Austenitic and Bi Metallic Weld Inspection II

Low Frequency Phased Array Methods for Crack Detection in Cast Austenitic Piping Components
M.T. Anderson, S.L. Crawford, S.E. Cumblidge, A.A. Diaz, S.R. Doctor, Pacific Northwest National Laboratory, USA

ABSTRACT

Studies at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, are being conducted to evaluate nondestructive examination (NDE) approaches for inspecting coarse-grained, austenitic stainless steel reactor components. The work provides information to the United States Nuclear Regulatory Commission (NRC) on the utility, effectiveness, limitations, and reliability of advanced inspection techniques for application on safety-related components in commercial nuclear power plants. This paper describes results from recent assessments using a low-frequency phased-array methodology for detecting cracks in cast austenitic piping welds.

Piping specimens that contain thermal and mechanical fatigue cracks located adjacent to welds were examined. The specimens have surface geometrical conditions and weld features that simulate portions of primary piping systems in many U.S. pressurized water reactors (PWRs). In addition, segments of vintage centrifugally cast piping were examined to assess inherent acoustic noise and scattering due to grain structures and determine consistency of ultrasonic (UT) responses from varied circumferential locations. The phased-array UT methods were applied from the outside surface of the specimens using automated scanning devices and water coupling, and employed a modified instrument operating between 500 kHz and 1.0 MHz. Composite volumetric images of the specimens were generated. Results from laboratory studies for assessing crack detection and sizing effectiveness are discussed, including acoustic parameters observed in centrifugally cast piping base materials.

INTRODUCTION

The relatively low cost and high-corrosion resistance of cast stainless steel (CSS) has resulted in extensive use of this material in the primary coolant piping systems of Westinghouse-designed PWRs. Alloying elements and casting processes used in the fabrication of CSS materials are responsible for its corrosion resistance and strength but also create complex and coarse-grained microstructures. This material is anisotropic and inhomogeneous. The manufacturing process can result in the formation of columnar (dendritic) grain structures often several centimeters in length, with grain growth oriented along the direction of heat dissipation, typically normal to the surface. Additionally, during the cooling and solidification process, columnar, equiaxed (randomly speckled microstructure), or a mixed structure can result, depending on chemical content, control of the cooling, and other variables in the casting process. The outer-diameter (OD) and inner-diameter (ID) surfaces of specimens used in the current study possess relatively smooth, machined conditions; this is a normal part of the fabrication method, performed to remove imperfections resulting from the casting process.

CSS piping is subjected to periodic UT based on requirements found in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components [1]. For ISI to be successful, service-induced flaws must be found and repaired prior to becoming of such size that the integrity of a component is challenged. Detection of flaws is the initial priority, and for UT this is accomplished by analyzing ultrasonic echo waveforms from reflections within the volume of inspected material that could potentially be caused by service degradation. Because of the large size of the anisotropic grains, relative to the acoustic pulse wavelength, the ultrasound is severely attenuated, scattered, and changes in velocity are evident. Refraction and reflection of the sound beam occur at the grain boundaries, resulting in defects being incorrectly reported, specific volumes of material not being examined, or both. To reduce the impact of the microstructure on the inspection technique, the work reported here
focuses on low-frequency (500-kHz to 1.0-MHz) ultrasonic energy propagation through the material as applied from the OD surface.

PHASED ARRAY EQUIPMENT

The phased array (PA) system used by PNNL was a Tomoscan III 32-channel instrument modified by ZETEC, Inc. (formerly R/D Tech, Inc.) to receive low-frequency responses. Multiple line scans with beam direction perpendicular to the weld and scan direction parallel to the weld were acquired at varied distances from the weld centerline to create a comprehensive dataset. Delay laws were calculated to focus the sound field at approximately 60 mm (2.4 in.) into the material, and the insonification angle was swept from 30° to 60° in increments of 1° as the probe was scanned across the specimen.

Three phase-array probes were used in this study, operating at 500 kHz, 750 kHz and 1 MHz. The longer the wavelength, the easier the sound can propagate through the large grains. However, the larger wavelengths have a lower resolution than shorter wavelengths. The 500-kHz probe has a 4 × 8 matrix of piezo-composite elements and a 50% bandwidth. The higher-frequency phased arrays used include a 1.0-MHz, 2 × 11 matrix with an 88.4% bandwidth and a 750-kHz, 2 × 11 matrix with a 58.8% bandwidth. In all cases, the probes were pulsed with a square wave of approximately 500 nanoseconds duration or pulse width, which is the proper pulse width for a 1.0-MHz probe, but this was the longest pulse duration allowed by the PA system employed. This means that the full bandwidth of the 500-kHz and 750-kHz arrays could not be attained. Theoretical simulations for the 500-kHz array show a primary beam diameter of approximately 20 mm. The 750-kHz array exhibits a slightly narrower beam, with a diameter of 17 mm, and the 1.0-MHz array has a theoretical beam width of 14 mm. Lateral resolution correlates to beam width.

CAST STAINLESS STEEL SPECIMENS

Vintage base metal specimens from Electric Power Research Institute (EPRI), Westinghouse, Inc., and IHI Southwest Technologies, Inc. were used to assess the affects of varied grain structure on the nondestructive evaluation. These base material specimens were without flaws. Specimens containing flaws included 15 welded piping segments on loan to PNNL from EPRI that were fabricated to be typical of primary coolant loop components in Westinghouse-designed plants and a number of PNNL segments. These Westinghouse Owners Group (WOG) specimens contain surface-breaking thermal or mechanical fatigue cracks (TFC or MFC, respectively) on either side of the weld. The PNNL specimens, originally fabricated for an NRC-funded round robin exercise [2] and used in the Programme for the Inspection of Steel Components (PISC) [3] in the early to mid 1980s, contain surface-breaking TFCs, also on either side of the weld.

Unflawed centrifugally cast stainless steel (CCSS) base metal material description

The oldest vintage, or initial CCSS piping fabricated (from early- to mid-1960s), is thought to be similar to the IHI Southwest Technologies piping segment, which is 15.24 cm in axial extent by 127 cm in circumferential extent. The segment has an 8.4-cm wall thickness and is approximately 91 cm in outside diameter (see Fig. 1). It consists of coarse-grained, mixed, and banded microstructure. The next class, or intermediate vintage, of CCSS microstructures is represented by the piping segment on loan from Westinghouse, Inc. This segment is believed to have been fabricated in the late 1960s to mid-1970s and, although the microstructure is very challenging to examine, this intermediate segment shows consistent grain orientation and size throughout the circumference (as contrasted by the mixed structure of the oldest vintage material), which may indicate the casting process was becoming more refined. The Westinghouse segment is 25.4 cm in axial extent by 130 cm in circumferential length, with a 6.4-cm wall thickness and an approximately 71-cm outside diameter (see Fig. 2). This segment exhibits a coarse-grained, dendritic (columnar) microstructure with a banding condition evident as
The most recently fabricated CCSS base material was loaned to PNNL by EPRI and was extracted from a cancelled nuclear power plant in Spain. The large blank spool piece has consistent fine-grained CCSS microstructure. The piece is 1.86 m in length, with a 6.35-cm wall thickness and an outside diameter of 86.4 cm (see Fig. 3). This segment has a relatively fine (for CCSS) equiaxed microstructure present over the entire circumference of the segment. This type of microstructure is believed to represent the latest class of CCSS piping installed in primary coolant systems of later vintage Westinghouse-designed plants (circa mid-1970s through mid-1980s).

Figure 1 - Polished and etched surface of the IHI-SW segment. Shown are the PA scan start and end as well as the approximate region of corner signal loss noted in the 750-kHz and 1.0-MHz scans.

Figure 2 - Polished and etched surface of the Westinghouse segment. Scan start and end points are shown for the 500-kHz, 750-kHz, and 1.0-MHz scans. The scale is 24-inches (61-cm) long.
Welded flaw specimen description

Fifteen welded WOG piping specimens typical of several component configurations in the primary coolant loop of Westinghouse-designed plants contain surface-breaking thermal or mechanical fatigue cracks located on either side of a weld joining CSS to CSS or CSS to wrought stainless steel (WSS) materials. The CSS material was either centrifugally cast (CCSS) or statically cast stainless steel (SCSS). The flaws are planar cracks oriented parallel to the weld centerline, and perpendicular to and connected to the inside-diameter surface. In general, the tightness and branched orientations of the TFCs make them more difficult to ultrasonically detect in comparison to the mechanical fatigue cracks. The piping configurations included CCSS pipe-to-SCSS elbow, SCSS elbow-to-WSS safe end, and CCSS pipe-to-SCSS pump nozzle with flaw depths between 13% and 42% through-wall. The microstructures of two of the specimens are shown in Figs. 4 and 5.

The PNNL specimens consist of sections cut from butt-welded, 845-mm-OD, 60-mm-thick CCSS pipe. This pipe material was from two different heats of American Society for Testing and Materials (ASTM) A-351 Grade CF-8A, a centrifugally cast material [4]. One side of the weld contained columnar grained material and the other side equiaxed (see Fig. 6). These specimens contain welds approximately in the middle of each section and were made by welders qualified [5] to meet Section III requirements of the ASME Code. The weld crowns were ground relatively smooth and blended with the parent pipe. The ID surface contours are significantly smoother than those of the WOG specimens described earlier. The cracks in these pipe sections are thermal fatigue planar cracks, parallel to the weld centerline and perpendicular to and connected to the ID. Flaw depths were estimated based on crack growth cycles and ranged from 10% to 48% through-wall. Two PNNL specimens from the earlier PNNL-conducted Piping Inspection Round Robin (PIRR) [2] were destructively analyzed for flaw sizing confirmation. One of the samples was 7% below expected crack depth while the other was 48% low, suggesting a possible large error in reported flaw depths.
Figure 4 - An axial-radial cross section of welded specimen INE-A-5. A wrought stainless steel safe end is on the left and a statically cast stainless steel elbow is on the right.

Figure 5 - An axial-radial cross section of welded specimen OPE 2. A statically cast stainless steel elbow is on the left and a centrifugally cast stainless steel pipe is on the right.
Material grain size

Cross sections in the circumferential-radial plane of the unflawed piping segments were polished, etched, and photographed to document the grain structures in these materials. The photographs were enlarged and used to determine average grain-size measurements via the lineal intercept method. Measurements of the intercepted grains along a circumferential line were averaged to assess approximate grain size by region. The EPRI base material had a grain size range of 0.5–7.4 mm, the IHI Southwest material a range of 0.2–25.0 mm, and the Westinghouse material a range of 0.64–16.32 mm. The flawed specimens were examined along an axial plane with the Westinghouse flawed specimens having a range of 0.21–26.67 mm and the PNNL flawed specimen a range of 0.6–12 mm. In general, grains in the range of 12–15 mm in diameter are found for the SCSS, while 17–20 mm grains are typical for the CCSS.

PHASED ARRAY ANALYSES

A metric for establishing background noise levels due solely to the microstructure was determined by measuring the signal response from the end-of-block corner-trap geometry from the specimens. This essentially measures the response from a 100% through-wall flaw. The segment length exceeding a 6-dB threshold (i.e., corner signal present at 50% of screen height or greater) was determined as a percentage of total scan length and is shown in Fig. 7 for representative specimens. The corner response was best detected at 500 kHz, with the 1.0-MHz probe performance slightly better than the 750-kHz probe. Average detected lengths of the corner signal for the three frequencies are 84%, 52%, and 55%.

The signal-to-noise values for this same data set are shown in Fig. 8. Because of noise variation between specimens, the peak responses of the corner signals were normalized to nearly 100% screen height. Signal-to-noise ratio values for almost all the specimens were greatest with the 500-kHz PA probe, and at this frequency the lowest signal-to-noise value was 3.7 (11.4 dB), well above a minimal value of 2 (6 dB) for a good detection call. The 750-kHz probe performed the worst of the PA probes and had a low of 2.2 (6.9 dB) on sample MPE-3. The 1.0-MHz probe’s lowest signal-to-noise value was 2.8 (8.94 dB) on specimens APE-1 and POP-7. Average signal-to-noise values were 4.7, 3.1, and 3.4 (13.4, 9.8, and 10.6 dB) for the three PA probes with increasing frequency.
Figure 7 - Detected corner response values for base material as determined from inspecting the end of CCSS specimens

Figure 8 - Signal-to-noise values for CCSS base material as determined from examining specimen end (corner-trap response)

Although these signal-to-noise values are useful, they do not show the influence of the presence or absence of the corner signal that is seen in this large-grained material over a scanned region. A weighted signal-to-noise ratio was obtained by multiplying the SNR in Fig. 8 by the detected length factor (Fig. 7) with the results shown in Fig. 9. The 500-kHz PA clearly outperformed the other frequencies, with the exception of the POP-7 specimen where results are similar. The average weighted signal-to-noise values for the three PA frequencies are 3.5, 1.6, and 1.8 (10.9, 4.1, and 5.1 dB). This weighted value implies that the 500-kHz PA probe produces the best results by giving a higher signal-to-noise ratio over a unit length of inspected material.
Figure 9 - Weighted signal-to-noise ratios for base CCSS specimens. The ratios have been weighted by the corresponding corner signal detection factor.

The data were analyzed for flaw detection with a priori knowledge of the approximate location of each flaw relative to side of the weld and position along the weld. This study was not intended to be a blind performance demonstration but an assessment to determine the performance of low-frequency PA technology in these coarse-grained materials. Based on analyses of data collected in this study, flaw detection is influenced by many factors including inspection frequency, side of weld inspected (i.e., near or far side of weld), signal-to-noise ratio, flaw area available for specular response, flaw location, flaw type, and signal discrimination in multiple images. As shown by the analysis of end-of-block corner-trap responses, acoustic scattering and beam redirection in certain microstructures may cause even the largest flaw signals to diminish over portions of their length. Therefore, large flaws thought easier to detect may be mischaracterized, and small flaws thought difficult to detect are potentially adequately imaged, depending on the microstructures present around the flaw location. Data from a detected and non-detected condition are shown in Figs. 10 and 11.

The summarized results (Table 1) suggest that flaw detection is most effective when employing the 500-kHz array. Cumulative flaw detection is 71% for the given flaw types, depths, and materials. At 750 kHz, the detection rate drops to 57%, and at 1.0 MHz, the overall detection rate is 52%.

Figure 10 - Mechanical fatigue crack in specimen MPE-3 as viewed from the SCSS side at 500 kHz is detected. Side view is on the left and end view is on the right.
Figure 11 - Mechanical fatigue crack in specimen MPE-3 as viewed from CCSS side at 1.0 MHz is judged to be not detected. Side view is on the left and end view is on the right.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Mechanical Fatigue</th>
<th>Thermal Fatigue</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kHz</td>
<td>93</td>
<td>57</td>
<td>75</td>
</tr>
<tr>
<td>750 kHz</td>
<td>64</td>
<td>44</td>
<td>54</td>
</tr>
<tr>
<td>1.0 MHz</td>
<td>64</td>
<td>33</td>
<td>49</td>
</tr>
</tbody>
</table>

Thermal fatigue cracks in these specimens are clustered in a range of approximately 20%–30% through-wall in depth for WOG specimens. These TFCs represent the mid-range of all flaws examined and yet appear to cause the most difficulty with regard to detection. Even the smaller MFCs are generally detected. Typically, cracks produced by the thermal fatigue process are tighter and more faceted than MFCs, making them more difficult to detect ultrasonically, as the data in this study confirm.

Additionally the flaws were more readily detected from the SCSS side than the CCSS side, likely attributed to the larger grains in this CCSS material. This held true for all three frequencies with the smallest effect noted at 500 kHz.

Time-of-flight diffraction techniques are the only proven and acceptable methods being used in the nuclear industry for through-wall depth sizing of detected cracks. The concept is to measure the differential time for signals to be detected from the inside surface-connected portion (corner-trap response) of the flaw and the diffracted pattern produced by the flaw tip. However, throughout this study, no tip-diffracted responses from the flaws could be distinguished from baseline noise in data collected from either the CCSS or SCSS side of the welded specimens.

A length-sizing analysis was conducted with flaw length determined by the 6-dB drop and the loss of signal (LOS) techniques on the flaws. The 6-dB drop technique sets crack-length endpoints where the signal falls below a 50% level of the peak response. The LOS technique sets the endpoints where the crack signal diminishes to background noise level. The signals generally had a sharp drop-off, so the two techniques produced fairly similar results. The flaws were typically undersized which is expected from the base metal study that showed the corner signal being intermittently detected. The error calculated as the root-mean-square error (RMSE) is shown in Table 2. The 1.0-MHz transducer gives the least error and is close to the 1.91-cm (0.75-in.) criteria imposed for acceptable length sizing error by the ASME Boiler and Pressure Vessel Code, Section XI, Appendix VIII, Supplements 2 and 3. This is likely due to a smaller beam size as compared to the other two probes. Note that this error is based on detected flaws, and the 1.0-MHz transducer had the poorest detection rate. The data also show that the 500-kHz and 1.0-MHz transducers perform similarly from either the CCSS or SCSS side of the weld, while the performance of the 750-kHz transducer is better from the SCSS side.
Table 2 - Length Sizing of Detected WOG Flaws Using the 6-dB Drop Method

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Flaw Length-Sizing Error (RMSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCSS</td>
</tr>
<tr>
<td>500 kHz</td>
<td>2.54 cm (1.0 in)</td>
</tr>
<tr>
<td>750 kHz</td>
<td>3.81 cm (1.5 in)</td>
</tr>
<tr>
<td>1.0 MHz</td>
<td>2.07 cm (0.81 in)</td>
</tr>
</tbody>
</table>

FUTURE WORK

PNNL is currently assessing the effectiveness of PA technology in evaluating CASS pressurizer (PZR) surge line piping. Preliminary PA data was acquired from a pipe-to-elbow section with a 1.5-MHz transmit-receive longitudinal (TRL) wave probe, and these results provided input to the design of a new PA probe specifically for inspecting this thinner (38-mm) pipe. The microstructures of the equiaxed CCSS pipe end and the columnar SCSS elbow end are shown in Fig. 12 from polished and etched rings taken from each end of the welded pipe assembly. This coarse-grained PZR piping supported ultrasound in the 1.0–1.2 MHz range. Based on these results and previous experience, an 800-kHz probe with a 50%–60% bandwidth or better was modeled. The probe submitted for manufacturing will consist of two $10 \times 5$ element arrays with a $43.2 \times 21.2$ active element and a 4.4-mm pitch in both the primary and secondary axes. A separate wedge will be designed to fit the pipe curvature. Plans are also underway for TFC implantations in this pipe with PA inspections to follow.

![Figure 12 - Digital photograph of polished and chemically etched CASS PZR ring segment showing the pipe-side (CCSS) grain microstructure (left), and ring segment showing the elbow-side (SCSS) grain microstructure (right)](image)

SUMMARY AND CONCLUSIONS

The reliable volumetric examination of CSS piping in operating nuclear power plants remains a significant challenge to NDE technologies. Low-frequency UT offers the capability to penetrate relatively thick-walled sections of primary piping circuits. In this study, longitudinal waves produced by dual phased arrays operating at 500 kHz, 750 kHz, and 1.0 MHz were applied to thick-section (65–80 mm) CSS piping segments to determine whether ultrasound at these frequencies could be expected to adequately penetrate the varied microstructures and detect cracks.

It is concluded that 500-kHz large-aperture phased arrays are capable of detecting ID-connected cracking in heavy-walled CSS piping when inspected from the OD surface of the pipe. The results show that for inside surface-breaking thermal and mechanical fatigue cracks greater than approximately 30% through-wall in depth, the 500-kHz method detected 100% of the flaws, provided that access to the outside surface was sufficient for adequate transducer placement and coupling.
Further, cracks smaller than 30% through-wall could also be periodically detected with the 500-kHz PA method. No through-wall sizing of flaws was performed because of an absence of tip-diffracted responses. Length sizing is possible, although the RMSE is slightly higher than currently allowed by the ASME Code. Many industry personnel have argued that current NDE technologies are not capable of inspecting cast austenitic piping materials. This study strongly refutes that contention and provides evidence that automated low-frequency PA methods, while not fully explored, have the potential to detect and length-size cracks in CSS reactor primary coolant piping welds.

REFERENCES