies; increasingly powerful, less expensive computing capabilities; and emerging artificial intelligence techniques such as pattern recognition/expert systems. Technologies, such as high intensity lasers, fiber optics, nonlinear optical materials, semiconductors, ultrasonics, eddy currents, etc., have progressed rapidly in recent years. They now offer the potential to noninvasively probe the previously inaccessible changes and reactions of complex dynamically evolving systems. Expert systems/pattern recognition promise new control strategies capable of exploiting sensor outputs, predictive process models, and computer accessible databases to achieve radical improvements in many existing manufacturing processes. These potentials are becoming available at a time of increased concern about international industrial competition.

One of the most exciting areas of sensor development is the control of materials processing. Here, at the juncture of the emerging advanced sensors—the predictive process models and the expert systems—the possibility of an intelligent materials processing strategy appears. In this scenario, sensors continuously measure key process and microstructure variables. Predictive process models use these measurements to determine the current status of the processing operation. Finally, control systems utilize the sensor outputs, predicted process conditions and the process models to adjust process variables, maintaining control within predetermined bounds and to feedback/forward through the process chain accommodating transient effects. The availability of inexpensive powerful computing and networking could then allow each step of a processing sequence to be integrated into a hierarchical factory automation scheme. Then, every step could be optimally phased for maximum productivity and product flexibility.

Thus, the principles of robotics and automation that are revolutionizing discrete parts manufacture and assembly can now be applied to materials processing. These new control strategies may also allow commercialization of new processes that produce advanced materials via routes which may have been considered too unstable for practical implementation in the past.

For materials processing, a premium is placed on those sensor methodologies capable of non-invasively probing the interior of generally high temperature opaque bodies surrounded by an aggressive environment. New laser techniques are finding particularly innovative application for this because of their remote sensing capability. The laser generation of ultrasound is one example. However, for this remote capability to be fully exploited, sensitive, robust remote receivers of ultrasound, laser interferometers for example, must be developed. These developments still appear to be many years away. For the interim, electromagnetic acoustic transducers (EMATs) show great promise as ultrasonic receivers in sensor systems because of their noncontact method of operation, potential ruggedness, and relatively low cost. They may become the permanent receiver of choice for sensors where sensitivity is more important than a remote capability.

To implement new process control strategies, including intelligent processing of materials, advanced sensors are required to nonintrusively evaluate process and microstructure variables. This overview examines the nature and characteristics of emerging sensors based upon nondestructive evaluation technologies and other new measurement methods. Also featured are various aspects of sensors emerging from recent R&D efforts and the trade-offs between sensor needs and process understanding. In general, sophisticated sensors can reduce the dependence upon quantitative process models for process control and vice-versa.

Figure 1. Schematic diagram of continuous strand caster.
Sensor Needs for Continuous Casting

**Process Flow Chart**

- **Ladle**
  - Solid Inclusion
  - Composition
- **Tundish**
  - Solid Inclusion
  - Oxygen Sensor
  - Solid Inclusion
  - Continuous Temp.
- **Solidification**
  - Microstructure
  - Discontinuity
  - Temperature Distribution
  - Liquid-Solid Interface Position
  - Temperature Distribution
  - Discontinuities
- **Bend/Cut**
- **Inspect/Ship**
  - Surface Discontinuity

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**SENSOR NEEDS FOR MATERIALS PROCESSING**

The specific needs for sensors depend on the level of process understanding (availability of predictive process models) and the degree to which the initial conditions of the process may vary (due to raw materials variability, for example).

This can be exemplified by considering a model process, continuous metal casting, shown schematically in Figure 1. In the process, metal is poured from a ladle into a distributor or tundish from which it enters a water-cooled mold where surface solidification begins. By the time the metal leaves the mold, a solidified "skin," several centimeters thick, physically constrains the molten material within. Further direct water cooling removes heat through the "skin" and facilitates complete solidification.

Figure 2 shows a partial list of sensor needs for casting steel. Included are sensors to assure melt cleanliness, determine oxygen content, liquid temperature, internal temperature distribution during and after solidification, etc. The performance required of these sensors depends upon the level of process understanding, the degree to which initial conditions can be maintained, and the intended role of the sensor in the control loop, i.e., direct process control or real time quality control.

**Process Control Sensors**

Sensors that measure quantities such as internal temperature distribution, composition, and microstructure are intended for direct process control. Recently, sophisticated process models have begun identifying sensor needs and enhancing the value of sensor data.

The contribution of process understanding to sensors used for direct process control can be illustrated by considering internal tempering sensing. An internal temperature distribution sensor, if available, would be the key sensor used to control caster speed. Presently, casters run at conservative speeds based upon previous knowledge and solidification model predictions, eliminating the incidence of breakouts. If the internal temperature could be mapped at various cross sectional locations in the solidifying region, the solidus and liquidus isotherm positions (and thus the thickness, both of the solidified skin and "mushy" zone) would be known with the gradients in the solid skin. This would require the determination of temperature to within 15°C with better than 5 mm spatial resolution—a considerable feat for any conceivable sensor.

However, very little use of available process understanding has been made in determining these needs. For instance, the cooling of a hot body is a well-understood process. Heat is removed from the surface at a rate determined by the heat transfer coefficient. The temperature gradients within are then dictated by the physics of thermal diffusion. Sophisticated process models embodying this understanding are available for alloy continuous casters and, in principle, are capable of determining the required internal temperature distributions alone. In practice, however, they are of only limited usefulness because the boundary (heat transfer) conditions are not reproducible and are not well defined, resulting in significant errors in...
isotherm location which causes enough uncertainty in the solid shell thickness to prohibit control.

A hybrid sensor that measures the effective heat transfer rates and couples this to a predictive heat flow model may be the optimal solution to this particular sensor need—especially if the initial temperature conditions are well defined, as when melt temperature is continuously monitored. Such a sensor could form the basis for casting speed control that would significantly enhance caster productivity.

**Quality Control Sensors**

A second class of sensor needs are concerned with ensuring, on-line, quality rather than the direct control of the process. Examples would be the real-time detection of internal discontinuities (for example, cracks, porosity and inclusions in metal alloys or dislocations in semiconductor single crystals). The impetus for this stems from the substantial savings that accrue if fault conditions during processing are detected as they happen rather than at the completion of processing or after shipping, as is occasionally the case.

It is thus important to apply knowledge of where and how the defects occur as a basis for identifying sensor needs. For example, thin strip metal alloys destined for drawing/forming can suffer from the presence of subsurface inclusions. These materials rupture during subsequent manufacturing operations due to inclusion nucleated ductile fracture. While inspecting materials prior to shipment could solve the problem, it might be better to detect them in process. The most obvious point to detect inclusions is in the melt prior to solidification. However, special mold fluxes are utilized during casting to remove these inclusions. Their presence in the melt does not necessarily indicate their presence in the solid. The efficiency of the melt flux in removing these inclusions is the key quantity to determine. One way for doing this is by monitoring the inclusion content shortly after solidification. Process understanding could simplify the sensor design for this by identifying the region where inclusions are most likely to be deposited during solidification (quarter on center line for example), thus limiting the location of the region to be probed by the sensor.

**EMERGING SENSOR METHODOLOGIES**

Without better sensor systems, there can be no real advancement in process control, and without the advancements in process control, there can be no significant advancement in the processes themselves. The hostile environments in which sensors are used, the limited time available for measurements, and the need to avoid interference with the process itself all introduce constraints upon practical sensor systems that ultimately result in less than ideal data. Relationships between sensing mechanisms/measurement and microstructure have not yet fully emerged. Thus, there exists a need to develop better models and algorithms of sensor-materials interaction, both for the analysis of collected data and to reduce the data into a useful form. The interplay between these factors can best be appreciated by examining some emerging sensors.

**Surface Defect Sensor for Strip Metal**

The surface quality of steel and aluminum sheet is very important. Optical reflectivity has been used successfully for surface inspection of slowly moving sheet. Real time determination of surface quality prior to coiling processed strip is extremely difficult because of the very high strip speeds (up to two thousand meters per minute) and the wide variety of imperfections that may occur. Furthermore, these imperfections must first be distinguished from benign blemishes and then characterized. In one development effort, the American Iron and Steel Institute (AISI) is coordinating a collaborative program funded by a consortium of steel and aluminum producers to develop a suitable sensor. Research is being conducted by the Westinghouse Corporation and is based upon a coherent light scattering approach, shown schematically in Figure 3. An intense collimated laser beam is rapidly scanned across the width of the moving metal strip. Detector arrays are positioned across the strip width at angles predetermined to optimize the defect scattering (signal) to background (noise) ratio. The voltage outputs of each detector are continuously digitized and digitally processed. Pattern recognition and other techniques are used to detect and characterize defects. This information can be stored for each coil so that quality is numerically cataloged.

The combination of high strip speeds and many different types of imperfections combine to pose major problems in high speed data acquisition and digital signal analysis. For example, to fully inspect a two-meter wide strip...
moving at 30 meters per second (5500 feet per minute) with a 1 mm laser spot size, requires state-of-the-art eight-bit digitization rates of 200 MHz. Digital signal analysis of these very dense data streams is too slow even with today's most advanced computers, and preprocessing of the data is therefore essential. Only then can pattern recognition and other AI software be used to characterize the defects from the condensed data. Software alone cannot solve this aspect of the problem, however. Data preprocessing may be too slow or may filter out desirable signal traits. Creation of sensor measurement methodologies that simplify preprocessing and defect characterization algorithms is a critical factor in the successful development of this sensor.

**Surface Modification Sensor**

Localized surface hardening through martensitic transformation of iron base alloys is being increasingly used for enhancing resistance to wear and fatigue. Directed high energy beams (laser or electron) with energy densities of $10^3$ to $10^4$ W cm$^{-2}$ are swept over the surface, causing transient local heating into the austenite phase field and subsequent rapid cooling back to ambient. This results in a surface hardened layer. The depth and hardness of the surface modification must be determined, preferably during the process so that the scan rate/beam shape can be adjusted to produce an optimal condition.

Velocity measurement of ultrasonic surface waves as a function of frequency is one method being explored to characterize depth varying properties. The amplitude of surface (Rayleigh) waves decays rapidly with distance below the surface on which they propagate. Furthermore, the rate of decay is scaled by the wavelength. Short wavelength waves decay rapidly beneath the surface and therefore propagate at a velocity controlled by surface elastic properties. Long wavelength waves decay more slowly with depth, and thus propagate at a velocity controlled by a combination of surface and substrate elastic properties.

Thus, as the wavelength of a probe wave increases, a critical wavelength is reached where the wavespeed starts to change as the wave begins to sample unmodified materials beneath the depth of transformation (between 0.8-1.0 mm in Figure 5). Furthermore, the difference in the long and short wavelength velocity is a good indicator of the hardness of the surface modified layer itself. The emergence of noncontact electromagnetic acoustic transducers promises a means of nonintrusively making these measurements during processing. Better inverse algorithms for determining layer properties from wavelength velocity relations are, however, needed to improve the accuracy of the approach.

**Molten Metal Inclusion Sensor**

The elastic constants and density of inclusions in molten alloys are different from those of the molten alloy itself. They thus have different acoustic impedances which scatter incoming elastic waves, especially as their wavelength approaches the inclusion dimensions. This scattering can be measured and provides a convenient means for both detecting and gauging the number of inclusions present in a molten alloy and (by varying ultrasonic frequency) estimating their size.

Mansfield et al. have developed a sensor based upon this principle for aluminum alloys. The sensor consists of two flat parallel titanium plates that are fully immersed in the liquid metal. An ultrasonic pulse is applied to one plate, and the reverberations between the plates are monitored. When many inclusions are present, energy is scattered out of the forward propagating ultrasonic pulse, and the reverberations rapidly ringdown. By measuring the attenuation at a fixed frequency (typically in the range 5-10 MHz), it has been possible to assess the melt cleanliness.

This ultrasonic approach is probably equally valid for steels and superalloys containing inclusions and/or ceramic particles. Although the

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**Figure 7.** Dependence of longitudinal ultrasonic velocity upon temperature for AISI 304 stainless steel (after Reference 13).

**Figure 8.** Schematic diagram of ultrasonic interstitial temperature sensor utilizing laser generation/EMAT detection.
higher steelmaking temperatures pose a significant practical problem, ultrasonic generation/detection can be achieved given the availability of laser generated ultrasound and noncontact high temperature electromagnetic acoustic transducers.

**Molten Metal Chemical Analysis Sensor**

Basic metals production could be significantly improved by a sensor capable of real time chemical analysis of molten metals and alloys. In an AISI collaborative program, Kim et al. at Lehigh University are exploring an in-situ transient emission spectroscopy approach.

In this approach, an intense laser pulse is used to evaporate and electronically excite a small representative sample of the alloy within the melt, Figure 6. This plasma subsequently decays back to the ground state by the same photon emission processes traditionally utilized for emission spectroscopy analysis. The electromagnetic emission is collected and transported to a high speed spectrum analyzer where the intensity of individual lines in the emission spectrum are used to infer the chemical composition on a millisecond time scale.

A key aspect of this approach concerns the degree to which the composition of the ablated material in the plasma truly represents the bulk composition. It obviously should not be heavily contaminated by slag, but a more insidious problem exists when the vapor is selectively enriched by the more volatile elements present in the sample. Approaches using very brief, very high intensity laser pulses and careful calibration show promise in overcoming this problem.

**Internal Temperature Distribution Sensor**

An internal temperature sensor is needed to image the temperature field within solidifying alloys so that solidification processing may be better controlled. One approach is to probe a body's interior with a penetrating radiation and attempt to measure a physical property that is temperature dependent. Ultrasound is a potential probe radiation, and ultrasonic velocity is a measurable physical quantity which is strongly temperature dependent. For many metals, the velocity decreases with increasing temperature at a rate of between 0.5-1.0 ms⁻¹°C⁻¹, Figure 7. Velocity changes due to temperature gradients are usually much greater than those due to microstructure variations and internal stresses.

At the National Bureau of Standards, one approach to internal temperature sensing involves using an intense laser pulse to generate ultrasonic signals, and a high temperature noncontact EMAT as a receiver, Figure 8. The time-of-flight (TOF) of the ultrasonic pulses along paths of known length allows measurement of the average velocity along the path. Using reference data such as that shown in Figure 7, this average velocity may be directly converted to average internal temperature.

If independent TOF measurements for propagation along different ray paths are made, an internal temperature image may be reconstructed using tomographic algorithms. However, it turns out to be better to use a least squares inversion procedure that facilitates incorporation of a priori information for the reconstruction. The information is a thermal model which exactly predicts the internal temperature distribution when the initial and boundary conditions are known. In practice, the TOF measurements are used to determine boundary conditions by comparison against predicted TOF values based upon successive interactions of the temperature model. Figure 9 shows the good level of agreement between such an ultrasonic (curve) and embedded thermocouple (points) measurement of temperature for a cooling 304 stainless steel sample.

Internal temperature sensors are needed for many other processes such as high speed aluminum extrusion, single crystal turbine blade growth, and the growth of single crystal semiconductors. While the ultrasonic approach under development for steel may provide a sensor development route for these other processes, the different process constraints may dictate an alternative methodology. For example, the high local stresses associated with laser generation of ultrasound do not disturb the solidification of steel but may cause highly deleterious dislocation generation during semiconductor single crystal growth. For aluminum extrusion, the ultrasonic approach has poor measurement precision due to the small part dimensions (a few millimeters thick). The use of multifrequency eddy current measurements of electrical conductivity is being explored as a sensor methodology for aluminum extrusion. This approach could perhaps also be used to profile temperatures during semiconductor single crystal growth because it induces very small stresses, and semiconductors exhibit strong temperature-conductivity relations.

**References**

5. Y. Kim, private communication.
11. Y. Kim, private communication.

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