Development of HOIS/NZTC guidance for ultrasonic NDT for non-intrusive inspection at elevated temperatures

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Abstract

The non-intrusive inspection (NII) of pressure vessels using external in-service ultrasonic NDT has multiple advantages compared to internal visual inspection, including the significant reduction of down-time related costs and safety benefits from avoiding man-entry into vessels. The HOIS joint industry project, with support from the Net Zero Technology Centre (NZTC), has recently been focussing on NII of components with operating temperatures of up to 250°C (typical of upstream applications). These inspections are challenging because they require probes to be in contact with the hot surface much longer than for spot thickness measurements.

The aim of the work has been to develop recommendations for in-service inspection of components at relatively high operating temperatures, thereby extending the benefits of the NII process, including avoiding or deferring internal visual inspection, to a wider range of vessels. Experimental trials have been performed on test components at up to ~250°C, with an emphasis on scanning ultrasonic systems used for corrosion mapping and weld inspection using TOFD and angled-beam phased-array (PA). The most successful trials gave corrosion mapping and TOFD weld examination results that had similar differences from benchmark values to those achieved in earlier ambient temperature trials. For angled-beam PA, it was found that some trials appeared to have issues with accurate correction of the data for the effects of the elevated component temperature on both the refracted beam angle and signal arrival times. Other trials were more successful in this respect. The lessons learned from trials on both ex-service and manufactured samples are leading to the development of specific guidance for NII at elevated temperatures.

The paper highlights the technical challenges associated with ultrasonic scanning systems at elevated temperatures, share the lessons learned from the experimental trials and summarise the guidance developed.

KEYWORDS: Guidance; good practice; non-intrusive inspection of pressure vessels; elevated temperatures; corrosion mapping.
1. Introduction

Reduction of down-time related costs and improvements in the safety of operation and inspection, compared to internal visual inspections, make external in-service ultrasonic inspection (or the non-intrusive inspection process, NII) increasingly attractive for asset owners and operators in energy industries.

The long running joint industry project on advancing NDT for the energy sector, HOIS, has previously developed publicly available guidance for the non-intrusive inspection of pressure vessels [1] and a recommended practice for precision corrosion mapping for periodic corrosion mapping which is confidential to HOIS members [2]. However, the guidance does not include recommendations on how to address the very specific challenges of in-service inspection of components at elevated temperatures.

This HOIS project focuses on inspection of upstream online inspection where the maximum surface temperatures are typically up to about 250°C, with many temperatures often considerably lower. At temperatures higher than 70-80°C there are challenges in performing ultrasonic inspection which typically include:

- Inspector safety
- Material property changes of steel with temperature including ultrasound velocity changes and increased ultrasound attenuation and scatter
- Material property changes in the probe shoe or wedge with temperature
- Requirement for high temperature ultrasonic probes, wedges and couplants
- Consideration of dwell time/duty cycle, depending on probe designs used
- Scanner considerations – materials, lubricants, and magnetic wheels
- Lack of availability of good practice guides and/or standards.

For downstream applications it is acknowledged that components are likely to be operating at much higher temperatures which would present a greater challenge for in-service online external inspection. However, the scope of this paper is to focus on recommendations for inspection of in-service upstream carbon steel components up to about 250°C for which there is a need for scanning ultrasonic inspection methods.

The guidance has been developed in a multi-stage process initiated by an information gathering phase to establish current practice and experience. This was followed by trials of ultrasonic methods on carbon steel test pipes at up to ~250°C. The test pipes had wall loss morphologies typical of in-service degradation including extended relatively uniform areas of wall loss, localised pits and clusters of highly localised pits, ex-service weld root corrosion and simulated weld root cracks. The NDT methods deployed in multi-vendor trials included 0° corrosion mapping, TOFD and angled-beam phased array. The lessons learned have been developed into a set of recommendations for good practice.
2. Experimental trials

2.1 Test pipes

Six test pipes were assembled. Three for trials of corrosion mapping equipment at elevated temperatures. The remaining three pipes contained circumferential butt welds and were intended for trials of weld inspection methods such as TOFD and angled-beam pulse-echo phased array (PA).

Internal ceramic heating pads raised the temperature of the pipe lengths to up to 250°C, thermostatically controlled using internal thermocouples. The pipes were supported on specially manufactured stands to which the pipes were bolted to prevent any rotation or axial slippage during the trials, visible in the bottom left image in Figure 1.

The trials reported the minimum remaining ligaments, and these were compared to benchmark measurements and previous trial results at ambient temperatures. The trials were carefully observed to record the equipment and procedures used.

2.2 Corrosion mapping trial results

Various different commercially available high temperature scanners and couplants were used and found to work effectively at the test temperature, provided that water contamination was avoided in the couplants.

The root-mean-square (RMS) differences between the benchmarking minimum remaining ligament and those reported by triallists were assessed. The smallest differences achieved at the elevated temperatures was only slightly larger than the average of the RMS differences obtained in ambient temperature trials performed within the HOIS joint industry project.

2.3 Trial results for pipes with welds

On the pipes with ex-service weld root corrosion, the TOFD results for overall minimum remaining ligament generally agreed well with the benchmark. These differences are similar to those obtained at ambient temperature using high frequency TOFD. For one of the two pipes, the results from the angled beam PA showed larger differences from benchmark. For the other pipe, the less severe corrosion was not reported by either of the two trial participants that scanned the pipe using angled beam PA.

One pipe, which had simulated weld cracks, was a particularly challenging component to inspect, having a relatively low wall thickness (9.3mm) and complex morphology of the simulated cracks. Nevertheless, the majority of the TOFD high temperature trials resulted in detection of all of the cracks, and the trials giving the smallest differences from benchmark remaining ligament agreed well with the ambient temperature measurements. Other trials using TOFD and/or angled beam PA gave somewhat larger differences from benchmark.

2.4 Summary of trials
There were useful lessons learned and a capability for UT scanning at temperatures up to at least 250°C clearly demonstrated, despite this being a challenging application for NDT with hardware developments of key components actively ongoing. It became clear that industry experience of external ultrasonic scanning inspection of online components at elevated temperatures is relatively limited.

Figure 1. Photographs of UT inspection trials of test components at elevated temperatures

3. Key recommendations

3.1 Ultrasound velocity changes in test component at elevated temperatures

The change in ultrasound velocity for an inspection at elevated temperatures needs to be accounted for. It is recommended to use a modified ultrasonic velocity based on the test component temperature, in the absence of any more accurate information use the figures for temperature dependence of the velocity given in ISO 16809 [3]. Where this is not possible, a calibration block at the same test temperature may be used. The assumed velocity at ambient and that at the elevated temperature should be in the inspection report for comparisons with previous or subsequent inspections of the same component.

3.2 Test component temperature measurement

Temperature indicating sticks should be used, in preference to infra-red temperature gauges. The sticks melt at a specified temperature and should give sufficient accuracy for the purpose of correction of ultrasound velocity.

3.3 Ultrasonic probes and delay lines/wedges

The attenuation and scattering of ultrasound during propagation both through the probe wedge and the test component increase with temperature. There are three main approaches to probe selection:

1. Probes designed for ambient temperatures with a high temperature wedge (uncooled). A duty cycle is then usually needed, therefore only feasible for circumferential scanning of welds.
2. Probes designed for ambient temperatures with a high temperature wedge actively cooled (circulating water). Suitable for weld examination and corrosion mapping.

3. Probes designed for elevated temperatures with high temperature wedges (no cooling required). Suitable for weld examination and corrosion mapping.

Note that probes suitable for prolonged contact with elevated temperature components should be left in contact with the hot surface to reach a steady state temperature before scanning starts. Where possible it is recommended to avoid the use of components that require a duty cycle operation as repeated cooling and heating can affect the stability of measurements and lead to drifts in key parameters such as probe delay.

### 3.4 Ultrasound velocity changes in probe wedge and calibration

The ultrasound velocity in the materials used for probe wedges has a strong temperature dependence, with the velocity decreasing with increasing temperature. The coefficient is generally substantially higher than that of steel and needs to be accounted for. Table 1 makes recommendations on how to do this.

| Table 1. Accounting for the effects of temperature on ultrasound velocity in probe wedge |
|---------------------------------------------------|-------------------------------------------------|---------------------------------------------------------------------|
| Probe type                                           | Effect                                                                 | Recommendation                                                                 |
| 0° pulse-echo                                        | Change in arrival time of signal corresponding to zero depth in component (probe delay) | **Single crystal** – calibrate depth measurement using strong front wall echo, **Twin crystal** – calibration of probe delay using measurements of first and second backwall echoes in an uncorroded area of component: adjust probe delay until arrival time of first backwall echo is equal to time difference between first and second backwall echoes. |
| Angled beam TOFD                                     | Change in probe delay and refracted angle in test component will affect apparent locations of any indications in the component both laterally and in depth. | TOFD – correct for the change in velocity of ultrasound in test material. Calibration of arrival times using lateral wave signal allows for change in arrival time due to the altered velocity in the probe shoe. |
| Angled beam pulse-echo PA                            | Change in probe delay and refracted angle in test component will affect apparent locations of any indications in the component both laterally and in depth. | Ideally use modified focal law files to take account of velocity changes in probe wedge and material. There is limited capability for this. Alternatively: use an unmodified focal law and include a high gain channel showing “backwall rumble” signals – these can be calibrated to that of known wall thickness measured using 0° probe in an uncorroded section of component. |
| Angled beam pulse-echo single probe angle (single /dual element probes) |                                               | Not used in HOIS trials. Requires demonstration of effective method for correction. |
3.5 Scanners

Scanners should be specifically designed for operation at higher temperatures and scanners for inspection of welds will have different requirements from those needed for corrosion mapping. Consideration should be given to the following:

- Materials, lubrication
- Drive motors (if fitted)
- Electronics
- Magnetic scanner wheels
- On-board cooling for motors and magnets
- Cable handling systems to avoid contact with scanned surfaces.

3.6 Couplants

Most common couplants e.g., propylene glycol, glycerine will vaporise on surfaces hotter than 100°C. Ultrasonic testing at higher temperatures requires specially formulated couplants that will remain in a stable liquid for paste form without boiling off, burning or releasing toxic fumes. Several high temperature couplants have high viscosity and are intended for spot thickness measurements only, they cannot be used effectively with ultrasonic scanning systems. Poor acoustic performance and/or safety hazard may result from using couplants beyond their intended range.

4. Conclusions

The paper highlights the technical challenges associated with ultrasonic scanning systems at elevated temperatures, has shared some of the lessons learned from the experimental trials and summarised the key points of guidance developed within the HOIS joint industry project. The aim of the guidance is to extend the range of components to which the non-intrusive inspection process to include components operating at elevated temperatures up to 250°C.

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