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Sensors for Monitoring the Quality of Molten Aluminum During Casting

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The quality of a cast product depends directly on the quality of the molten metal from which the product is cast. Techniques for determining melt quality often require the laboratory analysis of samples taken from the molten metal. In addition to reducing processing efficiency, delays associated with this laboratory analysis can lead to uncertainties because the melt conditions can change during holding at high temperatures. On-line monitoring of the melt quality provides more rapid feedback for improved process control. In this article, techniques for monitoring the important aspects of melt quality, specifically chemical composition, gas content, and inclusion content, are reviewed.

Keywords chemical sensors, gas content, hydrogen, inclusions, molten aluminum

1. Introduction

Increasing demands for improved quality control and process efficiency of industrial processes require the development of on-line sensors to provide feedback for process optimization. In the case of cast products, the cleanliness of the molten metal must be maintained to control the properties of, and to prevent defect formation in, the resulting castings. The three primary aspects of melt quality are chemical composition, gas content, and inclusion content (Ref 1-3).

Control of alloy properties requires the control of the alloy composition. For example, Na or Sr is used to control the eutectic microstructure and, thus, the properties of castings (Ref 4-7). These and other alloying additions can affect the castability (Ref 8) and mechanical properties (Ref 9) of cast products. Thus, loss of alloying additions due to preferential vaporization, or oxidation, while holding the melt at high temperatures can lead to degradation of the mechanical properties. In addition, Na and other alkali elements can lead to embrittlement or hot-cracking (Ref 10), and unwanted levels of these elements can be introduced during the Hall-Heroult process (Ref 11). However, like Na, Li is sometimes deliberately added as an alloying element, particularly for producing low-density alloys (Ref 12). Thus, controlling the amount of these elements in the desired range is critical to controlling the properties of aluminum castings. In addition to controlling the alloy composition prior to casting, monitoring the chemical composition is important in other processes, such as the removal of Mg during the reclamation of aluminum scrap (Ref 13).

The most important gas in processing aluminum is hydrogen, which is introduced when molten aluminum reacts with moisture in the surrounding atmosphere to form aluminum oxide and hydrogen. The solubility of hydrogen in solid aluminum is much lower than that in liquid aluminum, so dissolved hydrogen is evolved during solidification and can lead to porosity in the resulting casting (Ref 14, 15). Thus, the production of quality castings requires the removal of hydrogen from the molten aluminum by degassing processes (Ref 15-22). Efficient and effective control of these processes requires on-line measurement of the hydrogen content in the melt.

Inclusions can be incorporated in molten aluminum due to oxidation, erosion of refractories, or fluxing, and can lead to a variety of detrimental effects, such as degradation of the mechanical properties, appearance, and corrosion resistance (Ref 2, 22-24). Thus, the production of quality castings requires the development of processes for the removal of inclusions (Ref 2), and the control of these removal processes requires on-line monitoring of the sizes and amounts of inclusions in the molten metal.

There is clearly a need for monitoring the quality of molten aluminum, and the objective of this article is to review techniques for on-line monitoring of the chemical composition, gas content, and inclusion levels in molten aluminum.

2. Alloy Composition

The Office of Industrial Technologies of the U.S. Department of Energy has worked with the aluminum industry to identify key research and development needs for the industry (Ref 25, 26). The most recent Aluminum Industry Technology Roadmap, published in February 2003 (Ref 25), includes real-time chemical analysis among the seven issues identified as top priorities in the areas of melting, solidification, and recycling.

2.1 Laser-Induced Breakdown Spectroscopy

One promising technology for monitoring the chemical composition of alloys is laser-induced breakdown spectroscopy (LIBS) (Ref 26, 27). Laser-induced breakdown spectroscopy has been used for determining the composition of metal (Ref 27-32) and ceramic materials (Ref 33-35), including applications such as separating metal scrap (Ref 32) and analyzing historical objects (e.g., archeological artifacts [Ref 33] and daguerreotypes [Ref 36]). Laser-induced breakdown spectros-

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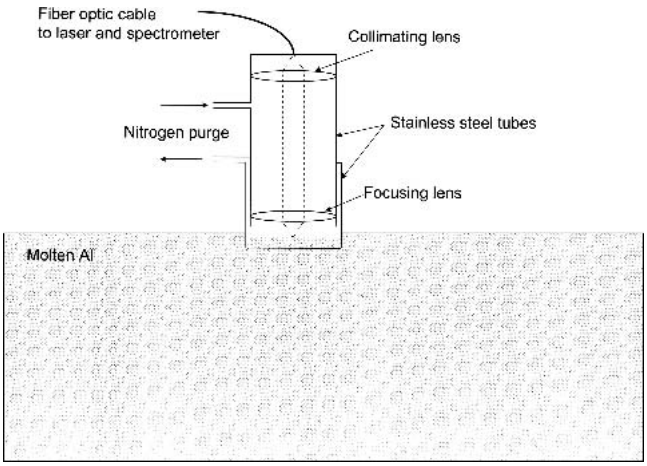

Fig. 1 Schematic of LIBS for the chemical analysis of molten metals (Ref 50)

copy has been used to determine the amounts of common alloying elements, such as Mg, Cu, and Si, in aluminum (Ref 37-41). Although most commonly used at low temperature, LIBS has been adapted for high-temperature applications, such as monitoring radioactive glass melts (Ref 35) and welding processes (Ref 42-45). These developments have led to the use of LIBS for measuring the composition of molten metals (Ref 46-52), including molten aluminum (Ref 26, 27, 49-52).

A schematic of a LIBS sensor for measuring the composition of a molten metal is shown in Fig. 1. The probe is connected to the analytical system with a fiberoptic cable that is used to transmit a pulsed laser, which is focused on the metal surface to create a plasma for chemical analysis. The surface of the molten metal must be situated in the focal plane of the laser, so the position of the molten metal surface is adjusted with the internal gas pressure by controlling the flow rate of the nitrogen purge gas. The spectral distribution of the radiation in the plasma generated by the laser is analyzed through the fiberoptic cable using a beam splitter.

Some of the issues in the use of LIBS include ensuring that the probe is sampling metal below the slag layer and that emission from the slag or slag particles is not affecting the measurement. In addition, the signal for a particular element is affected by the volatility of that element in response to excitation by the laser pulse, so these differences must be accounted for in the analysis.

2.2 Galvanic Cell-Based Chemical Sensors

Another approach to monitoring the chemical composition of molten aluminum is through the use of chemical sensors based on galvanic cells (Ref 53-58). These sensors are much simpler than a LIBS system, but each sensor is designed to measure a particular element, so multiple sensors are required for the simultaneous detection of multiple elements.

In galvanic cell-based chemical sensors, two electrodes (reference and sensing) are separated by an electrolyte, such that a voltage is generated across the electrolyte. The magnitude of the voltage is proportional to the ratio of the logarithms of the concentrations of the element to be detected at the two electrodes. Thus, the measurement of this voltage (typically hundreds of millivolts) for a known reference potential can be used to determine the concentration at the sensing electrode.

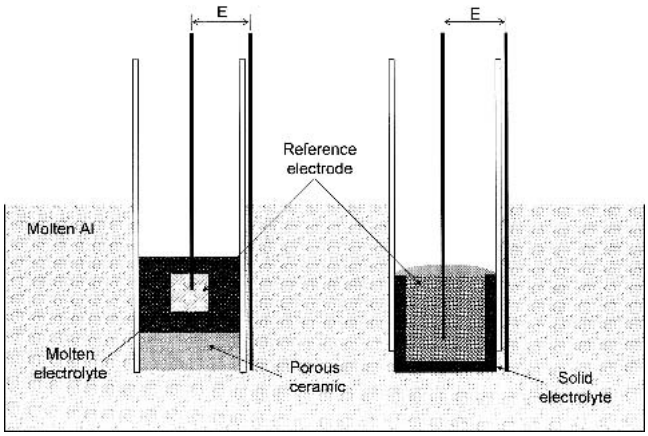

Fig. 2 Schematics of liquid and solid electrolyte-based chemical sensors (Ref 70). E is the cell voltage.

Solid and liquid electrolytes have been used in chemical sensors for use in molten aluminum. Molten electrolytes typically have faster response times compared with solid electrolytes. However, as shown in Fig. 2, the sensor design is slightly more complicated, because a porous ceramic is required to contain the molten electrolyte. In addition, during long operating times, some of the electrolyte can leach into the alloy, which can lead to erroneous readings. Sensors based on solid electrolytes are typically simpler and more durable compared with those based on molten electrolytes. However, the conductivities of solid electrolytes are typically lower than those of liquid electrolytes, so improved durability is sometimes achieved at the expense of a slower response time.

Molten electrolytes, specifically magnesium chloride-based electrolytes, have been used in the development of Mg sensors for molten aluminum (Ref 59-65). Solid electrolytes, including β-alumina (Ref 66, 67) and magnesium fluoride (Ref 68-70), have also been used for Mg sensors, but additional work is needed to avoid Na interference with β-alumina and to develop cost-effective fabrication techniques for fluoride electrolytes. Molten chloride-based sensors are more fully developed than solid electrolyte-based sensors and are likely to be commercially available first.

One of the most widely studied electrolytes is β-alumina, which is a sodium-aluminum oxide compound with a planar structure allowing for high ionic mobility. Although β-alumina can be doped with other ions, the most common material is a Na-ion conductor, which is suitable for use in a Na sensor. In addition to being used to monitor Na content (Ref 71-80), β-alumina has also been used for the controlled addition of Na by applying a current across the electrolyte (Ref 75). A Na sensor based on a fluoride electrolyte has also been reported (Ref 81, 82).

Solid electrolyte-based sensors have been developed for detecting several other elements including Sr (Ref 66, 82-84), Li (Ref 67, 76, 78, 85-87), Ca (Ref 66), and P (Ref 88). Electrolyte-based sensors are well-suited for measuring alloying elements, which are more active than the base element, but the detection of less active elements, such as Cu or Si in aluminum, is more difficult.

3. Gas Content

The most commonly used techniques for measuring the hydrogen content in molten metal involves analyzing the hydro-

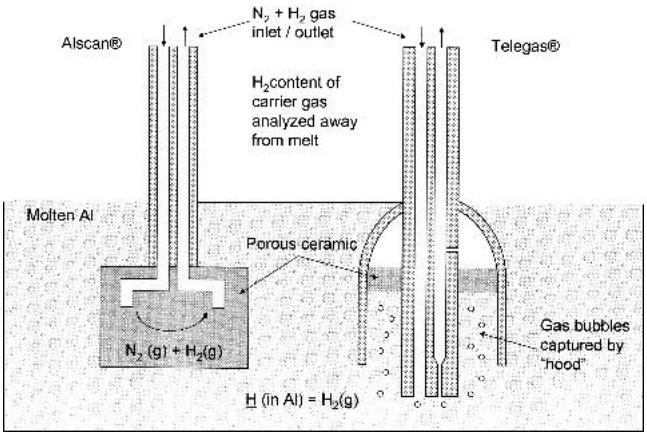

Fig. 3 Schematics of the AlScan and Telegas systems for the measurement of hydrogen content in molten aluminum (Ref 15)

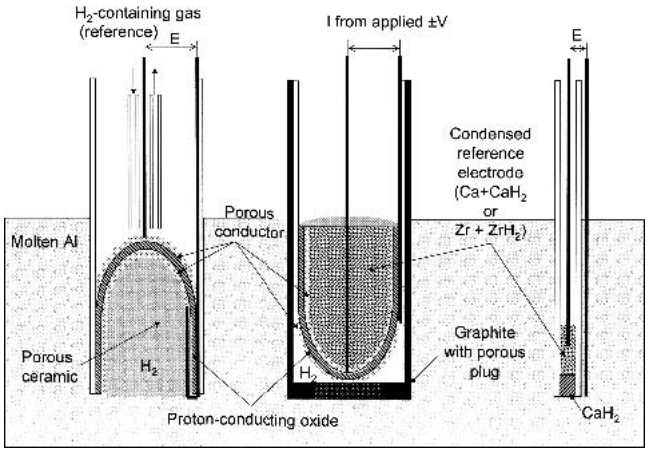

Fig. 4 Schematics of solid electrolyte-based hydrogen sensors (Ref 100, 105-107, 118, 119). E, I, and V are the cell voltage, current, and applied voltage, respectively.

gen content in a sample taken from the melt (Ref 1, 24, 89-91). The sample is heated in a vacuum, or nitrogen gas, and the amount of evolved hydrogen from either the solid or liquid sample is determined. To provide a faster response, techniques have been developed to determine the hydrogen content of the sample while it is solidifying. The most common of these techniques is the reduced pressure test (RPT) in which a sample is taken from the melt and placed directly in a vacuum chamber (Ref 15, 89, 92, 93). The change in pressure during solidification and the amount of porosity in the solidified sample are used to determine the hydrogen content in the melt. A variation on the RPT is the initial bubble test, in which observation of the initiation of bubbling during cooling of the molten sample is used to determine the hydrogen content (Ref 24). Although faster than laboratory tests, a more rapid response would improve process efficiency. More importantly, variable sampling procedures and inconsistent analysis can lead to erroneous results, so improved techniques for hydrogen measurement are needed.

3.1 On-Line Measurements Using a Carrier Gas

One approach to the on-line measurement of the hydrogen content in molten metals is to pass an inert gas (typically, nitrogen) through the melt and then analyze the hydrogen content in the gas (Ref 1, 15, 24, 89, 94-98). Schematics of commercial versions of this type of sensor (AlScan, Bomem, Quebec, QC, Canada, and Telegas, Alcoa, Pittsburgh, PA) are shown in Fig. 3. The nitrogen gas is either bubbled through the melt or passed through a porous ceramic that is in contact with the melt, so that the partial pressure of hydrogen in the gas can equilibrate with the hydrogen dissolved in the molten aluminum according to reaction 1:

$$H(\text{in Al}) = \frac{1}{2} H_2(\text{g}) \qquad \text{(Eq 1)}$$

such that the hydrogen partial pressure in the carrier gas is proportional the amount of dissolved hydrogen to the one-half-power according to Sievert's law.

The outputs of the AlScan and Telegas systems are more precise and less sensitive to operating procedure compared with the RPT test, but the results are generally less reliable compared with those from laboratory analytical techniques. However, the measurements take 10 to 20 min, and thus can be used for on-line process control.

3.2 Solid Electrolyte-Based Hydrogen Sensors

Another approach to measuring hydrogen content in molten aluminum is to use a galvanic cell similar to those described above for determining chemical composition, in which the cell voltage is proportional to the logarithm of the hydrogen content (Ref 99). Schematics of some solid electrolyte-based sensors are shown in Fig. 4. Gee and Fray (Ref 100) showed that a calcium hydride electrolyte with a Ca reference electrode could be used to measure hydrogen content (right side of Fig. 4). However, this system was not developed due to stability problems. The discovery of proton-conducting oxides provided a source of potential electrolytes with improved stability. Hydrogen sensors using the most studied of these proton-conducting oxides, strontium cerate (Ref 101-103), were found to have poor stability in molten aluminum. The proton-conducting oxide that has shown the best performance in molten aluminum is calcium zirconate (Ref 104-116), which is typically doped with indium oxide to increase the ionic defect concentration. Figure 4 (left side) shows a schematic of the calcium zirconate-based hydrogen sensor. There are two differences between this hydrogen sensor and the chemical sensors shown above in Fig. 2. One is that the reference electrode is a gas, which requires tubes for the transport of gas to and from the probe. The other is that the sensing electrode is not in direct contact with the melt. The sensor measures the partial pressure of hydrogen gas in the porous ceramic in contact with the melt.

A proton-conducting electrolyte can also be used to pump hydrogen into or out of the melt by passing a current through the electrolyte (Ref 117). Although this is not an effective method for removing large amounts of hydrogen, it can be used in a hydrogen sensor (the middle of Fig. 3) (Ref 118, 119). In this sensor, a voltage is applied across the electrolyte to pump hydrogen from one electrode to the other. The ratio of the currents in the forward and reverse directions is related to the hydrogen content in the melt. Another important feature of this sensor is that a solid reference electrode is used, which eliminates the need for the transport of a reference gas to and from the probe.

One of the challenges in the electrochemical measurement

of hydrogen is possible interference from oxygen and water. Conductivity measurements (Ref 104) indicate that calcium zirconate may be an oxygen-ion conductor in the very low oxygen partial pressures that are present in molten aluminum. However, oxygen-ion conductors have been shown to respond to hydrogen partial pressure (Ref 120-123), due to the establishment of a mixed potential, so this is not necessarily an insurmountable problem.

4. Inclusions

Two techniques for characterizing inclusions in molten aluminum are the porous disk filtration apparatus and the liquid aluminum inclusion sampler (LAIS), both of which involve passing the molten metal through a filter that collects the inclusions (Ref 1, 2, 23, 89, 124). The weight of the residue is used to determine the number of inclusions. Metallographic analysis of the filled filter can provide information on the sizes and types of inclusions. The prefil footprinter is a derivative of the LAIS technique in which, in addition to the collection of the filtrate, the filtration rate is recorded. The slope and curvature of a plot of the amount of filtrate as a function of time is used to evaluate the number of inclusions. Questions have been raised regarding the reliability of using results from the prefil filtration rate curves (Ref 3, 24), although a subsequent report has suggested that the reliability has been improved with a new crucible (Ref 125).

Chemical analysis has also been used to evaluate inclusion contents, but chemical composition is not always directly related to inclusion content (Ref 2, 23). Another technique for evaluating inclusion content is the K-mold tests (Ref 24, 89). In the K-mold test, a sample with a specific geometry is cast and fractured. The fracture surfaces are examined, and the number of inclusions is recorded.

As with chemical composition and gas content, a technique for on-line determination of the inclusion content would provide information to allow for better control of the processes for removal of inclusions.

4.1 Electromagnetic-Based Inclusion Detection

The electrical properties of inclusions are typically different from those of the molten metal, so electromagnetic probes can provide a means for measuring inclusion content. One such sensor is the liquid metal cleanliness analyzer (LiMCA). The system is derived from the Coulter counter (Ref 126), which is based on a change in the effective resistivity of a fluid upon the incorporation of particles. Specifically, if an electrical current (I) is passed between two electrodes, which are separated by a conducting fluid passing through an orifice with diameter D, the ohmic voltage drop (ΔV) resulting from the change in resistance (ΔR) between the electrodes is related to the size of the particle (d) according to:

$$\Delta V = I \cdot \Delta R = I \cdot \frac{4 \cdot \rho \cdot d^3}{\pi \cdot D^4} \quad \text{(Eq 2)}$$

where ρ is the resistivity (Ref 127). This principle has been used in the development of sensors for measuring the amount and size of inclusion in molten aluminum (Ref 2, 23, 128-142).

As shown in the schematic in Fig. 5, the LiMCA system uses a tube with a small orifice. Metal is forced in and out of this tube (through the orifice) by alternatively evacuating and pressurizing the inside of the tube. As a particle passes through the orifice, which is referred to as the electric sensing zone, a voltage change is measured according to Eq 2. The magnitude of the voltage change can be used to estimate the particle size, and the number of voltage changes can be used to count the number of particles. The duration of the voltage change is related to the transient time, which is related to the size of the particle. Thus, the relationship between the transient time and the magnitude can, in some cases, be used to determine the density of the particle (Ref 132). This analysis can be complicated if the particles are not spherical in shape.

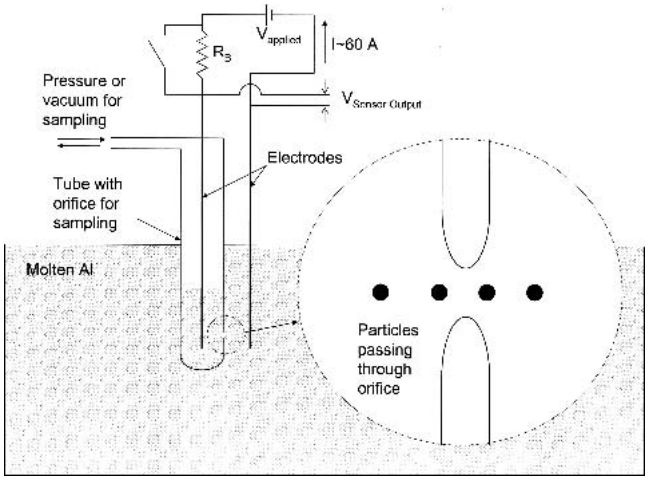

Fig. 5 Schematics of the LiMCA system for the detection of inclusion in molten aluminum (Ref 128, 129, 132-134). R_B, $V_{applied}$, $V_{sensor\ output}$, and I are the resistance, applied voltage, output voltage, and current, respectively.

The detectable particle size depends on the size of the orifice, but particles of 15 to 20 μm can be detected (Ref 133). In addition to strongly affecting the magnitude of the voltage (Eq 2), the size of the orifice must be properly selected to obtain reliable results. Too large an orifice may allow multiple particles to pass through the orifice simultaneously or in close succession, which may be interpreted as a single particle. On the other hand, too small an orifice may restrict particle movement, such that particles may become stuck or block the orifice, and the inclusion level may be underestimated.

Other techniques based on changes in electrical properties have taken advantage of the possibility of measuring electromagnetic properties without direct contact with the molten metal. For example, the measurement of the electromagnetic field induced by flowing current through a coil wrapped around a tube with molten metal has been used to measure inclusions and bubbles in molten Na (Ref 143). The induced electromagnetic field can also generate a force on the particles, and this phenomenon has been used to detect inclusions in molten aluminum (Ref 2, 144). Specifically, an electromagnetic Archimedes force is generated to force the particle to the liquid metal surface, and the particles at the surface are then detected and characterized with an optical imaging system.

4.2 Acoustic-Based Inclusion Detections

Ultrasonic probes have been used to characterize the inclusion content of molten aluminum (Ref 2, 23, 27, 145-157). Two such ultrasonic detection systems are shown in Fig. 6. In one

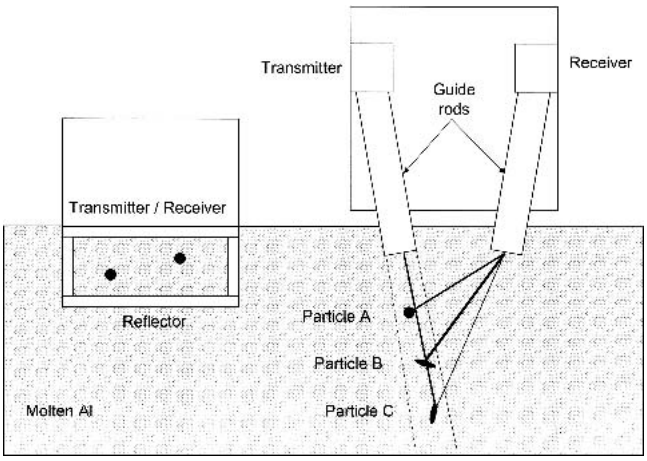

Fig. 6 Schematics of ultrasonic-based inclusion detection systems (Ref 147, 151, 152)

case (Ref 2, 23, 27, 145-148), the ultrasonic wave is transmitted down to a reflector, so that the particles measured are those that pass between the transmitter and the reflector. The other case (Ref 149-157) does not have a reflector, so that particles all the way to the bottom of the crucible can be detected. The former case, with the reflector, samples a smaller volume of metal but produces a simpler and, thus, more easily interpretable signal. The latter case, with more directed ultrasonic waves, monitors the melt to the bottom of the crucible but requires more analysis of the signal to extract the larger amount of useful information.

The particles are detected by increasing the amplification until a signal is measured, so the smaller the particle, the larger the amplification required for detection. The signal generated can be affected by the shape and orientation of the particle. For example, in Fig. 6 the signal generated by particle B would be larger than that generated by particle C, due to the relative orientations to the ultrasonic excitation. There is a time lag between the transmitted and the received signals. This time lag increases with increasing distance from the melt surface, and thus, can be used to determine the vertical position of the particle. The horizontal position of the particles can be determining by focusing ultrasonic signal using waveguides. The development of sensors for use in molten zinc has shown that this spatial resolution, as well as the signal-to-noise ratio, can be improved through improvements in the waveguide materials (Ref 158-162). The number of reflected signals corresponds to the number of particles. Thus, the ultrasonic signal provides information on the size, position, and number of particles.

The minimum size of the particle detected depends on the frequency of the ultrasonic wave. Particles 10 to 15 μm in size have been detected using a 2.25 MHz signal (Ref 153). In addition, large numbers of small particles (i.e., those smaller than the detectable limit) result in an overall attenuation of the signal. Thus, in addition to the characterization of the sizes and distribution of large particles, clouds of small particles, which can also affect casting quality, can be detected (Ref 152).

In addition to particles, ultrasonic waves can be reflected from other interfaces, such as molten-metal/flux or solidified-metal/molten-metal interfaces, and can generate signals. For example, the signal from the crucible bottom, and a similar signal from the flux/molten-metal interface has been used to measure the level of molten aluminum below the cryolite during the reduction of alumina by the Hall-Heroult process (Ref 163). In addition, ultrasonic measurements can be used to monitor metal levels, the position of molten metal fronts, and the properties of liquid-solid mixtures during the thixotropic processing of metals (Ref 164-166).

5. Conclusions

Although improvements in the reliability, sensitivity, and response times of techniques for monitoring the quality of molten metals have improved the quality of cast products, the additional refinement of existing techniques and the development of new techniques can provide further improvements in process control. The integration of monitoring techniques with degassing, filtration, and other processes will allow for the consistent production of high-quality castings.

References

1. F. De Schutter, J. Verwimp, W. Engelen, S. Kuypers, M. Ryckeboer, W. Verberckt, P. Hermans and C. Castelijns, PROCIAS: A Joint Project on Process Control of Aluminium Melts, *Light Metals 1999,* C.E. Eckert, Ed., The Minerals, Metals and Materials Soc., 1999, p 849-854
2. S. Makarov, D. Apelian, and R. Ludwig, Inclusion Removal and Detection in Molten Aluminum: Mechanical, Electromagnetic and Acoustic Techniques, *AFS Trans.,* Vol 107*,* 1999, p 727-735
3. L.A. Godlewski and J.W. Zindel, Capability Study of a Filtration Process to Predict Aluminum Melt Quality, *AFS Trans.,* Vol 109, 2001, p 555-566
4. S.-Z. Lu and A. Hellawell, Modification of Al-Si Alloys: Microstructure, Thermal Analysis, and Mechanisms, *JOM,* Vol 47 (No. 11), 1995, p 38-40
5. I.J. Polmear, *Light Alloys: Metallurgy of the Light Metals,* Edward Arnold, London, UK, 1989, p 153-155
6. J.E. Gruzleski, Aluminum-Silicon Eutectic Modification—Sodium or Strontium? *Production and Electrolysis of Light Metals,* B. Closset, Ed., Pergamon Press, 1989, p 131-141
7. D. Emadi, H. Liu, J.E. Gruzleski, and M. Brouchard, The Effects of Sr-Modification on the Melt Hydrogen Content and the Hydrogen Solubility in the Solid and Liquid Al-Si Alloys, *Light Metals 1996,* W. Hale, Ed., The Metals, Minerals and Materials Society, 1996, p 721-728
8. T.N. Ware, A.K. Dahle, S. Charles, and M.J. Couper, Effect of Sr, Na, Ca and P on the Castability of Foundry Alloy A356.2, *Proc. 2nd Int. Aluminum Casting Technology Symp.,* M. Tiryakioğlu and J. Campbell, Ed., ASM International, 2002, p 159-168
9. E. Carranza-Barraza, M. Castro, M. Herrera-Trejo, and M. Stapleton, Effect of Si, Cu, Mr and Sr Content on the Mechanical Properties of a 319-Type Alloy, *Proc. 2nd Int. Aluminum Casting Technology Symp.,* M. Tiryakioğlu and J. Campbell, Ed., ASM International, 2002, p 223-228
10. F. King, *Aluminium and Its Alloys,* Ellis Horwood Ltd, Chichester, UK, 1987, p 111
11. R.G. Cheney, Potline Operation with Lithium-Modified Bath, *J. Met.,* Vol 35 (No. 12), 1983, p 47-51
12. I.J. Polmear, *Light Alloys: Metallurgy of the Light Metals,* Edward Arnold, London, UK, 1989, p 104-110
13. B.L. Tiwari, Demagging Processes for Aluminum Alloy Scrap, *J. Met.,* Vol 34, 1982, p 54-58
14. S. Shivkumar, L. Wang, and D. Apelian, Molten Metal Processing of Advanced Cast Aluminum Alloys*, JOM,* Vol 43 (No. 1), 1991, p 26-32
15. M.M. Makhlouf, L. Wang, and D. Apelian, *Measurement and Removal of Hydrogen in Aluminum Alloys,* American Foundrymen's Society, 1998
16. G.K. Sigworth, Gas Fluxing of Molten Aluminum: Part I: Hydrogen Removal, *Light Metals 1999,* C.E. Eckert, Ed., The Minerals, Metals and Materials Society, 1999, p 641-648
17. G.K. Sigworth and T.A. Engh, Refining of Liquid Aluminum:

A Review of Important Chemical Factors, *Scand. J. Metall.,* Vol 11, 1982, p 143-149
18. G.K. Sigworth and T.A. Engh, Chemical and Kinetic Factors Related to Hydrogen Removal from Aluminum, *Metall. Trans. B,* Vol 13B, 1982, p 447-460
19. R.A. Rapp, The Closed-Circuit Degassing of Liquid Aluminum Alloys by Argon, *JOM,* Vol 49 (No. 5), 1996, p 16-19
20. R.A. Rapp, The Closed-Circuit Degassing/Fluxing of Liquid Aluminum Alloys by Nitrogen-Chlorine, *JOM,* Vol 49 (No. 5), 1996, p 21-23
21. R.A. Rapp, Degassing of Liquid Aluminum and Other Metals, U.S. Patent 5,917,114, June 29, 1999
22. J. Bildstein and J.M. Hicter, The Development of the Alpur Systems for the In-Line Treatment of Molten Aluminum and Aluminum Alloys, *Light Metals 1985,* H.O. Bohner, Ed., The Minerals, Metals and Materials Society, 1985, p 1209-1223
23. D. Doutre, B. Gariépy, J.P. Martin and G. Dubé, Aluminium Cleanliness Monitoring: Methods and Applications in Process Development and Quality Control, *Light Metals 1985,* H.O. Bohner, Ed., The Minerals, Metals and Materials Society, 1985, p 1179-1195
24. D.P.K. Singh and D.J. Mitchell, Analysis of Metal Quality in a Low Pressure Permanent Mold Foundry, *AFS Trans.,* Vol 109, 2001, p 333-345
25. The Aluminum Association. *Aluminum: Industry Technology Roadmap,* 2003. http://www.oit.doe.gov/aluminum/visions.shtml
26. J. Altdorfer, DOE Follows Roadmap to Al Technologies of the Future, *JOM,* Vol 52 (No. 11), 2000, p 19-25
27. H.N.G. Wadley, Sensors for Intelligent Processing of Materials, *J. Metals,* Vol 38 (No. 10), 1986, p 49-53
28. R. Noll, H. Bette, A. Brysch, M. Kraushaar, I. Mönch, L. Peter, and V. Sturm, Laser-Induced Breakdown Spectrometry: Applications for Production Control and Quality Assurance in the Steel Industry, *Spectrochim. Acta, Part B,* Vol 56, 2001, p 637-649
29. R. Sattmann, V. Sturm, and R. Noll, Laser-Induced Breakdown Spectroscopy of Steel Samples Using Multiple Q-Switch Nd:YAG Laser Pulses, *J. Phys. D: Appl. Phys.,* Vol 28, 1995, p 2181-2187
30. W. Tanimoto and K. Tsunoyama, Method of Laser Emission Spectroscopic Analysis of Steel and Apparatus Therefore, U.S. Patent 4,645,342, Feb 24, 1987
31. M. Potzchke, H.P. Sattler, K. Hohla, and T.R. Loree, Scrap Detector, U.S. Patent 5,042,947, Aug. 27, 1991
32. H.H. Telle, D.C.S. Beddows, G.W. Morris, and O. Samek, Sensitive and Selective Spectrochemical Analysis of Metallic Samples: The Combination of Laser-Induced Breakdown Spectroscopy and Laser-Induced Fluorescence Spectroscopy, *Spectrochim. Acta: Part B,* Vol 56, 2001, p 947-960
33. K. Melessanaki, M. Mateo, S.C. Ferrence, P.P. Betancourt, and D. Anglos, The Application of LIBS for the Analysis of Archaeological Ceramic and Metal Artifacts, *Appl. Surf. Sci.,* Vol 197-198, 2002, p 156-163
34. S.I. Gornushkin, I.B. Gornushkin, J.M. Anzano, B.W. Smith, and J.D. Winefordner, Effective Normalization Technique for Correction of Matrix Effects in Laser-Induced Breakdown Spectroscopy Detection of Magnesium in Powdered Samples, *Appl. Spectrosc.,* Vol 56 (No. 4), 2002, p 433-436
35. J.-I. Yun, R. Klenze, and J.-I. Kim, Laser-Induced Breakdown Spectroscopy for the On-Line Multielement Analysis of Highly Radioactive Glass Melt: Part I. Characterization and Evaluation of the Method, *Appl. Spectrosc.,* Vol 56 (No. 4), 2002, p 437-448
36. D. Anglos, K. Melesanaki, V. Zafiropulos, M.J. Gresalfi, and J.C. Miller, Laser-Induced Breakdown Spectroscopy for the Analysis of 150-Year-Old Daguerrotypes, *Appl. Spectrosc.,* Vol 56 (No. 4), 2002, p 423-431
37. V. Detalle, R. Héon, M. Sabsabi, and L. St.-Onge, An Evaluation of a Commercial Échelle Spectrometer with Intensified Charge-Coupled Device Detector for Materials Analysis by Laser-Induced Plasma Spectroscopy, *Spectrochim. Acta, Part B,* Vol 56, 2001, p 1011-1025
38. L. St.-Onge, M. Sabsabi, and P. Cielo, Analysis Using Laser-Induced Plasma Spectroscopy in Double-Pulse Mode, *Spectrochim. Acta, Part B,* Vol 53, 1998, p 407-415
39. M. Sabsabi and P. Cielo, Quantitative Analysis of Aluminum Alloys by Laser-Induced Breakdown Spectroscopy and Plasma Characterization, *Appl. Spectrosc.,* Vol 49 (No. 4), 1995, p 499-507
40. M. Sabsabi, P. Cielo, S. Boily, and M. Chaker, Laser-Induced Breakdown Spectroscopy on Aluminum Alloy Targets, *Proc. SPIE-Int. Soc. Opt. Eng.,* Vol 2069, 1993, p 191-201
41. B. Német, L. Kozma, L. Paksy, A. Lengyel, and J. Czekkel, Microanlaysis of Iron and Aluminum Alloys by Time-Resolved Laser-Induced Plasma Emission Spectroscopy, *Magyar Kémiai Folyóirat,* Vol 101 (No. 6), 1995, p 224-233 (in Hungarian)
42. S. Palanco, M. Klassen, J. Skupin, K. Hansen, E. Schubert, G. Sepold, and J.J. Laserna, Spectroscopic Diagnostics on CW-Laser Welding Plasmas of Aluminum Alloys, *Spectrochim. Acta, Part B,* Vol 56, 2001, p 651-659
43. B. Boudot, Process and Device for Laser Working with Remote Control, U.S. Patent 5,256,852, Oct 26, 1993
44. M.-S Chou, C.C. Shih, and B.W. Shirk, Method and Apparatus for Monitoring Laser Weld Quality via Plasma Size Measurements, U.S. Patent 5,961,859, Oct 5, 1999
45. M.-S Chou, C.C. Shih, and B.W. Shirk, Method for Monitoring Laser Weld Quality via Plasma Light Intensity Measurements, U.S. Patent 6,060,685, May 9, 2000
46. M. Sabsabi, P. Cielo, and L. St. Onge, Method and Apparatus for Materials Analysis by Enhance Laser Induced Plasma Spectroscopy, U.S. Patent 6,008,897, Dec 28, 1999
47. Y.W. Kim, "Transient Spectroscopic Method and Apparatus for In-Process Analysis of Molten Metal, U.S. Patent 4,986,658, Jan 22, 1991
48. C. Carlhoff, C.-J. Lorenzen, and K.-P. Nick, Method and Apparatus for Optically Coupling an Element Analysis System and a Laser to Liquid Metal in a Melting Vessel, U.S. Patent 4,995,723, Feb 26, 1991
49. T. Eivindson, Method for Direct Chemical Analysis of Molten Metal Using Spectrometer, U.S. Patent 5,644,401, July 1, 1997
50. A.K. Rai, F.Y. Yueh, J.P. Singh, and H. Zhang, High Temperature Fiber Optic Laser-Induced Breakdown Spectroscopy Sensor for Analysis of Molten Alloy Constitutents, *Rev. Sci. Instr.,* Vol 73 (No. 10), 2002, p 3589-3599
51. L. Paksy, B. Német, A. Lengyel, L. Karma, and J. Checked, Production Control of Metal Alloys by Laser Spectroscopy of the Molten Metals: Part 1. Preliminary Investigations, *Spectrochim. Acta, Part B,* Vol 51, 1996, p 279-290
52. L. Paksy, A. Lengel, O. Bánhidi, and J. Czekkel, In situ Analysis of the Composition of Molten Nonferrous Metals by Time-Resolved Laser Induced Breakdown Spectrometry, *Magyar Kémiai Folyóirat,* Vol 106 (No. 5-6), 2000, p 238-246 (in Hungarian)
53. D.J. Fray, The Use of Solid Electrolytes as Sensors for Applications in Molten Metals, *Solid State Ionics,* Vol 86-88, 1996, p 1045-1054
54. D.J. Fray, Possible Uses of Sensors in the Aluminium Industry, *Mater. Sci. Technol.,* Vol 3, 1987, p 61-65
55. D.J. Fray, Developments in On-Line Sensing in Molten Metals Using Solid Electrolytes, *Atb. Metall.,* Vol 3, 1990, p 63-68
56. D. Fray, Solid Electrolytes and the Analysis of Molten Metals, *Chem. Ind. (London),* 1992, pp 445-448
57. S. Seetharaman and D. Sichen, Development and Application of Electrochemical Sensors for Molten Metals Processing, *Emerging Separation Technologies for Metals II,* R.G. Bautista, Ed., The Minerals, Metals and Materials Society, 1996, p 317-340
58. G.M. Kale and R. Kurchania, On-Line Electrochemical Sensors in Molten Metal Processing Technology: A Review, *Ceram. Trans.,* Vol 92, 1992, p 195-220
59. B.J. Howie and B.L. Tiwari, Determination of Magnesium in Molten Aluminum Alloy Using an Electrochemical Sensor, *Light Metals 1989,* P.G. Campbell, Ed., The Metals, Minerals and Materials Society, 1989, p 895-902
60. D.H. DeYoung, J.B. Moreland, and R. Mutharasan, Closed Loop Melt Composition Control by In-Line Computer-Aided Alloying, *Light Metals 1995,* J. Evans, Ed., The Minerals, Metals and Materials Society, 1995, p 840-850
61. J. Vangrunderbeek, J. Luyt, F. Schutter, L. Zhang, and D. Fray, Immobilized Molten Salt Membrane Based Magnesium Sensor for Aluminum-Magnesium Melts, *Ionics,* Vol 1 (No. 1), 1995, p 59-62
62. L Zhang, D.J. Fray, J. Vangrunderbeek, and F.D. Schutter, Electrochemical Sensor for Measuring Magnesium Content in Molten Aluminum, *J. Appl. Electrochem.,* Vol 26 (No. 3), 1996, p 269-275
63. J. Vangrunderbeek, P. Lens, C. Castelijns, and P. Verstreken, Continuous In-Line Monitoring of Magnesium in Aluminum, *Light Metals 1999,* C.E. Eckert, Ed., The Minerals, Metals and Materials Soc., 1999, p 1005-1009
64. S.A. Gabelich and J. McHardy, Electrochemical Sensor for Measuring Magnesium Impurity Content in Molten Aluminium Scrap, U.S. Patent 5,632,881, May 27, 1997

65. J. Vangrunderbeek, P. Lens and J. Luyten, Sensor for Application in Molten Metals, U.S. Patent 6,514,394, Feb 4, 2003
66. S. Larose, A. Dubreuil, and A.D. Pelton, Solid Electrolyte Probes for Magnesium, Calcium and Strontium in Molten Aluminum, *Solid State Ionics,* Vol 47, 1991, p 287-295
67. G. Kale, Solid State Sensors for Analysis of Molten Metals, World Patent 2001061333, Aug 23, 2001
68. J.W. Fergus and S. Hui, Solid Electrolyte Sensor for Measuring Magnesium in Molten Aluminum, *Metall. Mater. Trans. B,* Vol 26B, 1995, p 1289-1291
69. J.W. Fergus, Chemical Sensors for Use in Processing Molten Metals, *AFS Trans.,* Vol 106, 1998, p 125-130
70. J.W. Fergus, Electrochemical Magnesium Sensors for Use in Processing of Molten Aluminum, *JOM,* Vol 47 (No. 11), 1995, p 36-41
71. R.J. Brisley and D.J. Fray, Determination of the Sodium Activity in Aluminum and Aluminum Silicon Alloys Using Sodium Beta Alumina, *Metall. Trans. B,* Vol 14B, 1983, p 435-440
72. L. Zhang, D.J. Fray, J.C. Dekeyser, and F.D. Schutter, Reference Electrode of Simple Galvanic Cells for Developing Sodium Sensors for Use in Molten Aluminum, *Metall. Mater. Trans. B,* Vol 27B, 1996, p 794-800
73. P.C. Yao and D.J. Fray, Sodium Activity Determinations in Molten 99.5% Aluminium Using Solid Electrolytes, *J. Appl. Electrochem.,* Vol 15, 1985, p 379-386
74. J.C. Dekeyser, F. De Schutter, C. Van der Poorten, and L. Zhang, An Electrochemical Sensor for Aluminum Melts, *Sens. Actuators, B,* Vol 24-25, 1995, p 273-275
75. G. Doughty, D.J. Fray, C. Van der Poorten, and J. Dekeyser, β-Alumina for Controlling the Rate of Sodium Addition to Aluminum Alloys, *Solid State Ionics,* Vol 86-88, 1996, p 193-196
76. A.A. Dubreuil and A.D. Pelton, Probes for the Continuous Monitoring of Sodium and Lithium in Molten Aluminum, *Light Metals 1985,* H.O. Bohner, Ed., The Minerals, Metals and Materials Soc., 1985, p 1197-1205
77. M. Stackpool, J.C. Dekeyser, A. Moores, and S. Devolder, Application of an Electrochemical Sensor to Measure Sodium Levels in Aluminium Alloys, *6th International AFS Conference on Molten Aluminum Processing 2001,* American Foundry Society, 2001, p 170-178
78. D.J. Fray, Apparatus for Detecting Elements, U.S. Patent 4,085,023, April 18, 1978
79. I.W. Jones, G. Atherton, and F.M. Stackpool, Solid Electrolyte Sensor for Monitoring the Concentration of an Element in a Fluid Particularly Molten Metal, World Patent 2002079772, Oct 10, 2002
80. R. Hartung and G. Toepfer, Manufacture of Alumina-Based Ion Conductors, Electric Sensors on Their Base, and Their Use for Measuring Impurity Concentration in Molten Metal Baths, World Patent 2002006804, Jan 24, 2002
81. Q. Zhang, "Fluoride-Based Sodium Sensor for Use in Molten Aluminum," M.S. Thesis, Auburn University, 1998
82. J.W. Fergus, Sensors for Use in Systems Containing Multiple Reactive Metals, *Light Metals 1999,* C.E. Eckert, Ed., The Minerals, Metals and Materials Soc., 1999, p 1131-1134
83. A.J. Kirchnerova and A.D. Pelton, Solid Electrolyte Probe for Strontium Employing a $SrCl_2$-AgCl/Ag Reference and a Thermodynamic Evaluation of the $SrCl_2$-AgCl System, *Solid State Ionics,* Vol 93, 1996, p 165-170
84. D. Hardy, "Fluoride-Based Strontium Sensor for Use in Molten Aluminum," M.S. Thesis, Auburn University, 1998
85. J.D. Dekeyser and F. De Schutter, An Electrochemical Lithium Sensor for Aluminum-Lithium Melts, *Aluminum-Lithium,* M. Peters and P.J. Winkler, Ed., DGM Informations GmbH, 1992, p 831-836
86. P.C. Yao and D.J. Fray, Determination of the Lithium Content of Molten Aluminum Using a Solid Electrolyte, *Metall. Trans. B,* Vol 16B, 1985, p 41-46
87. D.J. Fray, Determination of Lithium, Sensor Therefor and Method of Making Said Sensor, U.S. Patent 4,217,179, Aug 12, 1980
88. D.J. Fray, Method for Measuring a Minor Element in a Molten Metal, U.S. Patent 5,192,404, March 9, 1993
89. D.V. Neff, Methodologies for Evaluating Filtering Efficiency in Aluminum Casting Processes, *6th International AFS Conference on Molten Aluminum Processing 2001,* American Foundry Society, 2001, p 104-116
90. F. Degrève, J.-C. Carle, and N. Gonzalez, New Methods for the Determination of Hydrogen Content of Aluminum and Its Alloys: Part I. Improvements in the Vacuum Extraction Method, *Metall. Trans. B,* Vol 6B, 1975, p 539-544
91. F. Degrève and C. Jardin, New Methods for the Determination of Hydrogen Content of Aluminum and Its Alloys: Part II. Rapid Determination by the Nitrogen Carrier Fusion Method, *Metall. Trans. B,* Vol 6B, 1975, p 545-550
92. W. Rasmussen and C.E. Eckert, RPT Gauges Aluminum Porosity, *Modern Casting,* Vol 82 (No. 3), 1992, p 29-31
93. F. Degrève, N. Gonzalez, and J. Moriceau, New Methods for the Determination of Hydrogen Content of Aluminum and Its Alloys: Part III. Quantitative Vacuum Gas Test (Straubbe-Pfeiffer Test) by Use of a Mass Spectrometer, *Metall. Trans. B,* Vol 6B, 1975, p 551-556
94. D.A. Anderson, D.A. Granter, and J.G. Stevens, Telegas II™ for On-Line Measurement of Hydrogen in Aluminum Alloy Melts, *Production and Electrolysis of Light Metals,* B. Closset, Ed., Pergamon Press, 1989, p 163-172
95. M.F.A. Warchol and R.C. Wojnar, Method and Apparatus for Determining Soluble Gas Content, U.S. Patent 4,731,732, March 15, 1988
96. G.K. Sigworth, Gas Analyzer for Molten Metals, U.S. Patent 5,495,746, March 5, 1996
97. R.A. Falk and R.W. Nott, Hydrogen Sampler for Molten Metal and Method, U.S. Patent 5,591,894, Jan 7, 1997
98. D.A. Anderson, Solenoid Operated Probe for Determining Gas Content in a Liquid Metal, U.S. Patent 6,209,384, April 3, 2001
99. E.T. Turkdogan, Novel Concept of Disposable EMF Sensor for In Situ Measurements of Solute Contents of Liquid Metals in Metal-Refining Processes, *Scand. J. Metall.,* Vol 30, 2001, p 193-203
100. R. Gee and D.J. Fray, Instantaneous Determination of Hydrogen Content in Molten Aluminum and Its Alloys, *Metall. Trans. B,* Vol 9B, 1978, p 427-430
101. M. Zheng and X. Zhen, $SrCeO_3$-Based Solid Electrolyte Probe Sensing Hydrogen Content in Molten Aluminum, *Solid State Ionics,* Vol 59**,** 1993, p 167-169
102. M. Zheng and X. Zhen, Hydrogen Probe Equipped with $SrCeO_3$-Based Proton Conductor and Ca/CaH_2 Reference Electrode, *Metall. Mater. Trans. B,* Vol 24B, 1993, p 789-794
103. M. Zheng and Z. Chen, Preparation and Electrochemical Characterization of $SrCeO_3$-Based Proton Conductor, *Solid State Ionics,* Vol 70/71, 1994, p 595-600
104. N. Kurita, N. Fukatsu, K. Ito, and T. Ohashi, Protonic Conduction Domain of Indium-Doped Calcium Zirconate, *J. Electrochem. Soc.,* Vol 142 (No. 5), 1995, p 1552-1559
105. T. Yajima, H. Iwahara, N. Fukatsu, T. Ohashi, and K. Koide, Measurement of Hydrogen Content in Molten Aluminum Using Proton Conducting Ceramic Sensor, *Keikinzoku,* Vol 42 (No. 5), 1992, p 263-267
106. T. Yajima, K. Koide, H. Takai, N. Fukatsu, T. Ohashi, and H. Iwahara, A New Hydrogen Sensor for Molten Aluminum, *Sens. Actuators B,* Vol 13-14, 1993, p 697-699
107. T. Yajima, K. Koide, H. Takai, N. Fukatsu, and H. Iwahara, Application of Hydrogen Sensor Using Proton Conductive Ceramics as a Solid Electrolyte to Aluminum Casting Industries, *Solid State Ionics,* Vol 79, 1995, p 333-357
108. N. Fukatsu, N. Kurita, T. Yajima, K. Koide, and T. Ohashi, Proton Conductors of Oxide and Their Application to Research into Metal-Hydrogen Systems, *J. Alloys Compd.,* Vol 231, 1995, p 706-712
109. N. Fukatsu, N. Kurita, and T. Ohashi, Hyydrogen Sensor for Molten Metals and Its Application to Materials Processing, *Processing Materials for Properties II,* B. Mishra and C. Yamauchi, Ed., The Metals, Minerals and Materials Society, 2000, p 357-362
110. C. Schwandt and D.J. Fray, Hydrogen Sensing in Molten Aluminum Using a Commercial Electrochemical Probe, *Ionics,* Vol 6 (No. 3/4), 2000, p 222-229
111. J.W. Fergus and A.H. Setiawan, Hydrogen Sensor for Molten Aluminum, *AFS Trans.,* Vol 109, 2001, p 453-459
112. A.H. Setiawan and J.W. Fergus, Preparation and Characterization of In-Doped $CaZrO_3$ at the Electrolyte in Hydrogen Sensors for Use in Molten Aluminum, *Ceram. Trans.,* Vol 130, G. Kale, S. Akbar, and M. Liu, Ed., American Ceramic Society, 2002, p 47-56
113. V. Krishnan, J.W. Fergus, and F. Fasoyinu, Solid Electrolyte Based Hydrogen Sensor for Molten Aluminum, *Advances in Aluminum Casting Technology II,* M. Tiryakioglu and J. Campbell, Ed., ASM International, 2002, p 155-158
114. J.-P. Martin, G. Dube, and D.A. Doutre, Probe for the Determination

of Gas Concentration in Molten Metal, U.S. Patent 4,907,440, March 13, 1990
115. K. Koide and T. Yajima, Sensor Probe for Hydrogen Concentration in Molten Metal, U.S. Patent 5,439,579, Aug 8, 1995
116. K. Koide and T. Yajima, Sensor Probe for Measuring Hydrogen Concentration in Molten Metal and Method of Measuring Hydrogen Concentration, U.S. Patent 5,445,725, Aug 29, 1995
117. K. Katahira, H. Matsumoto, H. Iwahara, K. Koide, and T. Iwamoto, A Solid Electrolyte Hydrogen Sensor with an Electrochemically-Supplied Hydrogen Standard, *Solid State Ionics,* Vol 73, 2001, p 130-134
118. C. Schwandt and D.J. Fray, Determination of Hydrogen in Molten Aluminium and Its Alloys Using an Electrochemical Sensor, *EPD Congress 2003,* M. Schelsinger, Ed., The Minerals, Metals and Materials Society, 2003, p 427-438
119. C. Schwandt, D.J. Fray, M.P. Hills, M.A. Henson, R.M. Henson, and C. Powell, A Novel Electrochemical Hydrogen Analyzer for Use in Molten Aluminium and Its Alloys, *6th International AFS Conference on Molten Aluminum Processing 2001,* American Foundry Society, Des Plaines, IL, 2001, p 131-140
120. G. Lu, N. Miura, and H. Yamazoe, High-Temperature Hydrogen Sensor Based on Stabilized Zirconia and a Metal Oxide Electrode, *Sens. Actuators B,* Vol 35-36, 1996, p 130-135
121. G. Lu, N. Miura, and N. Yamazoe, Mixed Potential Hydrogen Sensor Combining Oxide Ion Conductor with Oxide Electrode, *J. Electrochem. Soc.,* Vol 143 (No. 7), 1996, p L154-L155
122. N. Hara and D.D. MacDonald, Development of Dissolved Hydrogen Sensor Based on Yttria-Stabilized Zirconia with Noble Metal Electrolytes, *J. Electrochem. Soc.,* Vol 144 (No. 12), 1997, p 4152-4157
123. Y. Tan and T.C. Tan, Characteristics and Modeling of a Solid State Hydrogen Sensor, *J. Electrochem. Soc.,* Vol 141 (No. 2), 1994, p 461-467
124. H.P. Krug and W. Schneider, A Contribution to Inclusion Measurement After In-Line Degassers with PoDFA and LiMCA, *Light Metals 1998,* B. Welch, Ed., The Minerals, Metals and Materials Society, 1998, p 863-870
125. A. Simard, J. Proulx, D. Paquin, F.H. Samuel, and H. Habibi, Capability Study of the Improved PREFIL-Footprinter to Measure Liquid Aluminum Cleanliness and Comparison with Different Techniques, *6th International AFS Conference on Molten Aluminum Processing 2001,* American Foundry Society, 2001, p 83-103
126. W.H. Coulter, Means for Counting Particles Suspended in a Fluid, U.S. Patent 2,656,508, Oct 20, 1953
127. R.W. DeBlois and C.P. Bean, Counting and Sizing of Submicron Particles by the Resistive Pulse Technique, *Rev. Sci. Instrum.,* Vol 41 (No. 7), 1970, p 909-916
128. R.I.L. Guthrie and M. Li, In Situ Detection of Inclusions in Liquid Metals: Part I. Mathematical/Modeling of the Behavior of Particles Traversing the Electric Sensing Zone, *Metall. Mater. Trans. B,* Vol 32B (No. 6), 2001, p 1067-1079
129. R.I.L. Guthrie and M. Li, In Situ Detection of Inclusions in Liquid Metals: Part II. Metallurgical Applications of LiMCA Systems, *Metall. Mater. Trans. B,* Vol 32B (No. 6), 2001, p 1081-1093
130. L. Mei and R.I.L. Guthrie, Numerical Studies of the Motion of Particles in Current-Carrying Liquid Metals Flowing in a Circular Pipe, *Metall. Mater. Trans. B,* Vol 31B (No. 4), 2000, p 855-866
131. L. Mei and R.I.L. Guthrie, Numerical Studies of the Motion of Spheroidal Particles Flowing with Liquid Metals Through an Electric Sensing Zone, *Metall. Mater. Trans. B,* Vol 31B (No. 2), 2000, p 357-364
132. M. Li, C. Carozza, and R.I.L. Guthrie, Particle Discrimination in Water Based LiMCA (Liquid Metal Cleanliness Analyzer) System, *Can. Metall. Q.,* Vol 39 (No. 3), 2000, p 325-338
133. G. Carayannis, F. Dallaire, X. Shi, and R.I.L. Guthrie, Towards Intelligent Detection of Inclusions in Liquid Metals, *Artificial Intelligence in Materials Processing, Proceeding of the International Symposium,* S.A. Argyropoulos and G. Carayannis, Ed., Canadian Institute of Mining, Metallurgy, and Petroleum, Montreal, Canada, 1992, p 227-244
134. C. Dupuis, F. Dallaire, and B. Maltais, The Measurement of Controlled Size Particles in Molten Aluminum Using the LiMCA II Technique, *Light Metals 1999,* C.E. Eckert, Ed., The Minerals, Metals and Materials Society, 1999, p 1069-1077
135. R.I.L. Guthrie, Molten Metal Inclusion Sensor Probes, U.S. Patent 5,789,910, Aug 4, 1998
136. R.I.L. Guthrie and H. Nakajima, Continuous-Use Molten Inclusion Sensor, U.S. Patent 5,241,262, Aug 31, 1993
137. D.A. Doutre and R.I.L. Guthrie, Method and Apparatus for the Detection and Measurement of Particulates in Molten Metal, U.S. Patent 4,555,662, Nov 26, 1985
138. D.A. Doutre and R.I.L. Guthrie, Apparatus for the Detection and Measurement of Particulates in Molten Metal, U.S. Patent 4,600,880, July 15, 1986
139. R. Hachey, Apparatus for the Detection and Measurement of Suspended Particulates in Molten Metal, U.S. Patent 4,763,065, Aug 9, 1988
140. R. Hachey and G. Deschenes, Apparatus for Particle Determination in Liquid Metals, U.S. Patent 5,039,935, Aug 13, 1991
141. D.A. Doutre, G. Hay, and P.A. Wales, Portable Device for Filtration of Molten Metal to Determine the Inclusion Content, U.S. Patent 5,827,982, Oct 27, 1998
142. D.A. Doutre, Electric-Conductivity Method and Apparatus for Detection and Size Measurement of Solid Inclusions in Molten Metal, U.S. Patent 5,834,928, Nov 20, 1998
143. F.R. Block, R. Dittmer, and G. Gerbeth, Electromagnetic Detection of Nonconducting Inclusions in a Liquid Metal Flow, *Proceeding of the First Symposium on Electromagnetic Processing of Materials,* ISIJ, Nagoya, Japan, 1994, p 61-67
144. S. Makarov, R. Ludwig, and D. Apelian, Electromagnetic Visualization Technique for Non-Metallic Inclusions in a Melt, *Meas. Sci. Technol.,* Vol 10, 1999, p 1047-1053
145. T.L. Mansfield, Probe for Ultrasonic Inspection of Molten Aluminum, U.S. Patent 4,261,197, April 14, 1981
146. T.L. Mansfield, Probes for the Ultrasonic Treatment or Inspection of Molten Aluminum, U.S. Patent 4,287,755, Sept 8, 1981
147. T.L. Mansfield and C.K. Bradshaw, Ultrasonic Inspection of Molten Aluminum, *AFS Trans.,* Vol 93, 1985, p 317-322
148. L.C. Lynnworth, *Ultrasonic Measurements for Process Control: Theory, Techniques, Applications,* Academic Press, 1989, p 515-518
149. C.E. Eckert, Apparatus and Method for Ultrasonic Detection of Inclusions in Molten Metals, U.S. Patent 4,563,895, Jan 14, 1986
150. R.C. Stiffler, R.C. Wojnar, M.F.A. Warchol, L.W. Cisko, and J.M. Urbanic, Apparatus and Method for Ultrasonic Detection in Molten Metal, U.S. Patent 5,708,209, Jan 13, 1998
151. N.D.G. Mountford, I.D. Sommerville, A. Simionescu, and C. Bai, Sound Pulses Enable the On Line Visualization of Liquid Metal Quality, *Proc. Int. Symp. Light Metals 1997,* C.M. Cickert and R.I.L. Guthrie, Ed., Canadian Institute of Mining, Metallurgy, and Petroleum, Montreal, Canada, 1997, p 197-211
152. N.D.G. Mountford, A. Simionescu, and I.D. Sommerville, Visualization of the Particle Content of Liquid Aluminum Alloys, *Light Metals 1997,* R. Huglen, Ed., The Minerals, Metals and Materials Society, 1997, p 937-943
153. N.D.G. Mountford, P.H. Mountford, I.D. Sommerville, and B. de Walle, On-Line Ultrasonic Monitoring of Liquid Metal Cleanliness, *Innovative Technology for Steel and Other Materials, Proceedings of the Gerald Hefferman International Symposium,* J. Guerard and E. Essadiqi, Ed., Canadian Institute of Mining, Metallurgy, and Petroleum, Montreal, Quebec, Canada, 2001, p 227-240
154. I.D. Sommerville, N.D.G. Mountford, and A. Simionescu, The Development of an Ultrasonic Sensor for Determination of the Cleanliness of Liquid Metals, *Alex McLean Symp. Proc.,* Iron and Steel Society, 1998, p 87-96
155. N.D.G. Mountford, Testing of Liquid Metals and Probes for Use in Such Testing, U.S. Patent 4,981,045, Jan 1, 1981
156. I.D. Sommerville, N.D.G. Mountford, and L.C.B. Martins, Laboratory and Industrial Validation of an Ultrasonic Sensor for Cleanliness Measurement in Liquid Metals, *Light Metals 2000,* R.D. Peterson, Ed., The Minerals, Metals & Materials Society, 2000, p 721-726
157. T.L. Mansfield, Molten Aluminum Quality Measured with Reynolds 4M™ System, *Light Metals,* The Minerals, Metals and Materials Society, 1984, p 1305-1327
158. A.-U. Rehman, C.-K. Jen, and I. Ihara, Ultrasonic Probes for High Temperature Immersion Measurements, *Meas. Sci. Technol.,* Vol 12, 2001, p 306-312
159. I. Ihara, C.-K. Jen, and D.R. Franca, Detection of Inclusion in Molten Metal by Focused Ultrasonic Wave, *Jpn. J. Appl. Phys., Part 1,* Vol 39, 2000, p 3152-3153
160. I. Ihara, C.-K. Jen, and D.R. Franca, Ultrasonic Imaging, Particle Detection, and V(z) Measurements in Molten Zinc Using Focused

Clad Buffer Rods, *Rev. Sci. Instrum.,* Vol 71 (No. 9), 2000, p 3579-3586

161. I. Ihara, C.-K. Jen, and D.R. Franca, C-Scan Imaging in Molten Zinc by Focused Ultrasonic Waves, *J. Acoust. Soc. Am.,* Vol 107 (No. 2), 2000, p 1042-1044
162. I. Ihara, C.-K. Jen, and D. Ramos Franco, High Resolution Measurements in Liquid Metal by Focused Ultrasonic Wave, *Rev. Prog. Quantitative Nondesctructive Evaluation,* D.O. Thompson and D.E. Chimenti, Ed., *AIP Conf. Proc.* Vol 509, 2000, p 1841-1848
163. C.-K. Jen and I. Ihara, Clad Buffer Rod Sensors for Liquid Metals, *Advanced Sensors for Metals Processing,* B.W. Brusey, J.F. Bussière, M. Dubois, and A. Moreau, Ed., Canadian Institute of Mining, Metallurgy, and Petroleum, Montreal, Quebec, Canada, 1999, p 275-285
164. J.-F. Moisan, C.-K. Jen, J.-W. Liaw, C.-Q. Zheng, T.-F. Chen, Z. Sun, and C.A. Loong, Ultrasonic Sensor and Technique for In-Line Monitoring of Die Casting Process, *Meas. Sci. Technol.,* Vol 12, 2001, p 1956-1963
165. C.-K. Jen, J.-W. Liaw, T.-F. Chen, A. Moreau, J.P. Monchalin, and C.C. Yang, Ultrasonic Evaluation of Semi-Solid Metals During Processing, *Meas. Sci. Technol.,* Vol 11, 2000, p 1570-1575
166. C.-K. Jen, B. Cao, K.T. Nguyen, C.A. Loong, and J.-G. Legoux, On-Line Ultrasonic Monitoring of a Die-Casting Process Using Buffer Rod, *Ultrasonics,* Vol 35, 1997, p 335-344