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Abstract
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Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

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WELD INSPECTION WITH SHEAR HORIZONTAL ACOUSTIC WAVES GENERATED BY EMATS

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ABSTRACT

The potential advantages of using electromagnetic acoustic transducers (EMATs) for nondestructive evaluation of metal parts have been known for some time. Recently a generically new EMAT has been perfected which can generate and receive horizontally polarized shear (SH) wave angle beams. SH waves offer considerable advantages over SV waves for inspecting metal parts of complex shape: 1) they reflect specularly from planes containing the direction of particle displacement, 2) they can be generated in any direction lying in the sagittal plane with equal efficiency, and 3) SH wave transducers inherently discriminate against Raleigh, L and SV waves. These advantages make SH waves particularly useful for weldment inspection.

A brassboard system was assembled for locating natural and simulated flaws in thick MIG welds, and a new technology for placing controllable defects in weld deposits was developed. It was then shown that the SH-wave inspection system was capable of producing an accurate map of the controllable defects introduced into the weld deposit. The ultrasonic map compared well with the notes taken by the welder and contained considerably more detail than the radiographic map. The inspection was performed at 1.7 MHz with the SH wave beam axis inclined at approximately 38° with respect to surface normal. Tungsten and alumina rod inclusions as small as 3/32 inch in diameter with localized within the weld deposit with signal-to-noise ratios of better than 10 dB and the inspection was performed on an "as-welded" sample without surfaces preparation through surface grinding or polishing.

INTRODUCTION

Bulk SH waves appear to be better suited than SV waves for ultrasonic inspection of metal parts of complex shape and microstructure. Unless the acoustic beam angle is judiciously selected for a particular application, at each reflection, an SV wave can be split up into shear (SV and SH) longitudinal (L) and surface wave reflections travelling in different directions at different velocities. However, in contrast to SV waves, SH waves are always reflected specularly and the SH wave transducers discriminate against all other polarizations which may be generated within the metal part through mode conversion. These properties of SH waves result in considerably cleaner ultrasonic displays which are usually easier to interpret than ultrasonic displays generated with SV waves.

For weldment inspection the use of SH waves may offer additional advantages: 1) The horizontal particle polarization may be more suitable for inspecting weld metal deposits which exhibit complicated microstructures and are very anisotropic, 2) SH wave beam angles may be frequency scanned, allowing a considerably greater flexibility in positioning transducers and selecting beam angles with respect to surface normal, and 3) since SH wave transducers are non-contact EMATs, inspections at elevated temperatures may be feasible.

In this paper we describe the experimental results obtained with a prototype SH wave system on realistic MIG weld deposit containing many controllable weld defects. We also describe a new technique for introducing controllable weld defects into weld deposits by placing tungsten and alumina rods in the weld puddle.

FABRICATION OF CONTROLLABLE DEFECTS

IN MIG WELD DEPOSITS

An in-house capability was developed at the Science Center for producing weld defects in a controllable and reproducible manner. In a production environment this was accomplished by assembling a high quality welding station which could be interfaced with SH wave ultrasonic systems. The system, shown in Poster 1, employs the Flux Core Arc Welding (FCAW) method using Flux Cord Arc Welding type filler material (FCAW). It is fully motorized and includes an accurate closed loop control system for weld head travel. The welding supply is a Tektron LSC.

Since literature studies and discussions with experienced welding engineers did not reveal a reliable method for generating defects of controllable size, orientation and type (inclusions, voids etc.), it was decided to place tungsten and alumina inclusions, as well as SiC chips from a grinding wheel, at various locations throughout the weld deposit. The method of placement is also illustrated in
Post 1 which shows a number of Al₂O₃ inclu-
sions placed along the centerline of the weld
deposit directly above the root pass. The
tungsten and alumina inclusions were 3/32 and
1/4 inch in diameter respectively and interpass
grinding was employed to avoid inadvertent slag
inclusions. A careful record of the defect
types, new and locations was maintained through-
out the building up of the weld deposit. A
sample of the welder's notes is also included in
Poster 1.

The weld preparation consisted of a simple
V-groove but-weld in a 2-1/4% Cr-1% Mo steel,
1" plate stock ordered and certified to meet
ASME Boiler and Pressure Vessel Code (B&PVC) SA
387 Grade 22, Class 2 requirements. The 2-1/4% 
Cr-1% Mo steel base metal was selected primarily
because it was found to exhibit particularly
high EMAT transduction efficiencies due to
magnetostrictive enhancement and because it is
in wide commercial use. The completed weld is
shown on the left in Poster 2. Also shown in
Poster 2 is a weld sample of the same type but
2 1/4 inches in thickness which as obtained from
the Energy Systems Group of Rockwell Interna-
tional. This weld did not contain controllable
weld defects in the weld deposit, but did con-
tain a number of side holes drilled for the pur-
purpose of for transducer calibration.

The method for generating defects of con-
trollable type, size and orientation proved to be
very successful. It was found that the
tungsten defects held their shape and only
showed slight melting of the skin as the molten
metal on arc passed over them. On the other
hand, the alumina rod showed some melting and
edge rounding when the weld puddle was carefully
positioned so that its edge cast against the
rod. When welding directly over the rod, the
material bubbled severely, actually deflecting
the arc to one side. Finally the SiC melt
into blobs and spheres, but remained essentially
in place in the puddle.

In addition to the alumina and tungsten
inclusions, a number of simple calibration
standards were also prepared by drilling side
holes ranging from 3/32 to 5/16 inch in diameter
in the 1 inch thick base metal.

DETECTION OF CONTROLLABLE DEFECTS 
AND SIDE DRILLED HOLES IN 
THICK MIG WELDS

A brassboard SH wave system was assembled
specifically for localizing the naturally occur-
rings and simulated defects described in the
preceding section.

The system used a pair of the periodic
magnet transducers and a tuned transmitter-
receiver electronics package capable of oper-
ating either in "pitch-catch" in "pulse-echo"
and the transducers were provided with special
metal "shutters", which enabled them to be
operated on plates of less than 2 inches in
thickness. The frequency of operation of the
system could be adjusted in the range 1-1.8 MHz;
corresponding to a range of acoustic beam entry
angles of 0°-30° with respect to surface
normal. The electronics package did not include
a detector stage. Instead, the received ultra-
sonic signals were displayed directly on a CRT
after preamplification. In addition, a digital
signal averager was included in the system for
added sensitivity. The digital signal averager
was used in some of the experiments resulting in
a 30 dB signal-to-noise ratio by averaging
1000 frames of data. However, it was unable to
follow the RF displays in real-time and could not
be transported outside the laboratory. The
transducer used a tandem periodic array of Sm-Co
permanent magnets with a period of 0.120 inch.
The overall usable length of the array was
approximately 1.5 inches and the aperture width
was approximately 0.5 inch. A 0.005 inch thick
copper foil "shutter" was used in conjunction
with the transducer to adjust the acoustic
length by shielding a eddy current from the
transducer electrode.

Using the EMAT system described above a
careful study was made of the weld sample con-
taining the controllable defects. The results of
the ultrasonic scan of the weld metal depo-
sit, radiographic data, and the welder's notes
were compared and are presented in Poster 3.
Ultrasonic data was taken from both directions
in order to establish the position of a particu-
lar defect within the weld deposit by triangu-
lation and the transducer was operated at
approximately 1.7 MHz corresponding to a beam
entry angle of approximately 38.5° with respect
to surface normal. The frequency of 1.7 MHz and
angle of 38.5° were used since it was found that
inspection at other beam angles resulted in less
sensitivity to flaws or more spurious signals.
In particular inspection at 1.5 MHz (45°) was
very difficult because of strong masking of the
flaw reflections by direct reflections from the
45° weld preparation.

The mapping of the weld deposit was accom-
plished by moving the transducer along the weld
in 1/2 inch increments over a total distance of
12 inches. Concurrently, a number of calibra-
tion measurements were also made using the empty
side-drilled holes. A comparison of the ultra-
sonic map with the x-ray data and the welder's notes
showed that all alumina and tungsten inclusions
were positively located with the SH wave system,
and their positions corresponded well to x-ray
data and welder's notes. In fact, some of the
alumina inclusions were not registered in the
radiograph because of their low density, but
they were easily detected with the SH wave
system. Also, detected and localized were the
lack of fusion areas generated by adjusting the
welding torch. However, defect characterization
based on the acoustic data was not attempted
although typical signals obtained from the 3/32
and 1/4 inch diameter inclusions had signal-to-
noise ratios of better than 10 dB.

The results of the back reflection cali-
bration measurements have been compared to
theory of SH wave scattering from cylindrical
voids. The results and the experimental
arrangement are shown in Poster 4 in which a
corner reflection of the signal was used to
normalize the back reflected signals from the
side drilled holes and a 3/32 inch diameter
tungsten inclusion. It is interesting to note that
the measured back-reflection from the 3/32
tungsten inclusion in the weld deposit exhibits
the same reflection coefficient as that from an
empty cylindrical hole of the same diameter; contrary to the theory. This result may indicate that the tungsten inclusion was not in intimate contact with the weld deposit - possibly due to the presence of "soft" impurities on the surface of the tungsten generated by the welding process.

**SUMMARY**

An ultrasonic inspection technique using SH waves and a welding procedure for placing controllable weld defects in weld deposits were demonstrated. The results clearly show that SH waves can offer potential advantages for weld inspection. SH waves generate fewer spurious signals and can be frequency scanned. In addition, EMATs offer the advantage of being able to operate at elevated temperatures. However, the advantages of SH systems for weldment inspection must be weighed against the inherently low transduction efficiencies of electromagnetic transducers, which may vary from material to material - depending on composition, heat treatment, etc. Nevertheless, it is believed that new SH wave applications in the area of weldment inspection are in prospect.

**TABLE I**

<table>
<thead>
<tr>
<th>Pass No.</th>
<th>Location</th>
<th>Type</th>
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<tbody>
<tr>
<td>1</td>
<td>1-22</td>
<td>Lack of fusion</td>
</tr>
<tr>
<td>2</td>
<td>3-7, 12-13</td>
<td>Porosity</td>
</tr>
<tr>
<td>3</td>
<td>12-14</td>
<td>Lack of fusion</td>
</tr>
<tr>
<td>4</td>
<td>1-4</td>
<td>3/4 in. Al2O3</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>3/4 in. Al2O3</td>
</tr>
<tr>
<td>6</td>
<td>10-20</td>
<td>51C</td>
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<tr>
<td>9</td>
<td>9</td>
<td>2/4 in. Al2O3</td>
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<tr>
<td>10</td>
<td>5-9</td>
<td>Al2O3 alloy</td>
</tr>
<tr>
<td>11</td>
<td>12-14</td>
<td>1-1/2 in. W</td>
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<tr>
<td>12</td>
<td>13</td>
<td>1/2 in. WC</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td>1/2 in. WC</td>
</tr>
<tr>
<td>14</td>
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<td>1/2 in. WC</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>1/2 in. WC</td>
</tr>
</tbody>
</table>

**WELD SAMPLES WERE PREPARED AT SCIENCE CENTER USING PRODUCTION WELDING EQUIPMENT.**

3/4 INCH DIAMETER ALUMINA AND 3/32 TUNGSTEN RODS WERE PLACED IN WELD PUDDLE AT SELECTED LOCATION.

LACK OF FUSION DEFECTS WERE GENERATED BY STOPPING THE TORCH.
RESULTS OF WELD INSPECTION

(A) RADIOGRAPH
(B) ULTRASONIC USING SH WAVES AT 1.6 MHZ AND INCLINED AT 40° WITH RESPECT TO SURFACE NORMAL

Comparison of experimental SH wave back scattering from cylindrical voids with theory.

RESULTS OF CALIBRATION MEASUREMENTS USING ROUND HOLES
DEMONSTRATION OF THE ALN 4000 MULTI PURPOSE PROCESSING SYSTEM FOR ULTRASONIC AND EDDY CURRENT QUANTITATIVE NDE*

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Adaptronics, Inc.
McLean, VA 22102

ABSTRACT

The ALN 4000 Multi Purpose Processing System (MPPS) is a significant new advancement in data acquisition, real time analysis, and control technology. This programmable instrument is ideally suited to high-speed signal processing using the most advanced algorithms, including Adaptive Learning Networks.

INTRODUCTION

The interactive capability of the ALN 4000 greatly reduces the need for operator training. The ALN 4000 MPPS consists of two compact, portable units, the ALN 4040 Controller/Processor and the ALN 4080 Storage/Display Unit.

New developments in semiconductors and the advent of miniature peripherals made the ALN 4000 concept feasible. The foundation of the instrument is a powerful dual microcomputer system with several peripherals and dedicated Nondestructive Evaluation (NDE) software. Highly specialized circuit boards perform NDE functions such as detection, location, and sizing of material flaws.

The ALN 4000 is designed to perform these NDE functions in as simple a manner as possible and with a minimum of equipment. In addition to the ALN 4000, only a transducer, a pulse-amplifier, and a receiver are necessary. When applicable, a positioning mechanism (scanner) for the transducer can be included in the NDE system.

SYSTEM COMPONENTS

The ALN 4000 MPPS is packaged in two cases. As shown in Fig. 1, the front panel of one of the cases, the 4080 Storage/Display Unit, has all the switches and status lights, the integral mini-printer and two miniature tape cassettes. The panel on the 4040 Controller/Processor Unit is blank except for a power light. There are only three switches, POWER, RESET, and PAUSE; all other functions are controlled via the terminal. There are three status lights to indicate the current operation: RUN, STANDBY, DIAGNOSTICS.

The peripherals consist of a hand-held LED terminal serving as the control unit and keyboard, and integral miniprinter for hard-copy display results, and a dual mini-cassette system for mass storage. Alternatively, an off-line typewriter terminal may be used for more printing capability as well as for providing a modem to transfer data to another computer system for Adaptive Learning Network (ALN) training or for archival data storage. There is digital-to-analog capability for oscilloscope display of waveforms and analog-to-digital capability for digitizing RF signals from the transducer. A rectified amplitude oscilloscope display is also provided in some models.

Fig. 1 ALN 4000 multi-purpose processing system.

*This work has been supported in part by the Electric Power Research Institute under Contract RP1125-1.
The MPPS contains, where the application requires it, the hardware and software to control a scanning device. This permits automatic inspection and increases the speed of the inspection as well as decreases the number of operations performed by the operator.

**HARDWARE/SOFTWARE**

Flexibility of both the system hardware and software has been achieved. The design reflects a desire to minimize the effort required to modify the instrument for different applications. The data acquisition system for ultrasonic applications can be programmed for different sampling rates (up to 20 MHz). To convert the MPPS for use with eddy current applications, the A/D board and associated software are simply replaced. Software changes are made as easily as changing a tape cassette. Data for specific applications can be entered via the keyboard, or prepared at an earlier date and stored on cassette. The software modules that are applicable in any NDE system are permanently resident in the ALN 4000. These will include supervisory programs, self-test diagnostics, I/O drivers, DMA routines, and signal processing routines. Those routines and data that are application-specific are stored on cassettes and include the transducer scanning protocols, ALN structure and coefficients, and routines to drive and control the scanning device.

**OPERATIONAL MODES**

Three modes of operation are possible using the ALN 4000.

One is a data collection and digitization mode to store sufficient data to provide a data base necessary for ALN network training, for example. If a scanner is present, it may be controlled by the ALN 4000 in this mode to automate the collection procedure.

The second mode is on-line analysis to be performed at the inspection site. This includes control of the scanning device, signal conversion, and ALN processing to provide NDE diagnosis such as crack detection and sizing on-line and in real-time.

A third mode of operation is off-line analysis to provide an inspector with the capability of selecting waveforms from the mass storage device and to perform signal processing operations as desired. The use of the off-line terminal in this mode will provide printing capability. The modem permits data transferal to another computer. Use of an oscilloscope will provide a display of the waveforms.

**ALN 4000 MPPS SIGNAL PROCESSING SOFTWARE**

A number of signal processing routines exist in pre-programmed (PROM) form and are supplied with the ALN 4000 MPPS as part of a signal processing library. Each routine has been coded to take full advantage of the high-speed arithmetic processing circuits. The user can incorporate these routines into new programs in a manner similar to the way scientific package sub routines can be incorporated into FORTRAN programs.

- **Fast Fourier Transform (FFT):**
  Complex FFT of any power-of-two length waveform up to 256 points; (the current limit can be extended easily to a larger number of points); routine returns the complex coefficients; arithmetic is performed in 32-bit fixed point form; the routine also incorporates an automatic scaling feature to prevent resolution loss for very low or high level signals.

- **Signal Averaging (Temporal Averaging):**
  Summing of several waveforms while holding a transducer at a fixed position; the random noise components in the received data will cancel but the coherent signal transients will add.

- **Beamforming (Spatial Averaging):**
  Averaging several waveforms recorded at different positions; each waveform is delayed before averaging so the signals add coherently; beamforming reduces coherent noise sources.

- **Bandpass Filtering:**
  Digitally filtering signal components outside of a desired bandwidth; the filter pass band characteristics can be changed easily to accommodate any bandwidth of interest.

- **Match Filtering/Convolution:**
  Convolving a known response with a noise waveform to detect a signal of interest.

- **Convolution/Deconvolution:**
  Adding/eliminating a specific signal to/from a noisy waveform.

- **Correlation**
  Auto-and-cross-correlation of waveforms.