The Solution for Quantitative Continuous Wall Thinning Measurements in High Temperature Field Applications

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Abstract
There have been many structural failures in power plants and pipeline industry caused by Flow Accelerated Corrosion (FAC). This damage has led to catastrophic failures and fatalities in the past. A reliable solution for a continuous monitoring of wall thickness loss in high temperature applications when exposed to the effect of flowing fluid is a strong requirement and the problem is still unresolved for power, oil & gas and pipeline industry due to lack of reliable permanent monitoring solutions. Applus RTD has been involved in the investigation of phenomena for a number of years and developed an early warning system that continuously monitors corrosion/erosion in high temperature applications accurately. The introduced system is a multi-channel ultrasonic equipment, capable of recording thickness readings simultaneously from a number of channels. The proposed system provides repeatable & reliable measurements within a temperature range of -60 to 500 °C and an accuracy of ~ 50 - 100 micron. The system is currently in testing and will be installed in some facilities in Europe and Americas for in-service and live inspection.

Keywords: Permanent monitoring, continuous inspection, flow accelerated corrosion, high temperature UT

1. Introduction

Current practices for inspection of oil & gas and power plant equipment is to carryout inspection during maintenance shutdown of plants, causing huge logistic problems and at a considerable cost. There is a clear trend in the industry to apply the concept of structural health monitoring (SHM) in order to increase reliability of equipment and minimize the shutdown inspection and maintenance time & cost. SHM techniques to these industries require sensors that are able to maintain high performance for many years in high temperature operational environment.

Some SHM Monitoring Solutions based on Ultrasonic Wall Thickness Measurements are available in the market, but they only address low temperatures environments. For oil and gas power plant industry, this temperature limitation is a huge constraint for the development of real time structural health monitoring solutions. Applus RTD is working for several years, to develop a SHM monitoring solution, for reliable measurements of wall-thickness loss due to corrosion /erosion in oil & gas and power plant industry. Since many equipment & structures
of interest in this industry sector operate at high temperature, the sensors in contact with the
equipment surface must continuously operate with required performance for many years at
these elevated temperatures.

The main application of SHM sensors is to install them permanently on the structure for
continuous sensing, e.g., thickness changes due to corrosion, erosion or crack initiation and
growth due to fatigue. The advantage over current technologies by periodic inspections, are
the shorter intervals between inspections (can be real time), the lower cost per inspection, no
need of special arrangements or material to have access to the inspection surface (e.g. taking
out thermal insulations) and an improved sensitivity due to permanent ultrasonic coupling.

This presentation covers a summary of design, development and testing of ultrasonic
transducers capable of monitoring continuously for wall thickness losses in high temperature
operations. Long term continuous monitoring results with different sensor configuration and
several temperature ranges are also presented.

2. Sensors for Permanent SHM in High Temperature Applications

Sol-Gel coating based sensors for structural health monitoring in high temperature
applications are being developed for more than 10-years. These sensors can be fabricated on-
site on the structure surface as Integrated Ultrasonic Transducers (IUT), or fabricated on thin
substrates to be bonded to the structure surface as Flexible Ultrasonic Transducers (FUT).

The technology of fabricating sensors using Sol-Gel is well documented, but needed a fair
amount of development work for making the technology viable in high temperature field
applications. Therefore, the efforts are concentrated for development of coupling, bonding
and attaching methods with extended performance evaluation.

2.1 Development of Coupling, Bonding and Attaching Methods

Soft metals are known to be interesting dry couplant options for high temperature
permanently attached ultrasonic transducers. To act as a couplant, the soft metal need to be
filling the roughness spaces between the surfaces of the transducer and structure to be
inspected. Typical stress (or mechanical pressure) needed for the soft metal to conform to the
roughness of the surfaces is quite high and difficult to apply in practical situations. One option
is to heat the soft metal to temperatures comparable to their melting points. Several soft
metals. The procedure has been tested for configurations where the piezo-film was fabricated
in pipe clamps.

According to temperature and materials restrictions, several soft metals, e.g., gold, tin,
aluminium & zinc are used as coupling materials. The ultrasonic transmission through a solid
coupling layer has two main constraints:

- First there is always some mechanical impedance mismatch among the metal foil, transducer
  and the material to be tested,
- Second, the surface of the coupling layer must be in an intimate physical contact with the
  transducer and materials surface to be inspected

In order to improve the partial physical contact imposed by the roughness of solid test
material surface, sufficient pressure must be applied in order to force a plastic deformation of
the couplant layer to fill the micro irregularities of a rough surface of transducers and material
to be inspected. Typical stress (mechanical pressure) needed for the soft metal to conform to
the roughness of the surfaces is quite high and difficult to apply in practical situations. One
option is to heat the soft metal to temperatures comparable to their melting points. An
experiment is conducted, where the aluminium foil is used as couplant for ultrasonic inspection, using FUTs. Figure 1 shows the schematic for the bonding and the resultant FUT bonded on the pipe sample. The same figure also shows the signal obtained on this FUT. The signal is very strong; echoes are clearly visible and should allow a fairly precise thickness measurement. This configuration, can also provide a possibility of filed fabrication of transducers with soft metal bonding in high temperature applications.

Figure 2 illustrate the latest “clamp design”, which is especially adapted to FUTs, as the entire transducer is fabricated before installation. The installer will only need to prepare the material surface, use bonding and apply the clamp. The main components of this design are:

- Electrical Insulation Layer – They need to be flexible and should sustain high temperature. Mica foils and thin fiberglass textile is currently being tested,
- Electrical Conductor Layer – Electrical connectors must be isolated from each other and form the transducer and clamp,
- Clamps – Commercially available circular clamps can be used for straight tubular structures or low curvature cylindrical objects. For more complex geometries, e.g., elbows and T-joints, fiberglass or metal textile can be used to have a more flexible clamp.

![Figure 1](image1.png)

**Figure 1.** Transducer bonded on a pipe-section after heating aluminium foil and signals obtained

![Figure 2](image2.png)

**Figure 2.** Exploded view of “clamp design” high temperature transducer transducers

Tests on “clamp design” configuration are conducted on “as-is” basis. A single element transducer based design (as shown in Figure 3) is manufactured and tested for 32 hrs at 220°C. Figure 3 shows the signal strength from single-element transducer configuration.
during the entire testing period. The curve showed that the signal strength decreased (while heating), and stabilized after some hours of starting the test.

Figure 3. Exploded view of “clamp design” high temperature transducer transducers

2.2 Transducer Assemblies for Long Term Performance Evaluation

Several FUT assemblies with silver paste & soft metals as couplants (with or without clamps) and IUT were configured for long term performance evaluation.

2.2.1 Experimental Results, using Silver Paste as Ultrasonic Couplant

There are many configurations considered for long term durability tests. One of the promising configuration is shown in Figure 4, which is designed to have long term performance for temperatures of up to 200°C and higher. The assembly is configured with Silver-paste as ultrasonic couplant and 2 mica layers with electrical conductors in between. As an initial test, the transducer was put in a furnace at 300°C and have its signals monitored for 2-days and the results are included in Figure 4. There is a clear decrease (~ 5%) in the amplitude of the first echo, which is less apparent for the subsequent echoes.

Figure 4. Transducer Assembly, with Silver Paste as Couplant (on left) and Signals Obtained

2.2.2 Experimental Results, using Tin Foil as Ultrasonic Couplant

Tin has the potential to be a good option as solid ultrasonic couplant. As its melting point is 232°C, its use is limited to temperatures of about 200°C. A 25 µm tin-foil (Sn 99.95%) is used and an FUT sensor assembly is clamped on a cylindrical section (Figure 5). The Figure 4 also shows signals obtained at 190°C after being for 15 hrs at this temperature. The signals are quite strong with good signal to noise ratio. This assembly will be placed in a furnace, operating at 200°C for long term performance evaluation, as discussed in Paragraph 3.
2.2.3 Experimental Results, using Zinc Foil as Ultrasonic Couplant

Figure 6 shows the assembly of transducer with zinc used as ultrasonic couplant and the signals obtained after heating the assembly for 2 hrs in 350°C operating temperatures. This assembly will also be placed in a furnace, operating at 300°C for long term performance evaluation, which is covered in Paragraph 3.

2.2.4 Experimental Results, using Gold Foil as Ultrasonic Couplant

An assembly with 25 μm gold-foil as couplant was prepared in order to do a preliminary evaluation. The assembly is similar to that used for other metallic foils. To provide better uniformity and higher pressure on the gold foil, a thicker but shorter mica-layer is used. The pressure, as indicated by a pressure sensor film, is estimated to be higher than 10 MPa. Figure 7 shows the signals obtained for the two transducer of the assembly at different stages.
Figure 7. Transducer Assembly, using Gold Foil as Ultrasonic Couplant and signals obtained for two transducers at different operating temperatures

First (just after assembly), echoes are weak, indicating a bad coupling behaviour. After heating for one hour at 300°C, signals are only slightly stronger. Signals became significantly stronger and echoes are clearly visible for both assemblies after being left in the furnace for 1-hr at 500°C. This indicates that at this temperature the gold foil softens and become an effective couplant.

2.2.5 Fabrication of Integrated Ultrasonic Transducers (IUTs)

For comparing performance of assemblies using FUTs with soft metal and silver paste as couplants, IUT assemblies where the film is deposited directly on the pipe was fabricated. It is expected that the bond between the pipe surface and the film will have the same behaviour as between the film and the FUTs’ foil. Therefore, the only difference between the IUT configuration and that of FUTs assembly should be coupling effect. IUTs were fabricated on two pipe samples, one for testing and comparison at 200°C and the other at 500°C. Figure 8 shows the assemblies and signals from selected sensors right after fabrication completion.

Figure 8. IUT Transducer Assemblies for 200°C & 500°C Operational Temperatures
3. Extended Performance Evaluation of SHM Sensor Assemblies

Hardware and software for extended SHM Sensor performance evaluation at higher temperatures was developed and configured. Figure 9 shows the hardware and software for continuous performance monitoring, which consists of a 32-channel multiplexer connected to an ultrasonic pulser-receiver.

![Figure 9. Furnaces used for extended time evaluation of transducer assemblies and computer hardware for continuous monitoring of sensor performances](image)

Transducer assemblies are placed in furnaces for long term performance monitoring. Different assemblies are placed in respective operating temperatures at different occasions. The furnaces are continuously set on selected temperatures and to-date, the sensor assemblies are being continuously monitored (Figure 10).

![Figure 10. Pipe samples with Transducer Assemblies FUTs & IUTs are placed inside the Furnaces for Continuous Performance Evaluation & Monitoring](image)

Transducer assemblies are placed in furnaces for long term performance monitoring. Different assemblies are placed in respective operating temperatures at different occasions. The furnaces are continuously set on selected temperatures and to-date, the sensor assemblies are being continuously monitored (Figure 10).
3.1 Long Term Testing & Performance Evaluation for Selected SHM Sensors

Assemblies are placed in furnaces for continuous performance monitoring on different dates and following pipe samples are being monitored continuously for long term performance evaluation.

3.2.1 Monitoring Sensors at 200°C FUT Bonded to a Pipe Sample with Silver-Paste

Two (2) Transducers assembled with Silver-Paste as the bonding agent (ultrasonic couplant, PzT/PzT FUT Assembly) and continuously monitored in operating temperatures of 200°C since Jan. 28, 2011. Both sensors are continuously monitored for 167-days. Figure 11 shows the signal strength for both sensors. The amplitude is decreased during initial days, but became stable since then, with an apparent small decrease in last few weeks.

![Figure 11. A-Scan signals at 167th day, as well as the Echo-Amplitudes collected continuously for entire period with transducer assemblies at 200°C operating temperatures](image)

3.2.2 Monitoring Sensors at 200°C FUT Bonded to a Pipe Sample with Tin-Foil

Two (2) Transducers assembled with Tin-Foil as the bonding agent (ultrasonic couplant, PzT/PzT FUT Assembly) and continuously monitored in operating temperatures of 200°C since Feb. 2, 2011. Figure 12 shows the evolution of signal strengths at high temperatures. The signal strength of one transducer keeps increasing, and the reason for this signal increase is probably a better coupling due to the better conforming of coupling foil to the pipe surface as well as with the surface roughness of FUT by plastic deformation at higher temperatures. The signal strength of the other transducer has decreased a little, but was still better than the strength it showed at the beginning of the tests. These results are encouraging, but much longer-term monitoring is needed to have confidence in this configuration.
3.2.3 Monitoring Sensors at 300°C FUT Bonded to a Pipe Sample with Zinc-Foil

Two (2) Transducers assembled with Zinc-Foil as the bonding agent (ultrasonic couplant, BiT/PzT FUT Assembly) and continuously monitored in operating temperatures of 300°C since Feb. 10, 2011. The evolution for of signal strength for 124-days, for this assembly is shown in Figure 13. The signal strength decreased for the first few weeks, but stayed stable mostly thereafter and now seems increasing for last couple of months. Longer term monitoring is needed to provide better view of the behaviour on this configuration.

Figure 12. A-Scan signals at 162th day, as well as the Echo-Amplitudes collected continuously for entire period with transducer assemblies at 200°C operating temperatures.

Figure 13. A-Scan signals at 154th day, as well as the Echo-Amplitudes collected continuously for entire period with transducer assemblies at 300°C operating temperatures.
3.2.4 Monitoring Sensors at 500°C FUT Bonded to a Pipe Sample with Gold-Foil

Two (2) Transducer assembled with Gold-Foil as the bonding agent (ultrasonic couplant, BiT/PzT FUT Assembly) and continuously monitored in operating temperatures of 500°C since Mar. 10, 2011. The evolution of signal strength for 126-days, for this assembly is shown in Figure 14. The signal strength of both transducers is increased at the beginning, became stable and now it is decreasing for past few months. The reason of this decrease is not clear, stress relaxation can be one of the reasons or there may be some other variables accounting for this decrease.

![Figure 14](image)

Figure 14. A-Scan signals at 126th day, as well as the Echo-Amplitudes collected continuously for entire period with transducer assemblies at 500°C operating temperatures

3.2.5 Monitoring of a Sol-Gel Spray (IUTs) Sensor on a Pipe Sample at 200°C

A Transducer is fabricated with Sol-Gel Spray method (BiT/PzT IUT Assembly) and continuously monitored in operating temperatures of 200°C since Mar. 11, 2011. Electrical contacts for this assembly are also engineered for continuous monitoring and performance evaluation at elevated temperatures. As shown in Figure 15, the continuously monitored signals are showing a constant increase in signal strength for 125-days the assembly has been continuously in high operating temperatures.

![Figure 15](image)

Figure 15. A-Scan signals at 125th day, as well as the Echo-Amplitudes collected continuously for entire period with IUT assembly at 200°C operating temperatures
3.2.6 Monitoring Sol-Gel (IUT) Sensors on a Pipe Sample at 500°C

Two (2) Sol-Gel spray BiT/PzT integrated transducers fabricated on stainless steel pipe sample and placed in a 500°C operating temperatures since Mar. 11, 2011. Connections for two transducers were made for monitoring at high temperatures. The evolution and signal strength of a two transducers for 125-days is shown in Figure 16. Signal strengths increased or were stable for the first month, and have been stable or slightly decreasing during the last few months. One transducer has become very unstable. The reason for this signal strength variability will be verified, but it is suspected to an electrical connection problem.

![Figure 16. A-Scan signals at 125th day, as well as the Echo-Amplitudes collected continuously for entire period with IUT assembly at 500°C operating temperatures](image)

3. Conclusion

For assemblies put into furnaces in operating temperatures of 200°C, the signals have been mostly stable for all configurations. The signal strength is slightly increasing for the BiT/PzT IUT assembly, quite stable for the silver-paste as couplant assembly (have shown fluctuation, but, generally very good signal strength for tin-foil as couplant assembly). The results span over 5-months of monitoring, suggests that for 200°C, many reliable solutions are possible. Longer time testing is needed for more reliable conclusions, but results until now are encouraging.

The sole assembly at 300°C (zinc-foil as couplant material), the signal strength was already weak for the beginning and decreased further in the first several week at higher temperatures. Although the signals are stable for last few months, but still would be too early to conclude about the performance. This can be a solution for the temperature ranges where the assembly is used.

The assemblies at 500°C, showing stable signals for one of IUTs (whereas the other seems to have some electrical connection issues) and for the FUTs with gold-foil as couplant assembly signal has been continuously decreasing for the last few months after having an increase in initial months. These results suggest that at 500°C the operating conditions are much more challenging than at 200°C and the present configurations have not yet demonstrated that it could be the final solution for longer term continuous monitoring at high temperatures.

References