A COMPARISON OF ULTRASONICS AND RADIOGRAPHY

FOR WELD INSPECTION

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INTRODUCTION

Since the 1940's, the accepted inspection method for structural welds in the U.S. Navy has been radiography (RT). This technique has been accepted as an inspection method for welds since the 1940's. A major advantage of radiography compared to other inspection techniques is the availability of objective quality evidence, the radiograph, as a permanent record of the inspection. Radiography has gained precedence as the inspection method to prescribe for these welds because this permanent record is perceived to evince all discontinuities and facilitates auditing. This technique and the criteria used to accept or reject discontinuities have generally proved adequate although technical limitations and cost disadvantages have been encountered.

Ultrasonics (UT), as an alternative method to radiography, has been applied in other industries such as the nuclear power industry and off-shore oil platforms for inspection of welds. In 1966, ultrasonic inspection of production and repair welds was formally introduced into the Navy to permit weld areas not accessible for radiography to be ultrasonically examined. The caveat for UT inspection was that "in no case shall the quality acceptance criteria be lower than the radiographic criteria." Currently, ultrasonic inspection of welds may only be substituted for radiographic inspection when the required radiography cannot be performed. This limited acceptance of ultrasonic inspection for welds is due, historically, to the lack of permanent objective quality evidence by this inspection technique, the purported inconsistency of inspection results, and the reputation that ultrasonics does not readily detect non-planar discontinuities (i.e. porosity or slag) and rejects more planar discontinuities (cracks or lack of fusion) than does radiography.

In the future vessel construction will use predominantly automated welding processes such as gas metal arc or submerged arc welding instead of manual shielded metal arc welding. With this change in emphasis to automated welding processes the typical discontinuity will change from non-planar to planar. In the literature cited ultrasonics has been reported to be more reliable for the detection of planar weld discontinuities such as cracks and lack of fusion while radiography has been reported to be more reliable for the detection of non-planar discontinuities such as porosity and slag [1-5]. Literature also indicates that there is rarely a
good correlation of ultrasonic and radiographic weld discontinuity
detection capabilities [6-7]. This is due to the difference in operating
principles of radiography and ultrasonics (absorption versus reflection,
respectively) and therefore different capacities for detecting certain types
of discontinuities.

The successful demonstration of an ultrasonic system which corrects
the perceived deficiencies will result in cost savings, increased
productivity, immediate inspection results, information concerning the
depth of rejectable defects, and the potential for more accurate sizing of
discontinuities.

The objective of this program is to determine if structural welds
may be ultrasonically inspected with repeatability and reliability
comparable to that currently obtained with radiographic inspection.

APPROACH

A review of literature as well as ultrasonic and radiographic
acceptance criteria from ASME, AWS, ABS, ANSI, U.S. Navy, and U.K.
Navy was performed. Standard practice manual ultrasonics (MUT), com-
puter assisted ultrasonics (CAUT), and radiography were compared by
inspecting 16 welds with purposely induced discontinuities and 17 welds
removed from service. The welds were fabricated from steel in the form
of double-V-groove joints, nominally 1.5-in. thick. Shielded metal arc
welding and automated and semi-automated gas metal arc welding pro-
cesses were used to fabricate the plates. The 33 welds contained a total of
191 discontinuities of the following types: slag, lack of fusion, incomplete
penetration, cracks, slugs, clustered porosity, and scattered porosity. Eight
inspectors performed the ultrasonic inspections on the 33 test welds.
Similarly, eight interpreters reviewed radiographs of the 33 test welds
produced by each of the following allowable techniques; x-ray with
Kodak type M film, x-ray with Kodak type AA film, Ir-192 with M film,
Ir-192 with AA film, Co-60 with M film, and Co-60 with AA film. Dis-
continuities were identified by reviewing all of the inspection results,
characterized as to type, and verified by sectioning and metallography.
This information was used to document the following: the ability of
MUT, CAUT, and RT to detect discontinuities of specific types and sizes;
the probability of accepting or rejecting specific discontinuity types and
sizes using current UT and RT acceptance criteria; the repeatability of
the inspection methods; and differences in rejection rate of weld using
MUT, CAUT, or RT.

RESULTS AND DISCUSSION

Acceptance Criteria Review

The acceptance criteria documents reviewed were those commonly
used for inspection of thick section weldments. In the radiographic
acceptance criteria cracks are not permitted by any of the standards. Lack
of fusion or incomplete penetration discontinuities are not permitted in
four of the standards while three of the standards permit limited
quantities depending on material thickness, spacing, and accumulated
length. All of the acceptance criteria standards allow limited amounts of
both slag and porosity, with acceptable sizes depending on proximity and
material thickness. In the ultrasonic acceptance criteria two of the
acceptance criteria standards attempt to classify discontinuities by type.
Generally, a reference amplitude level for the reflected sound is
established by interrogating a calibration standard with a side drilled hole

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of known diameter; discontinuities are evaluated with respect to this amplitude level. Acceptable discontinuity lengths vary with material thickness, accumulated length, and spacing between discontinuities.

The overall ranking of discontinuity type based on the review of the acceptance criteria standards is from most to least detrimental; cracks, lack of fusion/incomplete penetration, slag, porosity, and other inclusions. Thus, planar discontinuities are more detrimental than volumetric discontinuities.

Round Robin Inspections

UT and RT inspectors reported their findings on a common report form. The total set of 3322 inspection reports contained 4154 RT, 1127 MUT, and 546 CAUT calls that were associated with at least five indications recorded by any one technique. From the RT data, which required evaluation according to flaw type, the breakdown of discontinuities into type was: 43% lack of fusion or incomplete penetration, 31% slag, 21% porosity, and 5% cracks. These percentages indicate that a variety of conditions was introduced into the welds.

Figure 1 presents the results of the frequency of calls made by RT interpreters as a function of RT technique and discontinuity type. The results indicate the trend was for lower energy sources or finer grained film to result in more detections, that is, x-ray inspection resulted in more detection than did iridium or cobalt. In particular, Co-60 only detected 34 or 28% (M and AA film, respectively) of the significant discontinuities in this investigation. Additionally, the trend of lower energy radiographic sources resulting in more detections is consistent regardless of the flaw type. Finally, the ratio of calls for volumetric discontinuities (slag, porosity) to calls for planar discontinuities (lack of fusion, cracks) increases with increasing energy of the source. The ratios are tabulated in Table 1 and indicate that higher energy sources preferentially miss planar discontinuities.

In U.S. shipbuilding, the most commonly used radiographic technique for inspecting structural welds employs iridium with type AA film. The remaining discussion will compare UT to that common practice technique.

Figure 2 compares the percent of the discontinuities detected by MUT, RT, and CAUT. This figure presents the data by grouping all of the discontinuities without discrimination by type, as well as by differentiating the discontinuities into planar or volumetric categories. The data represented by Figure 2 indicates that MUT detects more discontinuities than RT or CAUT. In particular, more planar discontinuities are detected using either UT technique, while more volumetric discontinuities are detected by RT.

Figure 3 compares the results of the discontinuities rejected by MUT, RT, and CAUT. This figure indicates that MUT rejects more discontinuities than RT or CAUT reject, particularly those discontinuities categorized as planar. RT and CAUT reject equal percentages of planar discontinuities, while MUT and RT reject equal percentages of volumetric discontinuities.

Table 1 - Ratio of volumetric to planar discontinuities detected by radiography

<table>
<thead>
<tr>
<th></th>
<th>X-ray/M</th>
<th>X-ray/AA</th>
<th>Ir/M</th>
<th>Ir/AA</th>
<th>Co/M</th>
<th>Co/AA</th>
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<tbody>
<tr>
<td>Ratio of</td>
<td>1.99</td>
<td>2.02</td>
<td>2.31</td>
<td>2.22</td>
<td>3.14</td>
<td>3.11</td>
</tr>
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<td>volumetric to planar</td>
<td></td>
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FREQUENCY OF CALLS

<table>
<thead>
<tr>
<th>RADIOGRAPHIC TECHNIQUE</th>
<th>X/M</th>
<th>X/AA</th>
<th>Ir/M</th>
<th>Ir/AA</th>
<th>Co/M</th>
<th>Co/AA</th>
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<tr>
<td>FREQUENCY</td>
<td>362</td>
<td>234</td>
<td>204</td>
<td>199</td>
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<td></td>
<td>322</td>
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<tr>
<td></td>
<td>273</td>
<td>25</td>
<td>28</td>
<td>245</td>
<td>108</td>
<td>108</td>
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</table>

**Figure 1 -** Frequency of calls made by radiographic interpreters as a function of technique and discontinuity type.

The disparity between the detection and rejection percentages of MUT compared to CAUT is attributed to the recording technique of MUT compared to CAUT. The recording technique allowed by MUT enabled inspectors to record discontinuities that CAUT automatically disregarded owing to strict application of the disregard level in the computer algorithm. The disparity in detection and rejection percentages is also attributed to operator inexperience with CAUT.

Figures 4 and 5 present the results of detection and rejection, respectively, in the form of Venn diagrams. Figure 4 indicates that all

![Venn Diagram]

**Figure 2 -** Percent of discontinuities detected by manual ultrasonics (MUT), Ir/AA radiography, and computer assisted ultrasonics (CAUT).

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three of the inspection techniques missed discontinuities detected by other radiographic techniques, specifically, 1 crack, 2 lack of fusions, 11 slags, and 7 porosity clusters; however, all three inspection techniques detected the four classes of discontinuities. Figure 5 indicates that RT rejected more cracks than ultrasonics. Those cracks rejected by RT that were not rejected by UT were transverse to the longitudinal axis of the weld.

This lack of detection and rejection indicates a deficiency in the UT procedure used for transverse oriented discontinuities. It should be noted that one of the discontinuities identified as lack of fusion by the flaw characterization procedure was determined to be a longitudinal crack
Figure 5 - Breakdown of discontinuities rejected by manual ultrasonics (MUT), Ir/AA radiography (RT), and computer assisted ultrasonics (CAUT)

by metallography. This discontinuity was detected by MUT and CAUT but not by RT.

The probability of consistently detecting and dispositioning a discontinuity in the same manner was used as a measure of the repeatability of the inspection technique. This analysis incorporates technique detection sensitivity and consistency of agreement within the technique. The probability was determined by:

\[
\frac{[r(r-1) + (a)(a-1)]}{[N(N-1)]}
\]

where \( r \) is the number of inspectors rejecting a particular discontinuity, \( a \) is the number of explicit accepts (detect and not reject), and \( N \) is the number of inspectors.

Table 2 presents the probability of agreement between two inspectors for MUT, RT, and CAUT. This was done for planar, volumetric, and overall groups of discontinuities. In this table, misses are not counted as agreement either with each other or with accepts. The calculated values represent the consistency of the technique at finding and agreeing on the disposition of a discontinuity known to be in the weld.

The data indicates that MUT and CAUT are more consistent than RT when the discontinuity is planar. Radiography is more consistent than ultrasonics when the discontinuity is volumetric. Overall, ultrasonics and radiography result in comparable inspections on test welds with purposely introduced flaws that represent a wide range of discontinuities.

Table 2 - Probability of detecting and dispositioning a discontinuity in the same manner

<table>
<thead>
<tr>
<th>Flaw Type</th>
<th>MUT</th>
<th>Ir/AA</th>
<th>CAUT</th>
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<tr>
<td>Planar</td>
<td>0.49</td>
<td>0.19</td>
<td>0.29</td>
</tr>
<tr>
<td>Volumetric</td>
<td>0.26</td>
<td>0.32</td>
<td>0.21</td>
</tr>
<tr>
<td>Overall</td>
<td>0.39</td>
<td>0.25</td>
<td>0.26</td>
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Consequently, ultrasonics will be the most consistent method for rejecting flaws in automated welding processes where flaw types are expected to be planar, and radiography will be the most consistent method for rejecting flaws in manual welding processes where flaws are expected to be volumetric.

Metallographic Evaluation

Five plates were sectioned for verification of discontinuities. These five plates contained thirty-two discontinuities verified by metallography. Two of these discontinuities (porosity) were not detected by MUT, RT, or CAUT but were found by other radiographic techniques used. Five of the discontinuities were detected by MUT only and six were detected by RT only. Many additional discontinuities that were not reliably detected by either UT or RT were also revealed by metallography.

Table 3 presents the results of metallographic verification by summarizing the quantity of the discontinuities detected and rejected by metallography as well as the quantity of discontinuities detected and rejected by each inspection technique.

Four cracks were revealed by metallography. Of these cracks, three were transverse weld cracks detected and rejected by RT, and one was a longitudinal crack detected and rejected by MUT and CAUT. Fifteen lack of fusion discontinuities were revealed by metallography, of which twelve were rejectable. MUT detected fourteen of these lack of fusion discontinuities and rejected eight of the twelve rejectable defects. RT and CAUT both detected seven slag discontinuities and rejected three defects. These slag discontinuities detected and rejected were not necessarily the same discontinuities. Nine slag discontinuities were verified by metallography and six of these were rejectable. MUT performed best at detecting and rejecting slag followed by RT and CAUT. Metallography verified four porosity clusters and rejected one. Only RT detected any porosity - two clusters; however, none were rejected.

For 78% of the discontinuities verified by metallography, the classification assigned by the flaw characterization procedure agreed with the metallographic interpretation. When compared to the accept/reject decision made by the metallographic verification procedure, MUT accept/reject decisions agreed 47% of the time, RT agreed 59% of the time, and CAUT agreed 50% of the time. The higher agreement of RT with metallography is expected since the RT acceptance criteria concerning classification, length, and proximity were used in conjunction with metallography to verify acceptance or rejection.

Table 3 - Results of metallographic verification (MET) compared to manual ultrasonics (MUT), Ir/AA radiography (RT), and computer assisted ultrasonics (CAUT)

<table>
<thead>
<tr>
<th>DISCONTINUITY TYPE</th>
<th>MET DET</th>
<th>MET REJ</th>
<th>MUT DET</th>
<th>MUT REJ</th>
<th>RT DET</th>
<th>RT REJ</th>
<th>CAUT DET</th>
<th>CAUT REJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRACK</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LACK OF FUSION</td>
<td>15</td>
<td>12</td>
<td>14</td>
<td>8</td>
<td>7</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>SLAG</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>POROSITY</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
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CONCLUSIONS

Based on the results of the work reported herein the following conclusions are warranted:

a) Ultrasonics has a higher probability than radiography of detecting and consistently rejecting planar discontinuities. A review of literature has shown that planar flaws are considered to be more detrimental to weld quality than volumetric flaws.

b) Ultrasonics and radiography have comparable capacities for detecting and rejecting volumetric discontinuities.

c) Ultrasonics is an acceptable alternative to radiography for weld inspection.

REFERENCES


