Fiber-Optic Strain and Temperature Sensors that Can Take the Heat

Conventional sensors for pressure, temperature, strain, acceleration, and other physical measurements are intrinsically limited by the temperature-dependent electronic response of the transducer materials. Fiber-optic-based sensors have been proven to operate in extremely high-temperature environments. The transducing mechanism for certain fiber-optic sensors relies on mechanical and optical material properties that are nearly linear approaching the melting point. Luna Innovations Inc. has developed high-temperature physical sensors for temperature, pressure, strain, and acceleration based on an extrinsic Fabry–Perot interferometer (EFPI)—the interfering reflections are created outside the fiber instead of internally—and refractory ceramic construction. Pressure sensors have been demonstrated up to 1050°C at 500 psi, strain sensors up to 1100°C, temperature sensors up to 1400°C, and accelerometers up to 850°C. Sensors are needed that can operate at temperatures exceeding 1000°C for the control and structural health monitoring of high-temperature systems such as gas turbines, nuclear reactors, and industrial processes.

Fiber optic sensors have a number of intrinsic advantages, including immunity to electromagnetic interference, extremely long lead lengths, a high level of multiplexing, and extremely low mass. The transducing mechanism used by EFPI-based sensors is a distance measurement technique based on the formation of a low-finesse Fabry–Perot cavity (the reflecting surfaces are only partially reflective—about 4% of the incident light is reflected by each reflector) between the polished end face of an optical fiber and a reflective surface, shown schematically in Figure 1. Light is emitted from a broadband source, transmitted through a coupler, and passed through the fiber at the sensor, where a portion of the light is reflected off the fiber end face, which is the reference reflection (R1). The remaining light propagates through the transducer and is reflected back into the fiber, which is the sensing reflection (R2).

In a strain sensor (see Figure 2a), R1 is formed at the fiber/air interface, while R2 is formed at the surface of the reflector fiber. For a temperature sensor (see Figure 2b), R1 is formed at the fiber/sensor chip interface while R2 is formed at the polished face of the sensor chip. These two light waves interfere constructively or destructively, based on the path length difference traversed by the sensing reflection relative to the reference reflection, and travel back through the single-mode fiber to the demodulation unit. The resulting interference pattern is then interpreted and the absolute gap (optical path length) between the two reflectors is calculated with an accuracy of +/–2.0 nm. The physical quantity measured is the optical path length between R1 and R2.

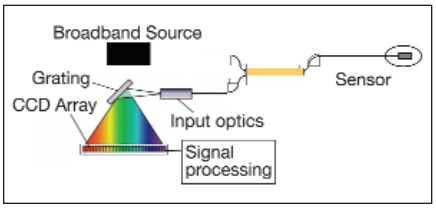

Figure 1. Basic diagram of a fiber-optic sensor system based on an extrinsic Fabry–Perot interferometer (EFPI).

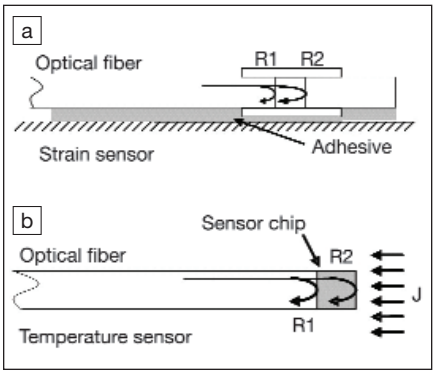

Figure 2. (a) A fiber-optic strain sensor; (b) a fiber-optic temperature sensor. R1 is the reference reflection; R2 is the sensing reflection. J represents heat flux.

The temperature sensor was developed using refractory ceramic transducers for high-temperature resistance and high-frequency response. The transducer, ~100 μm in diameter, is bonded to the optical fiber. Two key features of the temperature sensor design facilitate extremely fast response times. First, the extremely low mass of the transducer, ~0.15–1.5 μg, minimizes total heat absorption. Second, the transducers have a much higher thermal conductivity than the silica glass fiber. This feature causes the glass substrate to act as an insulator, compared with thermocouple leads, which act as heat sinks.

The strain sensors have been developed for operation at extremely high temperatures and high strains. They are designed as extensometers, which measure the change in distance between two fixed points on the structure being monitored. However, the extensometer is not strained in the process. The strain in the structure is what is being measured. But since the sensor is not strained, strain ranges can be measured that are far higher than the failure strain of the sensor material, which is typically silica. The transmitting and reflecting fibers are bonded independently to the substrate using a high-temperature process. The fibers are free to slip inside a silica capillary tube that is used to maintain alignment between the faces. This design has been demonstrated with both carbon–carbon composite and stainless steel structures at temperatures exceeding 1100°C. During room-temperature and high-temperature testing, strain ranges of up to 40% have been demonstrated.

Opportunities

Luna Innovations Inc. welcomes inquiries for licensing this technology and for contract research and development for specific applications.

Source: Bob Fielder, Director of the Optical Devices Group, Luna Innovations Inc., 2851 Commerce St., Blacksburg, VA 24060, USA; tel. 540-953-4266, fax 540-951-0760, and e-mail fielderr@lunainnovations.com. For licensing and partnering: Mike Gunther, Vice President of Operations, Luna Innovations Inc.; tel. 540-552-5128, fax 540-951-0760, and e-mail guntherm@lunainnovations.com.

Technology Advances provides up-to-date reports of materials developments that show potential to bridge the gap between research innovation and application of advanced materials technologies. If you encounter or are involved with materials research that shows potential for commercialization and would like to present these developments, contact Renée G. Ford, Renford Communications, renford@comcast.net.

https://doi.org/10.1557/mrs2005.235 Published online by Cambridge University Press

Thin-Film Solid-Oxide Fuel Cell Technique Reduces Costs

A solid-oxide fuel cell (SOFC) is a solid-state electrochemical device that converts the chemical energy of fuel directly into electricity. Its efficiency and low emission makes SOFCs a favorable option for power generation technologies for the 21st century. However, commercialization efforts have been hampered in part by the prohibitive cost of fabrication, specifically the high cost of producing thin, defect-free coatings. The economical production of coatings in the range of 10–40 µm is required to minimize resistance yet maintain mechanical integrity. Lawrence Livermore National Laboratory (LLNL) has addressed this problem with its colloidal spray deposition (CSD) method.

The deposition of films thicker than 10 µm in a single step using conventional techniques such as dip coating, spin coating, slurry painting, or electrophoretic deposition generally results in film cracking due to shrinkage as the solvent volatilizes. Therefore, the generation of thicker coatings necessitates repeated thin-film deposition, which leads to long processing times and thus increased costs.

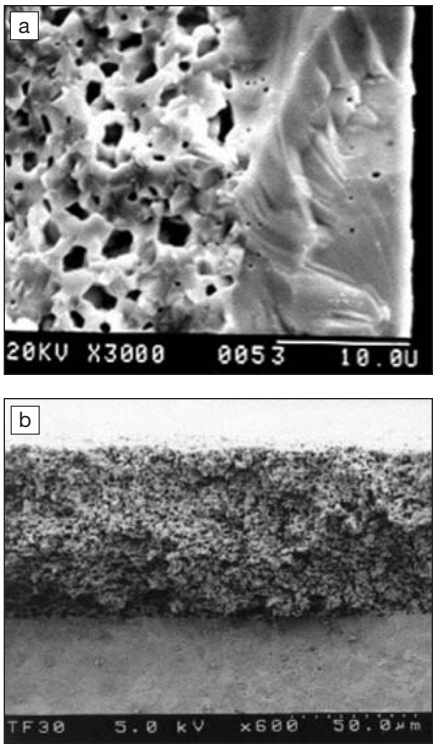

Figure 1. (a) Scanning electron micrograph (SEM) of the cross section of a dense, crack-free, porous 13-µm-thick YSZ film on a porous Ni/YSZ (anode) disk; the scale bar is 10 µm. (b) SEM of the cross section of a 70-µm-thick porous Ni/YSZ film on a YSZ disk; the scale bar is 50 µm.

With its CSD technique, LLNL has deposited dense, crack-free, yttria-stabilized-zirconia (YSZ) films of up to 100 µm thick on nickel oxide/YSZ substrates and porous $La_{0.85}Sr_{0.15}MnO_3$ (LSM) substrates. Alternatively, by adjusting solution compositions, porous electrodes can be deposited. The cross section of a dense, crack-free, porous 13-µm-thick YSZ thin film on a porous Ni/YSZ (anode) disk is shown in Figure 1a, and the cross section of a 70-µm-thick porous Ni/YSZ film on a YSZ disk is shown in Figure 1b.

The CSD method evaporates the solvent on contact with the substrate, depositing a dense, finely divided powder film. This is achieved by heating the substrate to a temperature above or close to the boiling point of the solvent. When the fine mist is sprayed onto the hot substrate, the solvent evaporates rapidly, leaving a compact layer of powder. Continuous removal of the solvent during extended periods of deposition results in a thick, defect-free film that is subsequently sintered. LLNL has optimized aspects of this technique, including the atomizing and spraying processes as well as the composition of the starting solution. Both dense and porous coatings can be created, resulting in a fabrication method suitable for the preparation of both the electrolyte and the electrodes.

The laboratory has deposited a graded bilayer film of YSZ and $Ce_{0.8}Y_{0.2}O_2$ (CYO), which is useful when transitioning from electrolyte to electrode with different thermal expansion coefficients. Three cell stacks using conventional materials—a Ni/YSZ anode, an YSZ electrolyte, and a LSM-YSZ cathode—were prepared using the CSD technique to deposit the cathode and electrolyte. The cells in this stack also had anodes that were microstructurally optimized by tailoring pore-former concentrations during fabrication. At 800°C in air/hydrogen, the peak power density of the stack was 1.05 W cm^2 at 65% fuel utilization. This is believed to be the highest value reported in the literature for planar fuel cell stacks fabricated using conventional methods was 0.67 W cm^2.

The CSD technique can facilitate the use of materials that can improve fuel cell performance. For example, doped ceria (CYO) has some electronic conduction in fuel conditions and cannot serve as an electrolyte by itself. A bi layer of YSZ and doped ceria has been proposed where the YSZ layer serves to block electrons. However, cracking and delamination have been observed due to the higher thermal expansion coefficient of doped ceria. Relaxing the mechanical stress by grading the interface from YSZ to CYO is difficult to achieve using existing thin-film deposition techniques. However, LLNL has been able to grade the composition of a thin film over several micrometers (shown in Figure 2a). No visible interface was observed. Since YSZ and CYO form a complete solid solution at temperatures higher than 1300°C, the graded film is believed to be a single-phase material with its composition changing progressively from pure YSZ to pure CYO. The concentration profile of the graded film, as determined by electron microprobe analysis, is shown in Figure 2b.

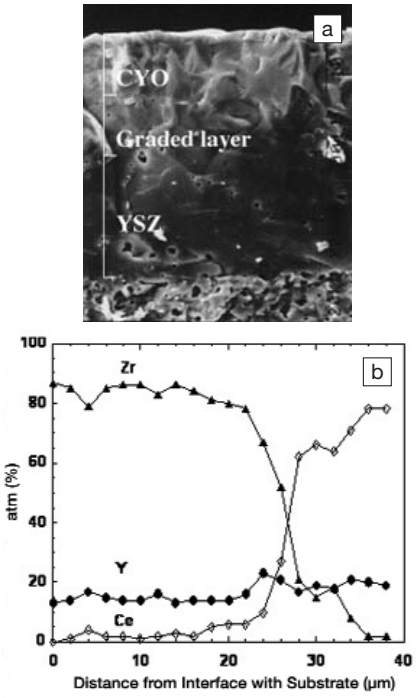

Figure 2. (a) A 40-µm-thick YSZ and CYO film with a graded interface. The size marker is 40 µm. (b) Composition profile of the YSZ/CYO graded film.

Opportunities

LLNL is seeking industrial partners that can assist in bringing this patented technology to the market for collaborative research and development, and /or to license the CSD technique.

Source: For the technology: Robert Glass, Lawrence Livermore National Laboratory, L-644, PO Box 808, Livermore, CA 94550, USA; tel. 925-423-7140, fax 925-423-7914, and e-mail glass3@llnl.gov. For licensing and partnering: Annemarie Meike, Industrial Partnerships and Commercialization Office, Lawrence Livermore National Laboratory, L-795, PO Box 808, Livermore, CA 94550, USA; tel. 925 422 3735, fax 925 423 8988, and e-mail meike1@llnl.gov.

https://doi.org/10.1557/mrs2005.235 Published online by Cambridge University Press