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DEVELOPMENT OF A HIGH-TEMPERATURE EROSION MONITOR
FOR FBC HEAT EXCHANGER TUBES

by

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ABSTRACT

Metal wastage in tubing of heat exchangers used in fluidized bed combustion (FBC) could affect plant operation and threaten the successful development of FBC technology. Monitoring of such wastage during operation would be very beneficial. The development of a high-temperature erosion monitor was undertaken as part of a larger program to understand and ameliorate wastage processes.

Two sensor principles, i.e., electromagnetic acoustic and piezoelectric transducers based on time-of-flight measurements, were evaluated. Spatial restrictions and high-energy requirements of electromagnetic acoustic transducers favored piezoelectric transducers as a prototype. Requirements for good coupling between sensor and tubing led to the exploration of two methods for accomplishing this task: pressure coupling and brazing. Initial disappointments with brazing led to the construction of a pressure-coupled transducer that was tested successfully to temperatures of up to 500°C. A brazing method to bond the lithium niobate crystal to stainless steel was finally perfected, but will require additional work for brazing to ferritic steel. The prototype pressure-coupled transducer also needs more development to compensate for the expansion of components and oxidation of coupling surfaces.

1 INTRODUCTION

Metal wastage of in-bed heat-exchanger surfaces is a serious problem in the development of fluidized bed combustion (FBC) technology. A project presenting a systematic approach to developing the necessary understanding of the wastage process and formulating guidelines for the design and operation of FBC units was undertaken by the U.S. Department of Energy (DOE) and a consortium of other organizations. One task of the overall project addressed the development of an erosion monitor to provide in-situ measurement of erosion in FBC plants. The envisioned on-line system would be capable of monitoring erosive wear of the fireside (outer) surface of heat-exchanger tubes in FBC systems. The heat-exchanger geometry and operating conditions require the use of one or more boreside sensors capable of long-term operation at temperatures up to 500°C and occasional excursions to higher temperatures. The boreside dimensions of the heat-exchanger tubes (~1.75-in. i.d.) determine the size of the sensors; the desired measurement accuracy and repeatability should be as high as attainable.

2 BACKGROUND

Erosive wear of FBC heat exchangers is produced by energetic solid particles of fuel and sorbent in the fluidized gas stream impinging on the outer surface of metal tubing containing the heat-transfer fluid (water, steam, or air). Locations on the heat exchangers where erosion is most severe can be approximately specified from past observations, from inspection after some wear has been experienced, or prospectively, from computer modeling. Erosive wear gained renewed attention with operation of coal conversion pilot plants. Argonne National Laboratory (ANL) became engaged in the development of a nondestructive metal wastage monitoring system for metallic process lines and vessels.¹ An automatic ultrasonic surveillance system, based on ultrasonic time-of-flight measurements, was developed and

installed in several coal-liquefaction and coal-gasification pilot plants. The system, which precisely assessed wall thickness of process components during plant operation, incorporated conventional ultrasonic transducers that were thermally insulated by specially designed acoustic waveguides attached to a specific point on the outside of the components of interest. Utilization of waveguides was feasible since the wastage occurred on the inside surfaces. Many transducers and waveguides were employed when a wastage profile was desired. The transducers were scanned sequentially from a remote, centralized instrument station, and the ultrasonic responses were automatically converted to indicate the remaining wall thicknesses at the monitored points, taking into account dimensional and ultrasonic velocity changes as a function of temperature. Precise measurements of ± 2 mil (0.05 mm) were typically achieved with steady temperatures.

The successful implementation of waveguides for erosion monitoring in pilot plants motivated a study of electromagnetic acoustic transducers (EMATs)² for use as ultrasonic transducers for erosion monitoring. The main advantage of the EMAT was that no couplant or permanent attachment to the monitoring points was required and an erosion profile could be obtained with a single-scanning transducer. The study showed that, with water cooling, EMATs could be applied to measure wall thickness from the outside to temperatures up to 500°C. However, there were some drawbacks to transducers of this type. They required a higher input power than piezoelectric transducers, had lower signal-to-noise (S/N) ratios, and operated only on metallic materials.

The experience gained from monitoring of material wastage on the inner surface of components was helpful in defining the approach to the problem of erosion measurements from the bore-side of FBC heat-exchanger tubing.³ Previous monitoring-system components, such as automatic gain control transmitters/receivers, sequential switching systems, and computer interfaces with temperature-correction software, could be used without significant modification. Other components, especially the transducer, required significant development effort; conventional off-the-shelf, high-temperature transducers that could operate in the required temperature range were not available.

3 APPROACH

Implementation of piezoelectric ultrasonic transducers for wall-thickness measurement from the bore-side of tubing called for a piezoelectric material with a Curie temperature above 500°C, a damping material that could withstand that temperature, and a bonding method (to attach the crystal to the tubing wall and the damping block) that would yield a good ultrasonic coupling at the required temperature. A high-temperature-resistant coaxial cable to connect the transducer to the ultrasonic pulser/receiver was also necessary. In addition, to adapt the previously investigated prototype EMAT for use in the tube bore, it was necessary to reduce its size drastically.

3.1 Evaluation of Transducers

Both types of ultrasonic transducers, piezoelectric and electromagnetic acoustic, were successfully tested for erosion monitoring of the inside surface of piping and coal-conversion components. Monitoring of FBC heat exchanger tubing from the boreside imposed more severe requirements on the transducers.

3.1.1 Electromagnetic Acoustic Transducers

Measurements of wall thickness were conducted on pieces of tubing removed from the Georgetown University FBC heat exchanger. A flat-surface, shear-wave EMAT with a permanent magnet for the static field was applied to the outside surface of the sample tubing [wall thickness of 0.132 in. (3.35 mm)]. Figure 1 shows the EMAT used in these preliminary tests. Figure 2 displays the ultrasonic multiple echoes from the wall. The elapsed time between successive echoes was 2.1 μ s, which, with an ultrasonic shear-wave velocity of 3.19×10^3 m/s, yields a wall thickness of 3.35 mm (0.132 in.). Implementation of an EMAT for wall-thickness measurements would be advantageous since no couplant is required. This enables operation of a transducer in a scanning mode to pinpoint areas of maximum erosion. There were, however, problem areas. Permanent magnets could not be used at elevated temperatures. An electromagnet in place of a permanent magnet would lose efficiency at elevated temperatures due to a pronounced decrease in yoke permeability. High currents would be necessary to generate a stronger static field in an air-core coil. The whole transducer assembly, moreover, would have to fit inside the tube bore.

A 24-VDC, 140-W relay coil with soft iron core was initially used as the static-field coil. A pancake coil of 50 turns was implemented as the RF coil (Fig. 3). Available power supplies were used to energize the static-field coil with DC ranging from 200 mA to 1 A. The test setup for the RF transmitting/receiving coil is shown in Fig. 4. It consisted of a

Fig. 1.

*Measurement of Wall
Thickness of Sample FBC
Heat-Exchanger Tubing from
the Outside with an EMAT*

Fig. 2.

*Trace of Multiple Echoes Obtained
with the EMAT Shown in Fig. 1
Vertical scale: 0.1V/Div
Horizontal scale: 0.56 μ s/Div*

Fig. 3.

*Experimental EMAT
for Bore-side
Wall-thickness
Measurement*

Fig. 4. Test Setup for EMAT Measurements

pulsed-power oscillator (to supply 1000-V peak power to the RF coil of the EMAT), a receiver with 95 dB gain, and an oscilloscope. The performance of the prototype bore-side EMAT was evaluated on sample tubing and flat specimens and compared with the performance of the permanent-magnet EMAT (shown in Fig. 1). No discernible ultrasonic echoes were obtained from the wall of the sample tubing or flat specimens. Detailed investigation of the performance of the RF pancake coils of both EMATs, with electromagnetic-field measurement and a small coil, showed that the RF coils performed equally well in both EMATs. Measurement of the static field with a Hall probe showed that it was one magnitude higher at the EMAT with the permanent magnet than with the prototype boreside unit (270 gauss versus 24 gauss at 200 mA). A difference of one magnitude in the static field results in a difference of two magnitudes in signal amplitude.

Different coils, pole-piece sizes, and DC amplitudes were tested to increase the magnitude of the static field, with limited success. Small pole pieces resulted in saturation (at 100 gauss), whereas air coils required very high current to sufficiently increase the field (~5000 ampere turns). The high current would require pulsed operation of the static field and cooling provisions. The low frequency of the EMATs (>5 MHz) required high-pass filtering to obtain the desired temporal resolution. In general, EMATs, are 60 dB less efficient at generating and receiving ultrasonic waves than piezoelectric ultrasonic transducers. Piezoelectric transducers, moreover, are smaller. These difficulties with EMATs led to the selection of piezoelectric ultrasonic transducers as more viable sensors for erosion monitoring.

3.1.2 Piezoelectric Transducers

The wall thickness of the sample tubing was ultrasonically measured from the outside of the tube with a commercial 5-MHz, 0.5-in.-o.d. gamma transducer. The transducer generated longitudinal waves with a velocity of 5.9×10^3 m/s in the tube material. Multiple tube-wall echoes are shown in Fig. 5. The time lapse between successive echoes is 1.1 μ s, from which a wall thickness of 3.25 mm (0.128 in.) was calculated. A shoe of ferritic steel was silver brazed, in a vacuum of 10^{-4} Torr, to the inside wall of the sample tubing to match the flat transducer to the tube radius. The vacuum brazing of the shoe resulted in a reflection from the braze and from the outside tube wall, as shown in Fig. 6. The tube-wall thickness was calculated from the two ultrasonic wave reflections and served to monitor the erosion losses.

Fig. 5.

*Trace of Multiple Echoes
Obtained with 5-MHz Commercial
Piezoelectric Transducers
on the Outside of the Tube.
Vertical Scale: 0.2 V/Div;
Horizontal Scale: 0.5 μ s/Div*

Fig. 6.

*Reflections from Braze between
Insert and Tube Obtained with
Commercial 5-MHz Transducer.
Vertical Scale: 0.5 V/Div;
Horizontal Scale: 0.5 μ s/Div*

High-temperature operation of the erosion sensors necessitated the selection of a high-Curie-temperature piezoelectric crystal such as lithium niobate and the procurement of a high-temperature ultrasonic damping material. The damping component in commercial ultrasonic transducers is made from epoxy that contains high concentrations of tungsten powder.

A 5-MHz lithium niobate crystal was tested in the sample tubing with a sintered aluminum-tungsten powder cylinder as the damping member. The crystal was coupled to the shoe and damping block with an ultrasonic coupling gel. Ultrasonic echoes of this arrangement are shown in Fig. 7. The results indicate that the desired features could be attained with proper coupling. A solid, ultrasonically transparent bonding was necessary for high-temperature application. Crystal brazing or high-temperature cement proved to be the most logical bonding methods. The damping block would have to be fabricated of different matrix material than aluminum for high-temperature applications. The crystal brazing assembly is shown in Fig. 8.

3.2 Assessment of High-temperature Cable

High-temperature cables with single or multiple conductors are commercially available (e.g., from GMI of Addison, IL). Single-conductor, stainless-steel-sheathed coaxial cable with magnesium oxide insulation was obtained and tested at room temperature in conjunction with a 5-MHz commercial transducer. The cable had an o.d. of 4.76 mm (3/16 in.) and a capacitance of 1 nF/m. Commercial coaxial transducer cables (Type RG-174/V) have a capacitance of 100 pF/m. The ultrasonic driving and reflection echo pulses were identical for the high-temperature and standard coaxial cable at room temperature. The high-temperature coaxial cable was therefore judged as applicable for erosion monitoring. The manufacturer-recommended temperature range for these cables extends to 2000°C.

3.3 Development of Damping Block

The sintered aluminum-tungsten damping component for the transducer exhibited the desired properties but posed potential bonding problems. Copper was selected as an alternate matrix material for the damping component. Three compositions of copper-tungsten (15-, 30-, and 45-wt.% tungsten) were prepared by powder metallurgy processes and sintered for 1 h at 810°C in vacuum. Damping properties were subsequently determined by ultrasonic amplitude measurements in the pulse-echo and through-transmission modes. The results indicate that the 45-wt.% tungsten damping cylinder would attenuate ultrasonic waves one order of amplitude (20 dB) higher than the block with 15-wt.% tungsten; therefore, it had the best damping properties. The damping block was subsequently tested in the sample tubing with a 5-MHz lithium niobate crystal and ultrasonic gel couplant. The trace of the signal was identical to that shown in Fig. 7, qualifying it for incorporation into the high-temperature sensor.

3.4 Development of Bonding Technique

A piezoelectric sensor requires good coupling between the crystal and the specimen in order to properly operate as a generator/receiver of ultrasonic vibrations. To achieve good coupling, commercially available couplants are used at room and slightly elevated temperatures. There is, however, no couplant on the market that sustains the coupling properties at prolonged exposure to 500°C or temperature cycling near this temperature. Three approaches to developing other coupling methods for the erosion monitor were explored: (1) dry pressure-coupling, (2) bonding with high-temperature cements, and (3) brazing with suitable materials.

Fig. 7.

**Reflections as in Fig. 6,
with Lithium Niobate
Crystal, Damping
Block, and Ultrasonic
Couplant. Vertical Scale:
0.5 V/Div; Horizontal
Scale: 0.5 μ s/Div**

Fig. 8. Arrangement for Brazing Crystal to Shoe inside Sample Tubing

3.4.1 Dry Pressure-coupling

A special yoke was designed and built to facilitate dry coupling on flat, ferritic steel specimens of approximately the same thickness as the sample-tube wall. The materials used for the dry couplant included: 0.5-mil and 3-mil aluminum foil, 3-mil gold foil, and yttrium chromite in both fine powder and slurry form. Pressure was applied by tightening the bolts with a torque wrench to a maximum of 5000 Nm (3690 lb/ft). The couplant was applied on both faces of the crystal. Two types of surfaces on the flat specimens were tested: one flattened on a grinder and the other highly polished by 300-grit abrasive. The best coupling was achieved with the 0.5-mil aluminum foil, although it was still inferior to ultrasonic gel couplant. The polished surfaces exhibited slightly better coupling than the ground surfaces. In all cases, the crystal was cracked by the high-pressure forces needed for coupling. The required coupling pressure would impose problems at 500°C operation because of elongation, distortion, and loss of pressure.

3.4.2 Bonding with High-temperature Cements

Two high-temperature cements, Sauereisen and Omega, were used to attach the crystal to the specimen and damping block. Although the mechanical bond was good, ultrasonic performance of the samples was poor, i.e., very little ultrasonic energy could be introduced into or received from the specimen. Closer examination revealed that small bubbles developed during the curing process and the coupling layer became very porous, thus scattering ultrasonic energy. Both cements attacked the surface of the flat ferritic steel sample and the damping block. These high-temperature cements were deemed unsuitable for bonding.

3.4.3 Brazing

The joining of ceramic parts to metal by brazing has found wide application in industry. It is a more difficult process, however, when the ceramic is a single crystal such as lithium niobate. Different brazing materials, processes, and crystal-surface preconditioning were evaluated. To prevent crystal damage, the manufacturers of lithium niobate crystals recommend slow heat-up and cool-down times (max. 200°C/h) for such operation.

As a first approach, 1-mil-thick braze shim material (Braze No. 603/604 AWS A5.8.B Ag-18 by Handy and Harman) was sandwiched between the crystal and shoe in the sample tubing and between the crystal and damping block to simultaneously effect brazing of both components. Brazing was performed in a vacuum of 10^{-6} Torr at 660°C. The assembly was maintained at this temperature for 15 min before cool-down. Heating and cooling rates were 200°C/h. The crystal had sputtered platinum electrodes on both surfaces. This brazing operation resulted in satisfactory mechanical bonding between the crystal and the ferritic shoe, but no bonding to the damping block. Because the crystal moved "off center" during brazing, the ultrasonic quality of the bond could not be assessed.

The same brazing operation was repeated, under identical conditions, using a crystal with thicker bias-sputtered platinum electrodes and evaporated gold electrodes. These brazing operations caused lift-off and dissolution of the electrode materials without bonding.

Lucanex 559 brazing paste (manufactured by Lucas-Milhaupt, Inc.), was used in subsequent experiments. The optimum brazing temperature for this paste is 925°C; a minimum pressure of 10^{-4} Torr is recommended for the vacuum (or inert gas) brazing procedure. This paste was deposited as crystal electrodes by air brazing and resulted in good adherence to the crystal with no metallic appearance. Vacuum brazing of two copper cylinders, one on either side of the crystal, resulted in good bonding. Ultrasonically, the cylinders provided low damping and therefore long ring-down time.

The vacuum brazing operation was repeated with a crystal and damping block placed on the shoe of the sample tubing, resulting in a good bond between the crystal and damping block, but a poor bond between the crystal and the shoe in the sample tubing. The copper in the damping block appeared to enhance bonding to the crystal during vacuum brazing. The lithium niobate crystals discolor when heated in vacuum because of the internal migration of lithium atoms. The process can be reversed by reheating the crystal in air or oxygen.

In 1988, investigators in France successfully developed process sensors by brazing lithium niobate to titanium with a DuPont conductive paste. This paste, a platinum/silver conductor composition (DuPont No. 9770), was acquired and tested. A crystal with sputtered electrodes was air brazed at 850°C to a stainless steel cylinder. A very strong mechanical bond resulted and showed good ultrasonic properties. Due to the lack of damping, the transducers had a long ring-down time, as shown in Fig. 9. A procedure similar to that implemented by the French investigators was applied to increase the damping properties of the crystal. The nonbonded surface of the crystal was ground concave with a radius of 75.7 mm (2.98 in.), equal to a diopter of 7.00. Grinding the crystal broadened its frequency spectrum, thus effectively introducing more damping, as shown in Fig. 10. A very thin layer (>200 Å) of gold was evaporated onto the stainless steel cylinder prior to the air brazing to protect the surfaces from oxidation.

In a subsequent brazing experiment, a crystal ground concave on one surface was air brazed to the shoe in a sample tube. The ferritic shoe material oxidized heavily during the brazing operation because no protective layer of gold was applied. While the flow of the brazing material was very uniform, it lifted off after cooling, forming a layer of scale during brazing. The same result occurred when attempting to braze a crystal to a copper cylinder representing a damping block. It is evident that for air brazing with DuPont paste 9770, the components must be coated with some nonoxidizing material such as a noble metal.

4 PROTOTYPE PERFORMANCE

Initial difficulties encountered in brazing lithium niobate crystals to ferritic steel components caused renewed interest in pressure coupling. An assembly, shown in Figs. 11 and 12, was designed and constructed. The tungsten-copper damping block, which was destroyed in one of the brazing experiments, was replaced by a tungsten-filled Sauereisen cement block. The assembly was placed in an oven and the temperature was increased slowly to ~500°C. Temperature measurements were performed with a chromel-alumel thermocouple and an "Omegatemp" digital-readout instrument. The assembly was kept at each set temperature (every 100°C) for 0.5 h to allow for equilibration. The expanded ultrasonic signal was recorded at every 100°C interval, and the elapsed time was registered. Figures 13 and 14 show the ultrasonic reflections at 21°C (room temperature) and at 518°C, respectively. Table 1 lists the elapsed times, ultrasonic velocities, and calculated wall thicknesses. The ultrasonic velocities were extrapolated from the 2-1/4 Cr-1 Mo data shown in Fig. 15.

As shown in Table I, the wall thicknesses measure within ±1 mil when ultrasonic velocity variations are corrected as a function of temperature. The following observations were made during the temperature test run: (1) the coupling deteriorated with temperature, owing to expansion; (2) the pressure screws had to be tightened at ~300°C to restore the coupling and obtain a signal with adequate S/N ratio; and (3) the response after cool-down to room temperature exhibited a higher noise level than before the temperature test run, probably owing to partial oxidation of the contact surfaces. It is evident that pressure coupling is a viable solution to the erosion monitor design, but some modifications need to be implemented to overcome some of the shortcomings encountered in the prototype model.

Fig. 9.

*Brazed -Crystal Response
from a Stainless Steel
Cylinder; No Damping
Block*

Fig. 10.

*Response of Same Crystal
as in Fig. 9, after
Grinding One Crystal
Surface Concave; No
Damping Block*

Fig. 11. Diagram of Pressure Coupling Arrangement

Fig. 12. Prototype Used in Temperature Experiments

Fig. 13.

*Backwall Reflection
of Pressure-coupled
Transducer at 21°C*

Fig. 14.

*Backwall Reflections
of Pressure-coupled
Transducers at 518°C*

Table 1. Parameters of Wall Thickness Measurements

Temp., °C	Elapsed Time, 10 ⁻⁶ s	Ultrasonic Velocity, 10 ⁵ cm/s	Wall Thickness	
			mil	mm
22	0.982	5.94	115	2.92
105	0.984	5.90	114	2.90
204	0.998	5.84	115	2.91
313	1.016	5.76	115	2.93
406	1.036	5.70	116	2.95
518	1.056	5.59	116	2.95

Fig. 15.

Measured Ultrasonic Velocity Changes as a Function of Temperature for Various Metals

5 DISCUSSION AND CONCLUSIONS

The investigation demonstrates the viability of two approaches to the construction of high-temperature ultrasonic erosion monitors. One of them, a pressure-coupling technique, was developed to the prototype stage and tested up to 500°C. Recently, it has been shown that lithium niobate crystals can be brazed to stainless steel and the damping block requirement can be avoided when one of the crystal surfaces is shaped. Additional effort is required for both approaches. The design of the pressure-coupled transducers will need modification to compensate for coupling deterioration by the elongation of components at elevated temperatures. Protection of surfaces facing the crystal by coating with noble metals may be required for temperature cycling. Brazing of the insert (shoe) into a piece of sample tubing will require reforming of the tube to obtain a good fit and, subsequently, a good ultrasonic braze.

Air brazing of the crystal to an insert requires coating of the surface to prevent oxidation, as pointed out earlier in the text. The temperature range of the crystal-tube-insert braze will have to be assessed. Raising the brazing temperature of the tested experimental assembly to 850°C introduced a much higher noise level after cool-down. It should be established whether concave or convex shaping of one crystal surface would be more advantageous in deleting the damping block. It is anticipated that, from a coupling standpoint, the brazing method would be more advantageous than pressure coupling because it appears to be more stable.

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