High Temperature Sensors For On-line Critical Equipment Health Monitoring

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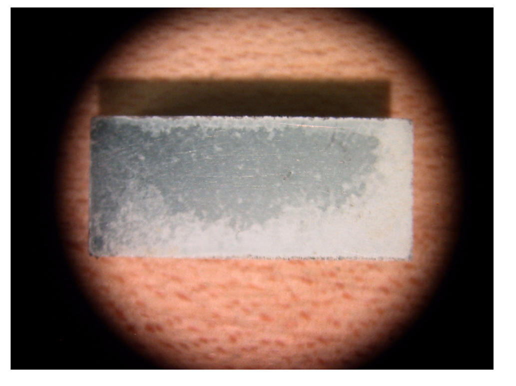


Abstract

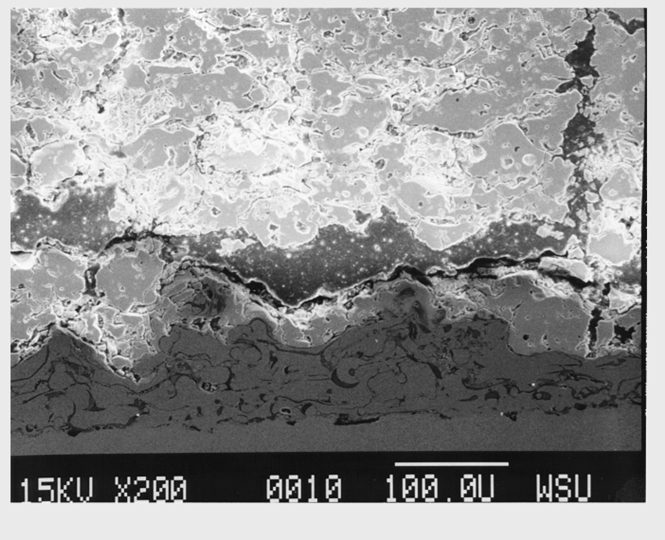
The objective of this research program is to improve high temperature piezoelectric aluminum nitride (AlN) sensor technology to make it useful for instrumentation and health monitoring of current and future electrical power generation equipment and related applications. The sensor's practical use temperature range is being extended from approximately 700ºC to above 1000ºC. Ultrasonic coupling to objects at very high temperatures was investigated and tailored for use with the sensor. The sensor will be demonstrated in a laboratory simulation of an application of health monitoring for power generation equipment.

For this work, the sensor is constructed as an ultrasonic transducer used to measure the thickness of a material or to look for the formation of cracks or voids in a material. Performed on-line at high temperature, a thickness measurement could be used to monitor the extent of corrosion or erosion damage in metallic or ceramic components. These ultrasonic sensors may additionally be used to monitor bonds, such as that between a metal and a ceramic, as found in thermal and environmental barrier coatings commonly found in power generation equipment.

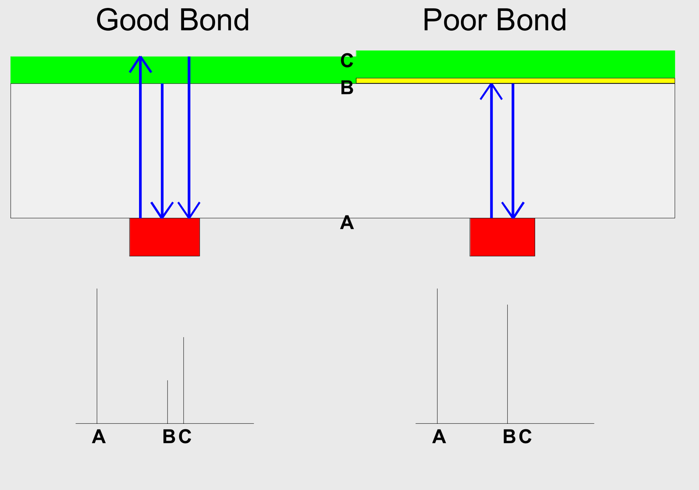
Potential Applications of Health Monitoring Sensors

Gasifier refractory material wear and erosion: The harsh environments encountered by refractory materials lead to finite lives and frequent replacement. For example, the refractory liners of coal gasifiers must be replaced at intervals of ~1-3 years, with a significant expense in materials and downtime. While the development of improved refractories has increased this interval, variations in the chemical environment and temperature during operation cause uncertainties in lifetime prediction. Shutdowns for inspection are expensive and have the potential to cause additional damage to the refractory or other components. The ability to monitor the remaining thickness of a gasifier liner could potentially increase the replacement interval, while ensuring that refractory is not replaced until its useful life has ended. Crossover applications include refractory monitoring in glass and steel production.

Thermal and environmental barrier coating integrity: TBCs and EBCs are often used to protect critical components, such as gas turbine blades. These material systems often consist of a ceramic coating on a metal component, and can be subject to cracking or delamination. Sensors which could warn of such degradation would be of use both during the development of advanced material systems, and eventually in deployed systems.

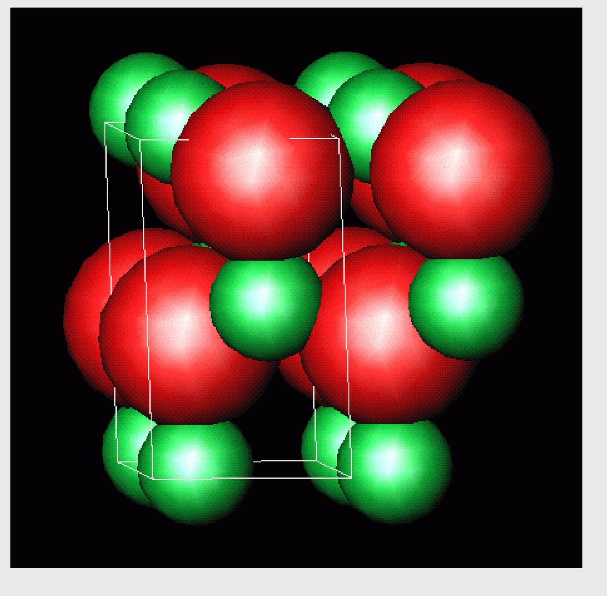


Corrosion and erosion of other components at elevated temperature: Other components in power generation systems are subject to corrosion or erosion at elevated temperature. One example is gas-to-liquid heat exchangers, or "water walls" operating at high temperatures and pressures and subjected to combustion exhaust. Even simple water and steam piping can develop cracks from thermal cycling or corrosion. The deployment of sensors to monitor these effects at critical locations could be used to reduce system downtime and to help reduce unplanned shutdowns for maintenance and repair. Again, crossover of a successful sensor to other energy-intensive industries, such as chemical production and petroleum refining, could be expected.

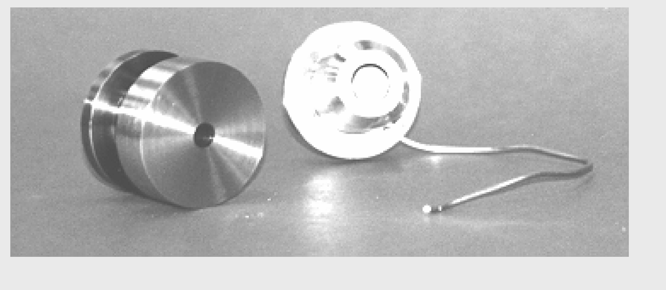


Introduction to Aluminum Nitride (AlN) Sensors

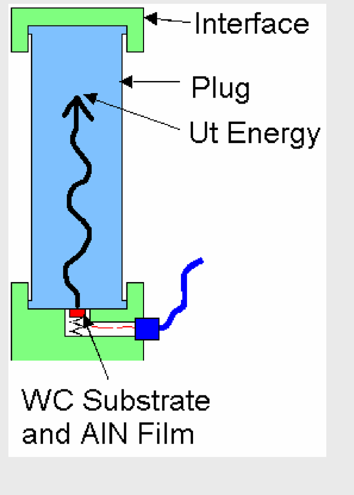
Aluminum nitride is a ceramic compound with unique properties. Its most important use today is probably as a heat sink material because of a high thermal conductivity (for a ceramic insulator) surpassed only by beryllium oxide, which is poisonous. It is chemically inert, even to molten metals, but does begin to oxidize around 700º C. Very thin films of piezoelectric AlN are commercially used as the foundation for some of the surface acoustic wave filters used to tune radio frequency equipment such as televisions.

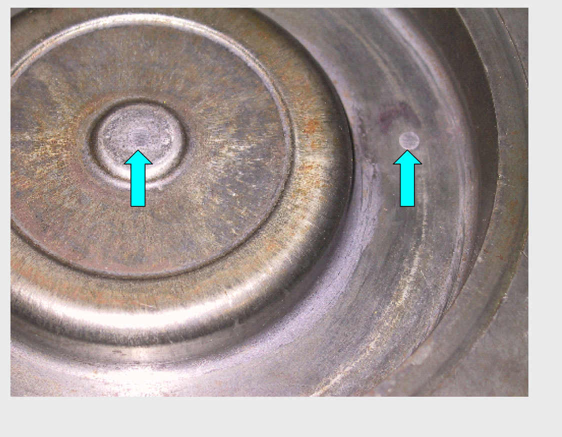


Possessing the unbalanced Wurtzite crystal structure, AlN is a naturally piezoelectric material, similar to the well-known quartz crystal. Unlike quartz, AlN maintains its structure, and its piezoelectric properties, until it dissociates into its components near 2000C. Similarly, it does not require poling like PZT and other common (and more powerful) piezoceramics, and therefore cannot be depoled by heating. By 1990, Dr. N.D. Patel of McMaster University had shown that AlN remained piezoelectric at temperatures exceeding 1150ºC for 24 hours.



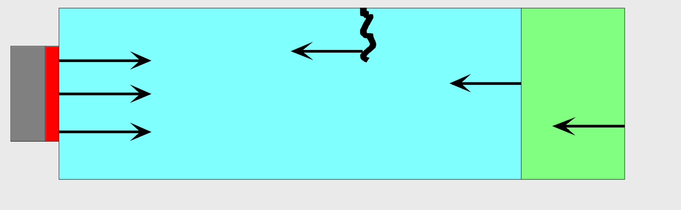
In 1994, UDRI demonstrated the use of AlN as part of a high temperature ultrasonic transducer in a project funded by the Air Force Research Laboratory (>900ºC , 140 MPa pressure). The University of Dayton subsequently patented the use of AlN in ultrasonic transducers (US Patent #5,886,456), acquired the ability to make oriented AlN films in-house, and advanced the technology through improvements in the AlN film deposition process and investigations into various sensor applications. Applications have included the high temperature ultrasonic load cell, forging die sensor, and pressure sensor shown below; and other ultrasonic or charge-mode sensor investigations.

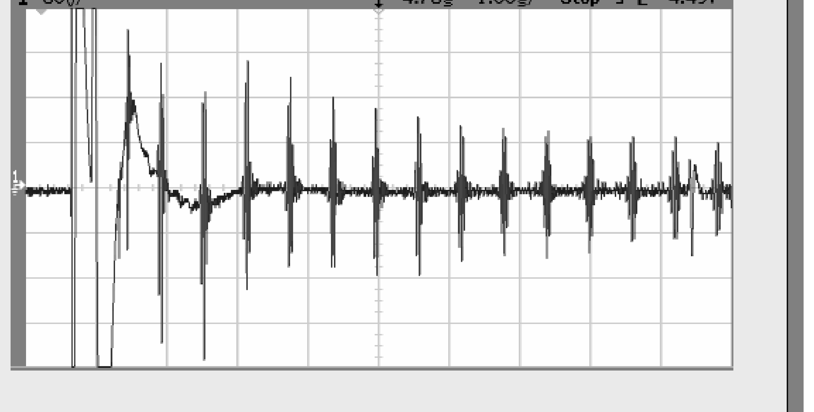


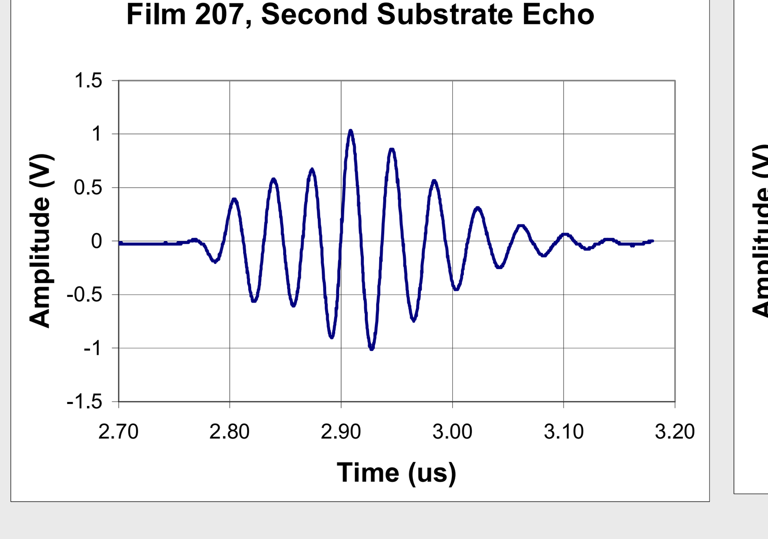


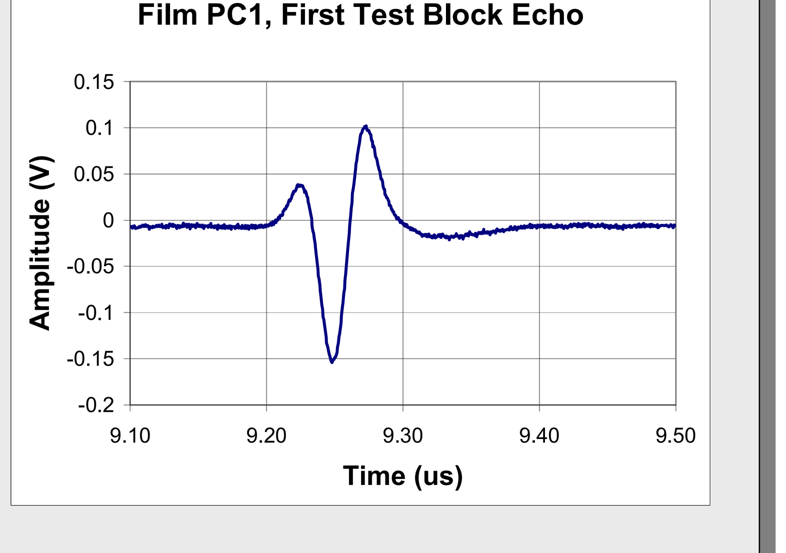
While single-crystal AlN is now being grown commercially, its cost is considerably higher than the thick-film AlN films resulting from the current CVD-based process. An oriented polycrystalline AlN film can be grown to a thickness of ~30 microns in about an hour; in an ultrasonic transducer, such a film will produce energy centered at ~30 MHz and will withstand voltage pulses above 400V.

The figure to the right shows a representation of an AlN ultrasonic transducer (red/gray) applied to a test object. When a voltage pulse is applied to the AlN film, it expands, sending a sound wave into the material which interacts with cracks, layers, voids, etc. The returning sound wave causes a corresponding voltage pulse which is amplified and recorded; its amplitude, phase, and timing provide information about the material or structure being interrogated. The waveform shows the result if good sonic coupling to the test object is not achieved- the sound simply bounces around in the substrate material supporting the AlN film. The bandwidth of the sonic pulse also affects its usability; the wide-band pulse on the right provides much better resolution of flaws or features.



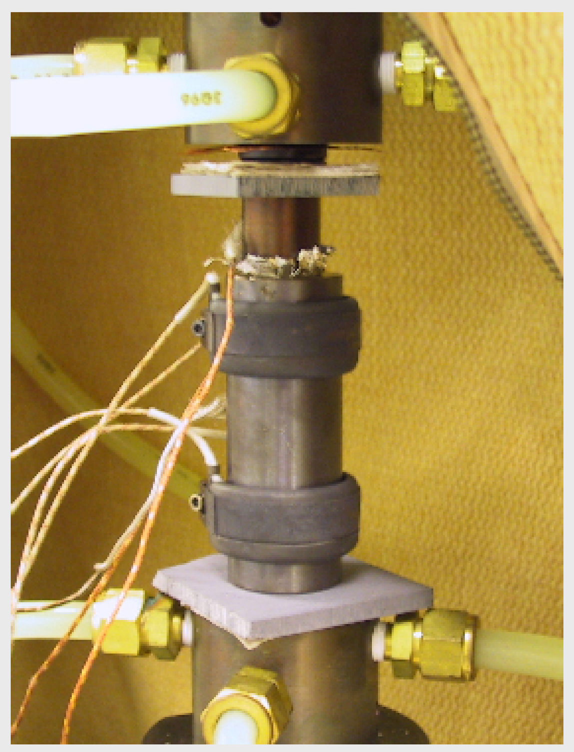




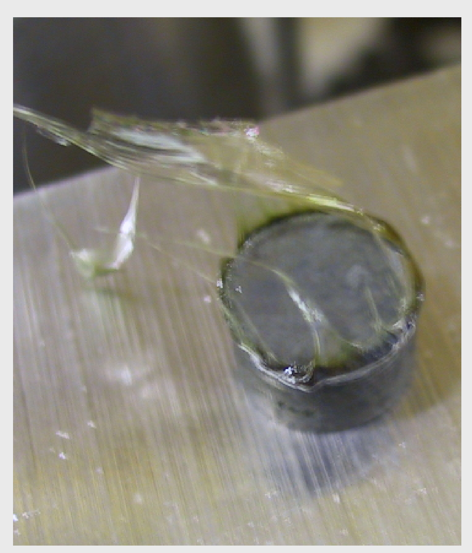


High-Temperature Ultrasonic Coupling Investigation

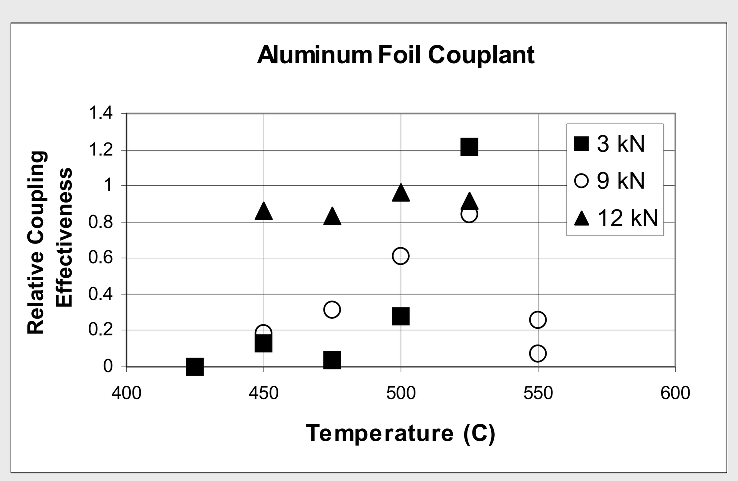
Problem Statement: Unlike audible sonic energy, the high frequency sound waves used for materials testing do not travel well through air. A couplant is therefore required to conduct the sound between the transducer and the test object. Water is generally used; at higher temperatures, commercially available preparations are available for use up to ~600ºC but these tend to have limited use temperature ranges and short use times. To operate at higher temperatures, a coupling medium is required to fill the gap between the sensor and test object.

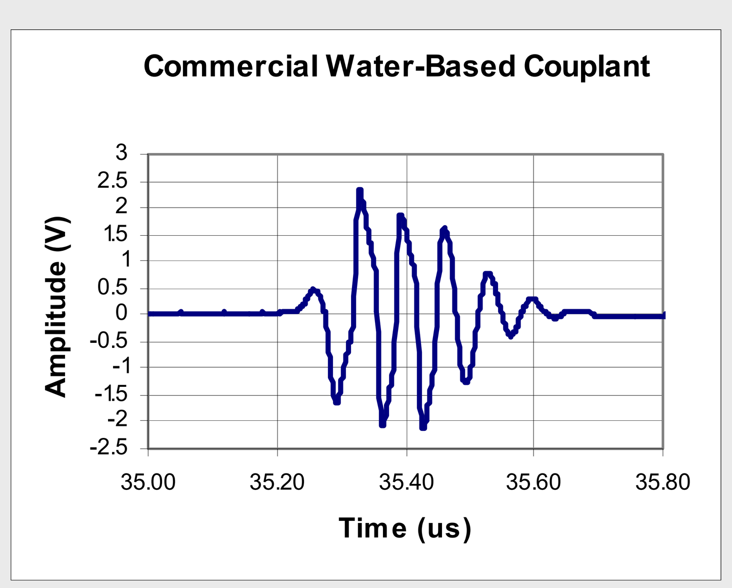


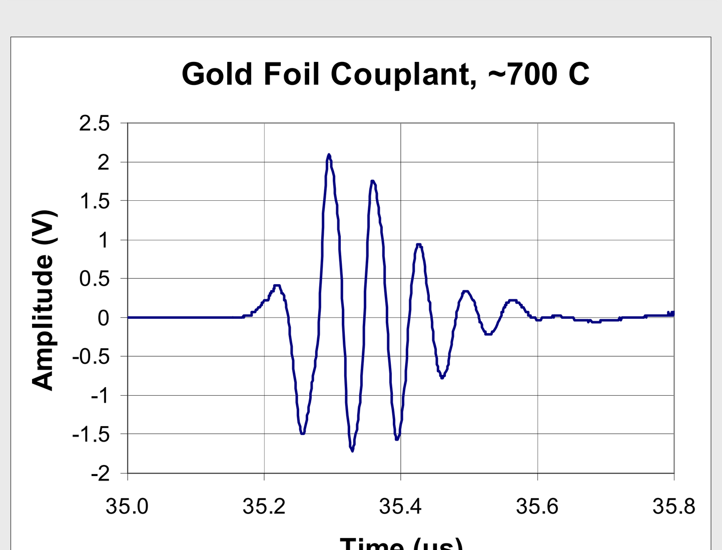
Approach: An extensive literature survey was performed to identify past solutions to this problem. Unfortunately, the technical community appeared to have had limited success in developing ultrasonic coupling methods suitable for use at high temperatures. Metal foil and molten glass couplants appeared to have the most promise for health monitoring applications, and the apparatus shown to the left was designed to test the couplants. An AlN sensor core, couplant layer, and a steel cylinder wrapped with band heaters are placed under compressive load for the test. Temperature and pressure are varied to evaluate the couplant's effectiveness- successful coupling results in an echo from the far end of the cylinder.



Results- Molten Glass: Low-melting-point glasses were selected for initial testing; the figure at the right shows glass drawn off the AlN face of the sensor core after a test. While the glasses do couple sound, they have a limited operating temperature range. There are also concerns about chemical reaction of the glasses with the sensor or test object during long-term exposure.







Results- Metal Foil: Prior experiments with aluminum foil at moderate temperatures indicated that good results could be achieved. Tests were performed on metal foil coupling, beginning with aluminum and progressing to silver and gold. Aluminum and silver both underwent oxidation as their melting points were reached. Gold, however, has a meting point above 1000ºC and good oxidation resistance.

The first graph provides insight into the tradeoffs between temperature and pressure requirements for coupling. Essentially, the foil must be deformed between the sensor and the cylinder. High loads alone will provide the deformation, or elevated temperature will soften the foil, achieving the same effects at lower loads. In many cases, the coupling is retained, even as the temperature and pressure are reduced to ambient conditions.

The other two figures show the first ultrasonic echo in the test cylinder from two different tests. The commercial water-based couplant at room temperature provides a reference to which other couplants were compared. The signal coupled through gold foil reached the same amplitude at 700ºC, proving its effectiveness.

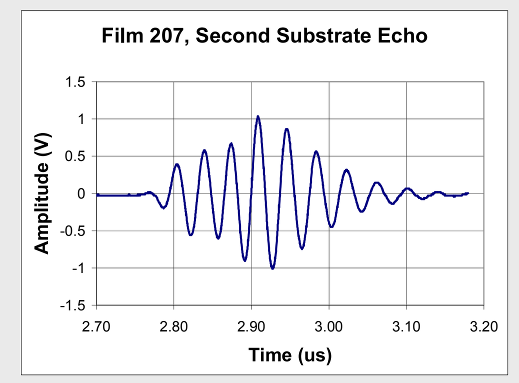
Continuing Research: Recently, coupling has also been achieved using gold leaf, an extremely thin sheet used by artists. While leaf is more difficult to work with than foil, it has a significant cost advantage. In addition, the pressure required for coupling appears to be significantly lower than for foils. Gold leaf coupling is expected to be incorporated into the final sensor design.

Improved Sensor Cores

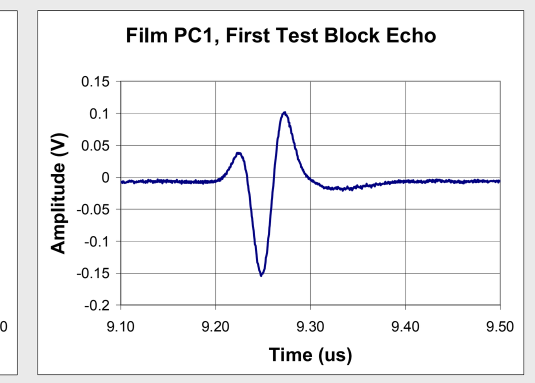
Sensor Cores: Sensor cores consist of a polycrystalline AlN film grown through a CVD process on a conductive substrate. The AlN film is polished to emit coherent sound and to provide a flat surface where an electrode (often the test object) may be added. This core will emit ultrasonic pulses upon the application of a voltage pulse, and will also convert received stress waves to electrical signals which can be amplified and monitored. Prior to this research program, films could be produced only on tungsten carbide (WC) substrates, which have a close thermal expansion match to AlN.

Tungsten Carbide Disadvantages

Poor acoustic impedance match: Like AlN, WC has a high modulus of elasticity. Unfortunately, WC is much denser and has a correspondingly higher impedance. This causes ringing upon the production of a sonic pulse, which is less desirable than a broadband pulse.

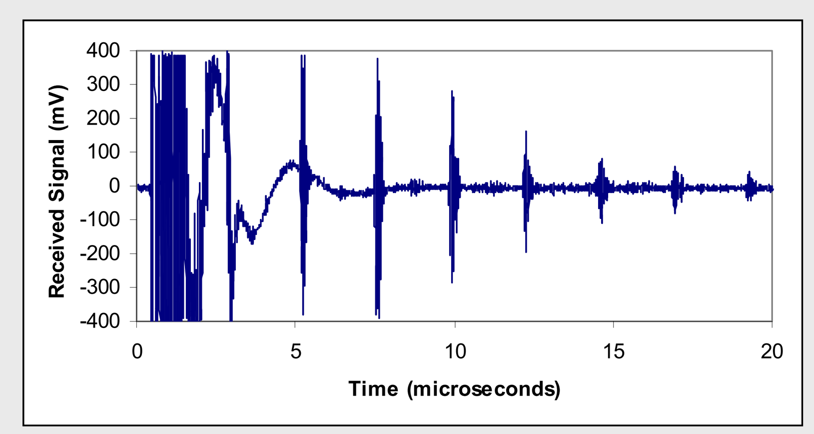


Narrowband



Broadband

Low ultrasonic attenuation: WC possesses a very fine grain structure, leading to minimal scattering or attenuation of ultrasonic energy. Room temperature transducers incorporate an attenuative backing material that prevents sound produced by the transducer from reverberating and producing internal echoes that obscure and confuse returning signals.



A number of alternative materials were considered:

Titanium

- Good impedance match
- Relatively easy to machine
- Might allow for AlN deposition directly onto components
- Poor thermal expansion match

Deposition on grade 5 (Ti-6Al-4V) titanium was unsuccessful; films were successfully deposited on grade 2 (CP) titanium. The unsuccessful attempts generally created a film, but the film disintegrated during cooling to room temperature at the end of the deposition. The process was advanced such that films on grade 2 titanium did survive the deposition process and subsequent polishing. These films produced ultrasonic energy of a strength equivalent to the films on tungsten carbide, but debonded upon reheating above room temperature.

Conclusion: Unsuitable substrate due to thermal expansion mismatch

Also eliminated due to thermal expansion or oxidation concerns:

- Tungsten
- Rhenium
- Molybdenum Disilicide
- Titanium Diboride
- Titanium Carbide

Novel materials considered:

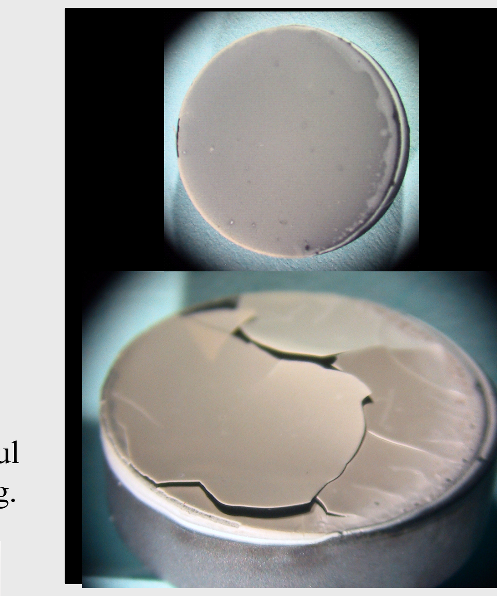
- Conductive AlN
- Titanium Silicocarbide
- Silicon Carbonitride

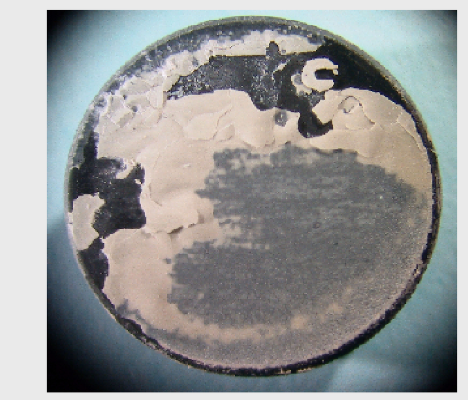
Unpolished AlN on AlN

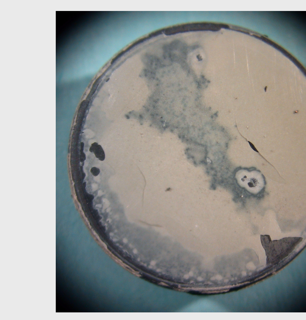
Selected core material: silicon carbide (SiC)

- Good impedance match
- Difficult to shape
- Excellent thermal expansion match
- Available in many forms

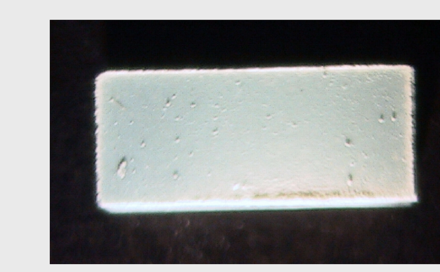
Early depositions on SiC were successful but had adhesion problems upon heating.



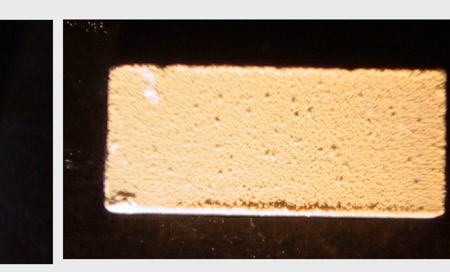




Solution: After trying various reaction bonded, direct sintered, and CVD SiC substrates with minimal success, a "good" material was discovered. It is a porous version of sintered SiC, which helps provide a mechanical bond. The thermal expansion is well matched, and the porosity makes it attenuative- proper shaping of this material should eliminate the undesirable internal echoes.



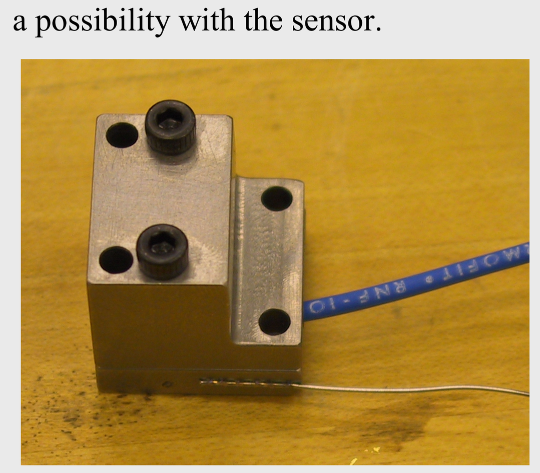
AlN on SiC As-Deposited



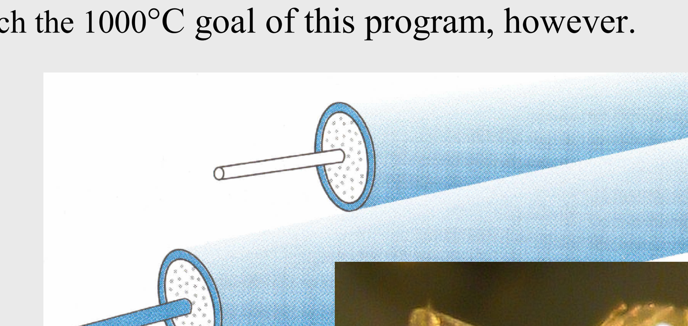
AlN on SiC After Thermal Cycle

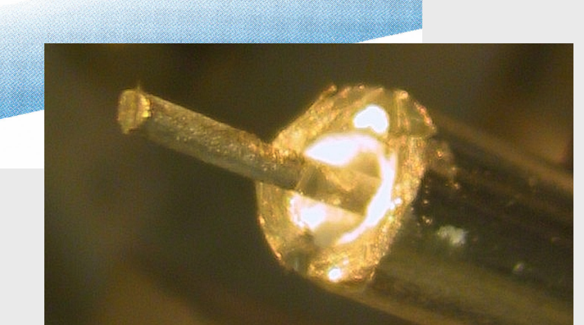
Additional Results / Lessons

Gasifier refractory material is too porous for monitoring with the AlN sensor: Several pieces of Zirchrom 90 refractory brick, used to line portions of gasifiers, were obtained from Saint-Gobain Ceramics and subjected to a number of ultrasonic tests with a commercial transducer. It was determined that the porosity and grain structure of these ceramics will not pass the relatively high frequency ultrasound produced by the AlN transducers. Therefore, refractory monitoring is not currently a possibility with the sensor.



An AlN-based accelerometer functional above 400°C is successful: Although this work was performed under separate funding, it ties in well with the health monitoring goals of this program. Such an accelerometer could be used to look for excessive vibration, or a sudden change in vibration modes that would indicate a possible problem. The maximum temperature of such a device is unlikely to reach the 1000°C goal of this program, however.





Superior mineral-insulated cable was evaluated: Cabling to transmit useful signals into and out of harsh environments is a key to successfully implementing high temperature sensors. Two promising cable types were discovered: MI-Dry and Thermocoax. Thermocoax is readily available and is intended for signal transmission applications; MI-Dry, by Accutru, uses a proprietary mineral insulation which extends the life of thermocouples and is not hygroscopic.

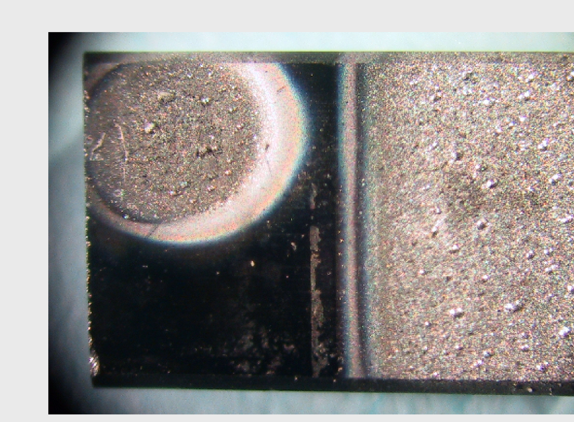
Publication and dissemination of information: An overall goal of the UCR program is to publish and disseminate knowledge acquired during the program. Papers describing this research will be presented later this year at the Review of Quantitative Nondestructive Evaluation (QNDE), Brunswick, ME; and the American Society of Nondestructive Testing (ASNT) Conference, Columbus, OH. In addition, knowledge gained under this program will be further disseminated as portions of future program build upon this work.

Remaining Research

Several items remain to be completed in the final four months of the grant period:

Final evaluation of new sensor cores: The new sensor cores on porous SiC must be more fully investigated. Additional films will be deposited, thermal cycling tests will be completed, and the ultrasonics will be more fully characterized. AlN on unpolished porous SiC does not create a strongly oriented film; polishing decreases mechanical bonding and adhesion and the two must be balanced. An optimum means of attaching a leadwire to the porous SiC must be determined.

Additional testing of films produced by pulsed laser deposition (PLD): Early in the program, several AlN films were deposited on SiC with PLD. The resulting films were too small to be practical for the further investigation, but the technology holds promise for repair of defects in films or for possible small sensors. An ultrasonic test for these films will be performed.



Health monitoring sensor prototype demonstration: The new sensor cores will be used to build up a prototype sensor with a 1000ºC operational goal. The sensor will operate in an oxidizing environment, with gold foil or gold leaf coupling. Both pulse-echo and pitch-catch sensor configurations will be considered. A metal or ceramic block will be used to simulate a component being monitored; the design incorporates appropriate housing materials and takes leadwire issues into account

Final report and conference paper presentation: Knowledge gained during the program will be collated, organized, and submitted as a final report. In addition, conference papers are being prepared.