Use of NDT computerized ultrasonic method with phased array technique in substitution of radiographic method on butt welds of type C independent tanks.

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Abstract
This paper describes the application of computerized phased array ultrasonic examination (PA) on cargo tanks for ethylene carriers made of 5% Nickel steel grade. With reference to provisions of the applicable standard, the IMO “International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk (IGC Code)”, PA has been applied, based on a detailed procedure approved by RINA, in addition to radiographic examination (RT) to verify if the former is at least equivalent to the latter in the detection of weld flaws.

Examination results showed the substantial equivalence of the two methods in detecting volumetric flaws such as slag and the high sensitivity of phase array in detecting planar flaws such as lack of fusion.

The impact of computerized ultrasonic method on repair working hours reduction has been evaluated also.

0. Foreword
Gas carrier ships are one of the most practical way for gas transportation due to the fact that liquid product stored in cargo tanks has about 1/600 of the specific volume of the same gas product. This means large amount of gas carried every voyage (fig. 1-2). Gas carriers are constructed under the provisions of an international statutory regulation, the “International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk (IGC Code)” issued by the International Maritime Organization (IMO), the specialized agency of the United Nations for maritime safety.

Inter alia, the IGC Code contains technical requirement for design, material selection, fabrication and testing of the cargo system (tanks and piping).
Cargo may be stored in “integral tanks” which form a structural part of ship’s hull, in “membrane tanks” which are non-self supporting tanks consisting in a thin layer supported through insulation by the hull structure (fig. 3) or in “independent tanks” which are self supporting (fig. 4).

The self-supporting tanks are defined in the IGC Code as being of Type-A, Type-B or Type-C. Type-A containment comprises box shaped or prismatic tanks (i.e. shaped to fit the hold). Type-B comprises tanks where fatigue life and crack propagation analyses have shown improved characteristics. Such tanks are usually spherical but occasionally may be of prismatic types. Type-C tanks are the pure pressure vessels, often spherical or cylindrical (fig. 4 to 6), but sometimes bi-lobe (fig. 7 and 8) in shape to minimize broken stowage.

This paper describes the application of computerized Phased Array ultrasonic method in the non destructive testing activity on the weld joints of type C independent tanks, for a liquid ethylene carrier ship, produced by Gas and Heat S.p.a (Pisa, Italy).

The PA inspection has been performed by CND Service Srl (Civitavecchia, Rome - Italy) at GAS and HEAT factory.
1. **Introduction**

Computerized Phased Array ultrasonic examination (PA) has been applied on butt welds of type C independent tanks for ethylene carriers having the following design data (fig. 9 and 10):

- Minimum design temperature: -104°C
- Base material: EN 10028-4 X12Ni5 (RINA 5,0 Ni grade)
- Filler metal: 316 LM grade
- Dimensions: 9000 m³ 4500 m³
  
  | Int. diameter | 12140 mm | 10000 mm |
  | Length        | 42000 mm | 32200 mm |
  | Shell thickness | 22,8÷ 25 mm | 25,7÷ 28,5 mm |
  | Heads thickness | 28,9÷ 31 mm | 22÷ 34,5 mm |

Keeping into account the possibility of substituting the radiographic examination (RT) with ultrasonic examination given by IGC Code, the scope of the application was to verify if PA is at least equivalent to the Radiographic Examination (RT), in the detection of weld flaws. At this purpose PA has been applied, in addition to, in partial and complete substitution of RT (X-ray) on three tanks according to the following NDT plan.
Joint type and welding processes

Tank 1, 9000 m³:
- Shell longitudinal (pos 1), single V / one side, fully mechanized GMAW process with ceramic backing 100% RT + 100% PA
- Shell circumferential (pos 2), single V / one side, partly mechanized GMAW process with ceramic backing + fully mechanized SAW process 100% RT + 100% PA
- Head longitudinal (pos 3 - petal), single V / one side, fully mechanized GMAW process with ceramic backing 100% RT + 100% PA
- Head longitudinal (pos 4 - cap), double V / two sides, partly mechanized GMAW process 100% RT + 100% PA
- Heads circumferential (pos. 5), single V / one side, partly mechanized GMAW process with ceramic backing + fully mechanized SAW process 100% RT + 100% PA

Tank 2, 4500 m³:
- Pos 1 joints 100% RT + 100% PA
- Pos 2 – 3 – 4 – 5 joints: 10% RT + 100% PA

Tank 3, 9000 m³:
- All butt joints with thickness > 15 mm 100% PA

Said NDT plan has been agreed between GAS and HEAT and RINA that is the Classification Society charged to certify that the ship on which the tanks will be installed and all relevant equipment have been constructed in compliance with all the applicable regulations.

Fig. 9
PA has been applied on butt joints having thickness > 15 mm. All remaining butt joints (Pos. 6 on the above drawings) having thickness ≤ 15 mm have been examined by means of RT only.

2. Rules requirements

The RINA Rules for the Classification of Ships requires that “Ships which are intended for the carriage of liquefied gases are to comply with the requirements of the latest version of the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code ), as amended”.

In particular IGC Code states that type C independent tanks are to be subjected, as a minimum, to the following NDT plan:
- 100% radiographic testing on butt joints
- 10% die penetrant testing on all joints
- 100% die penetrant test on reinforcement rings around holes and nozzles.

Concerning radiographic testing, IGC Code states that ultrasonic testing may be accepted as a partial substitute for the radiographic testing subject to prior agreement with the ship’s flag Administration and its relevant Recognized Organization (in this case RINA).

3. PA technique description

Conventional pulse-echo ultrasonic examination uses a single transducer and beam, phased arrays use multiple ultrasonic elements. In fact, the PA probe consists of many small elements, each of which can be pulsed separately.

In figure 11 the element on the right is pulsed first, and emits a pressure wave that spreads out like a ripple on a pond (largest semi-circle). The second to right element is pulsed next, and emits a ripple that is slightly smaller than the first because it was started later. The process continues down the line until all the elements have been pulsed. The multiple waves add up to one single wave front travelling at a set angle.
The phased array beams can be steered, scanned, swept and focused electronically (fig. 12). Beam steering permits the selected beam angles to be optimized ultrasonically by orienting them perpendicular to the predicted discontinuities, for example lack of fusion in automated welds.

Beam steering (usually called sectorial scan or S-scan) can be used for mapping components at appropriate angles to optimize the probability of detection of discontinuities: sectorial scans use a fixed set of elements and alter the time delays to sweep the beam through a series of angles.

Depending primarily on the array frequency and element spacing, the sweep angles can vary from ±15 to ±80 degrees, making sectorial scans applicable for weld examination (fig. 13). Furthermore, depending on the transducer size, joint geometry and thickness, sectorial scans may cover part or the entire weld, allowing, in the second case, the full examination of the joint in a single scan.

Being a computerized technique, the scans are recorded in electronic format allowing the offline elaboration and analysis of the ultrasonic signals previously acquired. All the records may be kept as long as required and re-analyzed in future. Sectorial scan has been used in present application both on “single V” and “double V” joint types. Figure 14 shows the capability of the S-scan to investigate the fusion line which is the typical location of lack of fusion.
Two scan presentations are shown below (fig. 15 and 16). Each picture contains C-scan (top image) and B-scan (bottom image) views of the joint length examined, drawn up by the computer scanning system.

Fig. 15 - View of a joint length with defects (lack of fusion) shown as yellow marks.
B-scan presentation is a longitudinal profile (cross-sectional) view of the joint. In the B-scan, the time-of-flight (travel time referable to the material thickness) of the sound energy is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction is determined.

The C-scan presentation provides a top view of the joint (same view of the radiographic film), the plane of the image being parallel to the scan pattern of the transducer. The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the joint.

The received relative signal amplitude or the time-of-flight is displayed as a color scale from light white to brown. So, a certain color corresponds to the various grades of flaw reflectance: e.g., the dark blue spots in the middle of the weld zone (on C-scan image) or in the weld root (on B-scan image) correspond to root profile irregularities, while the yellow marks in the same positions correspond to lacks of fusion.

4. **Pre-requisites**

For the acceptance of the application of PA, RINA required a detailed NDT procedure to be submitted by the Manufacturer for approval.

In particular, the procedure is to contain the following information:

a. Reference standards.

b. Personnel qualification: all operators are to be qualified and certified according to RINA Rules (at least level II ISO 9712 or SNT-TC-1A or EN 473 certification). Moreover, documentary evidence is to be supplied that a specific training in phased array technique, on same product classes to be tested and using the same equipment has been satisfactorily followed by operators. All operators are to participate to the demonstration as described at point e. below.

c. Phased array equipment description.
d. Calibration blocks and equipment calibration procedure.

e. Procedure demonstration: welded “qualification block(s)” is(are) to be prepared having material, joint design and thickness similar to the examination condition and is(are) to contain flaws oriented to simulate flaws parallel to the production weld fusion line. The Manufacturer is to demonstrate the adequacy of the procedure through tests on qualification block(s).

f. Performance of the examination.

g. Recording of scans.

h. Flaw sizing, evaluation and acceptance criteria.

5. PA Instrumentation

The PA instrumentation adopted by CND Service has the characteristics listed below:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>R/D TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Equipment</td>
<td>Omniscan MX 32 : 128</td>
</tr>
<tr>
<td>Software</td>
<td>2.0 R12 – Module OMNI-M-PA32128 P/R</td>
</tr>
<tr>
<td>Encoder</td>
<td>Baumer Electric Mod. BDK 16.05A500-54</td>
</tr>
<tr>
<td>Probes</td>
<td>2L64-A2 with 64 elements</td>
</tr>
<tr>
<td>Base</td>
<td>SA2-N60L-IHC</td>
</tr>
<tr>
<td>Coupling medium</td>
<td>Sonotech Soundclear grade 60 or water</td>
</tr>
</tbody>
</table>

6. Results of Inspections performed on Tanks 1, 2 and 3

The weld joints have been examined with PA technique, with 1000 mm length scans, from both sides of the joints and both sides of plate surfaces, each scan detecting the entire thickness of the plate.

Shell and heads longitudinal and circumferential joints, realized with “single V” bevel, welded from one side with ceramic backing, have been scanned after the root has been smooth ground in order to reduce indications due to the root irregular profile.

Furthermore, ultrasonic examination with traditional pulse-echo technique, aimed to detect joint transversal flaws (which could not be properly detected by PA), has been carried out moving the pulse echo 60° angle probe on the weld root surface along the joint.

The examination results showed that:

- PA is equivalent to RT in detecting some types of volumetric flaws in the weld zone such as slag. Moreover, the ultrasonic method is more accurate in locating the flaws along the weld thickness.

- PA is particularly sensitive to linear indications such as lack of fusion (fig. 17 to 20), especially along the bevel. It is to be considered 5% Ni steel, due to its magnetic properties, is particularly sensitive to this type of defect caused by arc blow during welding. Considering the total number of such defects found on the joints fully examined with both methods, less than 10% were detected by RT.

The following table summarizes the results on 80 joints which were 100% examined with both methods. In this occasion, the radiographic examination has been carried out before the PA examination in order not to influence the operator during radiographic film interpretation.
Defects to be repaired | Detected with RT and not detected with PA | Detected with PA and not detected with RT | Detected with both methods
--- | --- | --- | ---
Slag inclusion | - | - | 45
Clustered porosity | - | - | 13
Lack of fusion | - | 98 | 8

The acceptance criteria adopted is in compliance with the RINA “Rules for carrying out NDE of welding”.
Beside the above results, it is to be noted that the general number of repairs on the tanks examined with both methods was reduced, since ultrasonic examination permits a more accurate sizing and interpretation of the volumetric flaws.
It is to be highlighted that some indications such as isolated or clustered pores, which have been detected with RT, were not properly detected with PA. Anyway, in all such cases, the dimensions of the indications were always within the limit accepted by the reference standard.

Fig. 17 - View of a joint length with lack of fusion 12÷16 mm from joint face
Fig. 18 - View of dye penetrant test on defect shown in figure 17 after excavation

Fig. 19 - View of a joint length with lack of fusion on the weld root bevel
7. Some inspection details on Tank 1

Some further considerations on PA and RT inspections on Tank 1 (serial number TK 2-43) are shown below. They are referred to a circumferential weld (W60) of the head, having 30.043 mm of total length.

The PA inspection results are shown in figure 21:
- Number of defects detected: 10. None of them was revealed by RT
- Cumulative defects length = 2.130 mm
- Maximum length of a single defect = 900 mm
- Type of defect: all defects have been categorized as lack of side wall fusion

All above defects have been repaired.

The RT inspection results are shown the histogram in figure 21:
- Number of indications detected: 74. Most of them are gas inclusion.

These indications have been evaluated as acceptable according to the applicable standard.
7.1 PA images

Figures 22 to 27 represents C scan and B scan images of some lack of fusion revealed by PA method. Positions shown in the figures below correspond to RT positions described in paragraph 7.2.
Fig. 22 – Joint position A: defect at radiographic position 2-3 before repair

Fig. 23 - Joint position A: radiographic position 2-3 after repair
Fig. 24 - Joint position B: defect at radiographic position 17-18 before repair

Fig. 25 - Joint position B: radiographic position 17-18 after repair
Fig. 26 - Joint position C: defect at radiographic position 28-29 before repair

Fig. 27 - Joint position C: radiographic position 28-29 after repair

7.2 Radiographic imaging by digitalization
Some radiographic films of the weld W60, taken from joint positions A, B and C shown in figure 21 before repair, have been submitted to imaging digitalization (figures 28 and 29). During film reading, operators detected face side undercuts only and no evidence of lack of fusion was found.
In this paragraph some considerations on production time management are given. The performance of radiographic testing on large pressure vessels requires that all manufacturing activities in the workshop area are interrupted. So films are shot during nighttime and read in the next morning when eventual repair may be carried out. Then RT on repair is planned. This means that 2 or 3 working days might be required to obtain final RT outcome.

Ultrasonic testing may be carried out contemporaneously to the various production activities. Operators may test weld joints while welders perform other joints in adjacent areas. Prompt testing evaluation allows production department to plan repair works directly after testing has been completed, so time required to obtain final testing outcome may be reduced, at least, to 50%.

In order to increase the reliability of PA results reducing thus risks of false indications, roots of “single V” joints have been smooth grinded. This has lead to a 2-3% increase of planned working hours. Anyway smooth grinded surfaces improved die penetrant testing performance and reduced total number of indications detectable with PA up to 40%.

Finally, due to the good capability of ultrasonic method to characterize indications, compared to radiographic method, working hours for repair have been reduced up to 60%.
9. Conclusions
Having reviewed the results of the two methods applied on the butt welds of type C independent tanks, the following conclusions can be given:

1. PA resulted more or less equivalent to RT in detecting volumetric flaws in the weld zone such as slag, but it is not so effective in detecting gas inclusions (isolated or clustered of pores). Regarding this type of defects, at the time being, PA is less reliable than RT.
2. Ultrasonic is accurate in locating the flaws along the weld thickness.
3. PA is particularly sensitive to planar indications such as lack of fusion, especially on the bevel. Such defects have not been properly detected by conventional RT.
4. The better flaw sizing and interpretation capability of the ultrasonic method compared to the radiographic one lead to a reduction of repairs.
5. The ultrasonic computerized technique records the scans in electronic format allowing the offline elaboration and analysis of the ultrasonic signals previously acquired. All the records may be kept as long as required and re-analyzed in future.
6. PA requires a specific personnel skill and qualification to be ascertained by the third party inspection body.
7. Detailed NDE procedure to be produced by the NDT company and approved by the third party inspection body. The demonstration of the adequacy of the procedure through tests on qualification block(s) is required for the procedure approval.
8. The minimum plate thickness allowed for present PA application was 15 mm. Further technical improvement of the equipment and probes is expected in near future: this may result in a reduction of the minimum plate thickness to which PA may be applied.

On the basis of the above, having ascertained that PA is even more sensitive than RT in the detection of planar weld flaws (the most critical ones), RINA agreed the adoption of PA in lieu of RT on butt weld joint having thickness > 15 mm.