Cast Stainless Steel

Ultrasonic Inspection Techniques Possibilities for Crack Detection in Centrifugal Cast Stainless Steel

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ABSTRACT

Modelling was used to assist the development of guided wave and bulk wave techniques for inspecting centrifugally cast stainless steel (CCSS). Some bulk wave techniques are effective for specific but not all CCSS structures. Guided waves can be used to determine grain structure as it varies around the circumference of a pipe, and then to determine the appropriate bulk wave and/or guided wave technique for inspecting specific regions of the pipe. Finite-element modelling of bulk wave and guided wave propagation in anisotropic media (e.g. CCSS) also provided the basis for probe design along with the appropriate ultrasonic parameters for CCSS inspection. This work was extended to include studies on the inspection of large weldments (OD ~ 30” or greater) composed of dissimilar metals such as Inconel 82, Inconel 82/182, and cast austenitic stainless steel (CASS). The results of these studies are discussed in this paper.

INTRODUCTION

There is currently no reliable method for inspecting centrifugally cast stainless steel (CCSS). CCSS piping wall thicknesses are on the order of 3 ½ “ and columnar-dendritic grain structures present a technical inspection challenge regarding present day ultrasonic approaches. See Figure 1. Columnar grains tend to be near the outside of a pipe and equiaxed grains tend to be near the inside of a pipe. Modeling provides the understanding necessary to move toward the development of sensors with appropriate ultrasonic parameters for grain determination and CCSS inspection. Determining the grain structure prior to examination should provide the understanding necessary to improve the examination of CCSS.

Finite-element models of CCSS piping were created for studying bulk wave and guided wave propagation. Modeling results were used as a design basis for sensors for the CCSS inspection and for characterization of CCSS grain structures as they vary around a pipe’s circumference. Modeling was supplemented with experimental exercises on the CCSS specimens available at the EPRI NDE Center in Charlotte, North Carolina. After some preliminary study, two techniques were demonstrated.
GUIDED SURFACE WAVE EXPERIMENTS

Some preliminary experiments were performed to discover good frequencies and inspection techniques for cast stainless steel inspection. A mock-up at the EPRI NDE Center, Charlotte, North Carolina was made available to us for these experiments. Guided surface waves were used on the inside surface as shown in Figure 2.

The mock-up consisted of a section of a carbon steel pipe welded to a section of cast stainless steel (CCSS) pipe. Both pipe sections had a wall thickness of approximately 3” and an inner diameter of 30”. The wall thickness of the CCSS sections varied slightly around the circumference. The circumferential weld consisted of Inconel 182/82 with stainless steel roll-bonded cladding.

Two variable angle probes were designed and fabricated to match the curvature of the inner wall of the mock-up. See Figure 2. The 60° incident angle was chosen to generate a low-frequency surface (guided) wave along the weld region. After frequency tuning from 100 kHz to 800 kHz ($f = 10$ kHz), an optimal excitation frequency of 350 kHz was chosen. Through transmission was used because of the large main-bang obtained from wedge reflections in the pulse-echo mode. This can be overcome in the future with the design of an optimized fixed-angle wedge. A pitch-catch setup was also tried but abandoned due to transducer cross-talk and other issues.

Figure 3 shows the analytic envelopes of signals obtained from crack and no crack regions of the mock-up. Flaw #13 is the axial crack (of 4 detected) that was at the location shown in Figure 2.

Another, tandem like (one transducer behind the other) arrangement using bulk waves, was also explored with good results. Thus, these experiments provided the identification of a good frequency to work with and indicated that tandem transducer approach might also be possible.
BULK WAVE EXPERIMENTS FROM THE OUTSIDE SURFACE

Modeling

Centrifugally cast stainless steel (CCSS) pipes can be considered as transversely isotropic media for low frequency ultrasonic guided waves [1, 2], which are isotropic in the \( \theta-z \) plane. See Figure 4.

Our studies have shown that the commercial FEM software product, ABAQUS, has excellent accuracy for simulating ultrasonic wave behavior in arbitrary structures, including anisotropic materials.

Based on the results of experiments conducted at the EPRI NDE Center, tandem and/or dual element transducer arrangements were identified as a possibility for assessing local grain structure. Figure 5
shows the tandem transducer arrangement. The need for a dual element transducer configuration, if possible for certain angle selections, can improve the S/N ratio by working in a forward scatter mode. Figure 6 shows the transducer design parameters that must be found.

The key parameters for probe design are the incident (transmitter) angle, $\theta_1$, receiver angle $\theta_4$, and transducer spacing $D$ being a function of $\theta_1$, $\theta_2$, $\theta_3$, and $\theta_4$.

The finite-element package ABAQUS was used to generate refracted angle and reflected angle data based on a sequence of incidence angles. The assumed excitation frequency was 350 kHz. Figure 7 provides an example of the modeling sequence used to acquire the refracted angles for a 3” thick model of centrifugally cast stainless steel (CCSS). The parameters of Figure 6 were used for the model. A similar sequence was calculated for obtaining reflected angles.

The results for both cases are shown in Figures 8a. and 8b.. In Figure 8a., a least squares power function provided an excellent fit to the data save one point. [Sinusoidal segment]

Figure 4 - Reference directions for cylindrical coordinates and the stress tensor for Hooke’s law as used for modeling.

RESULTS

Figure 9 shows the result of combining these data into a form amenable for transducer design. Table 1 shows selected design parameters.

Note in Table 1, the 55° incident angle case, that the distance between the transducer and receiver is negligible. This means that the transducers must be side-by-side and will need a “roof” angle that provides a path from the transmitter to the receiver. Figure 10 shows photographs of a tandem probe (45° incident, 55° receive) and a dual element probe (55° incident, 5° roof angle), both fabricated according to the design values in Table 1.

EXPERIMENTAL RESULTS

Initial experiments on a CCSS large weldment with these types of transducers showed the complications of dealing with CCSS and tandem probe design. The purpose of these experiments was not the end use, grain characterization, but rather for an evaluation of the transducer design approach. Grain characterization is considered as future work at this time.
Figure 11 shows one of the complications, crosstalk between transducers, and how it was handled. Figure 11a. shows the unprocessed results in a region of a 78% through wall crack. The $45^\circ/55^\circ$ was placed outside of the flaw region and is then walked toward the crack region. Figure 11a. and 11b. were taken outside of the flaw region. The signals were comprised mostly of coherent noise from transducer crosstalk. The overall character of the signals did not change with position In Figure 11c. there is a large echo from the 78% through-wall crack along with some coherent noise. The flaw echo was verified by rastering the probe back and forth and watching the echo move in time.

To minimize the coherent noise in the signals and to improve the signal-to-noise ratio of the flaw echo, a spatial averaging technique was employed. Essentially, the signals seen in Figure 11a. and Figure 11b. were averaged together to produce a characteristic signal. Since the majority of signals do not contain a flaw, the average will be representative of the coherent noise signal. The average signal was then subtracted from all collected signals and the ones containing spurious echoes (such as flaw echoes) showed an increase in signal-to-noise ratio, such as seen in Figure 11d. for the 78% through-wall crack.
Figure 6 - Schematic showing the definitions of the various angles used to characterize wave interactions with a planar defect and to provide tandem angle beam transducer design parameters, angles $\phi_1$ and $\phi_2$ and $D$

Figure 7 - Modelling results of finite-element simulations for refracted angle $\phi_2$ versa input angle $\phi_1$ when the material is CCSS.
\[ \phi_1 = 40^\circ \]
\[ \phi_2 = 18^\circ \]

\[ \phi_1 = 45^\circ \]
\[ \phi_2 = 25^\circ \]

\[ \phi_1 = 50^\circ \]

\[ \phi_1 = 55^\circ \]
\[ \phi_2 = 47^\circ \]

\[ \phi_2 = 50^\circ \]
Figure 7 (continued) - Modeling results of finite-element simulations for refracted angle $\phi_2$ versa input angle $\phi_1$ when the material is CCSS

$\phi_1 = 55^\circ$

$\phi_2 = 60^\circ$

$\phi_1 = 65^\circ$

$\phi_2 = 70^\circ$

$\phi_1 = 70^\circ$

Surface wave

$\phi_2 = 90^\circ$

Figure 7 (continued) - Modelling results of finite-element simulations for refracted angle $\phi_2$ versa input angle $\phi_1$ when the material is CCSS
CONCLUDING REMARKS

An experimental / numerical modelling method was developed to act as a basis for transducer design for an CCSS anisotropic material.

Guided surface waves

Experiments on a large scale CCSS weldment mock-up showed that, with careful attention to incident angles and excitation frequencies, guided surface waves can be used to effectively defect cracks in CCSS. Variable angle probes and frequency scanning facilitated the discovery of a good angle and frequency for CCSS crack detection. Eleven of eleven defects in the mock-up were detected.

Bulk waves

Bulk wave experiments on the exterior surface of mock-up prior to modeling indicated that 350 kHz as a particularly good frequency for the CCSS specimens at hand. The Hooke’s law stress tensor [2] for CCSS was formulated with the ABAQUS finite-element modeling package to obtain design criteria for transducer angle separation distances. These angles and transducer separation distances were based on 350 kHz excitation and a 3” CCSS wall thickness.

Two sets of bulk wave transducers were designed and fabricated; one tandem, one dual element. For evaluation purchases, the transducers were used on the previously mentioned mock-up. Crosstalk between transducers was encountered when evaluating the transducers. Spatial averaging was used to reduce the crosstalk (or coherent noise) from signals.
Future work

Future work will involve well characterized specimens, in terms of grain structure, and the cataloguing of those transducer designs most effective for penetrating those structures while exhibiting good S/N ratios prior to carrying this sensor design data and data acquisition concept to the field. Crosstalk reduction via hardware (e.g. damping material) and via signal processing will also be implemented. One possible signal processing technique would be split-spectrum processing [See 3, 4].

\[
x = \frac{\ln y - \ln(1.8009)}{0.0595}
\]

\[
y = 1.8009e^{0.0595x}
\]

\[
R^2 = 0.9719
\]

Figure 9 - The graphic shows the empirical relationship between angles. The table shows the relationships between all angles and the wedge separation distances. The highlighted items are presently being fabricated.
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<th>$\phi_4$</th>
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<td>56.8</td>
<td>47.7</td>
<td>55.1</td>
<td>-1.29*</td>
</tr>
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</table>

Table 1 - The relationship between all angles and wedge separation distance. “*” indicates the receiver is ahead of the transmitter.

45° – 55° Tandem probe
55º Duel element probe [5º roof angle]

Figure 10 - Photographs of prototype probes for CCSS
Figure 11 - Waveforms gathered from a 3" thick CCSS specimen. a. and b. acquired at different positions away from the defect region. c. was acquired within the defect region. Waveforms a. and b. were averaged and the result and subtracted from waveform c. to produce waveform d. which exhibited an improved S/N ratio. The defect was a 78% through wall circumferential crack.
REFERENCES


