Application of cylindrical guided wave modes for the inspection of solid state butt welds in tubular structures

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Abstract

The studies conducted on the application of long range Ultrasonic Testing (LRUT) using fundamental cylindrical guided waves modes viz., longitudinal L (0, 2), Torsional T (0, 1), for the evaluation of solid state butt welds in Carbon and alloy Steel tubes are presented in this paper. Induction Pressure Welding (IPW), one of the prominent solid state welding process used for joining tubes in the fabrication of tubular products of boiler, is considered for this study. The major defect in the IPW process is lack of bonding, which is hitherto inspected by pulse echo contact ultrasonic testing method.

Experimental and Finite Element analysis based simulation studies on guided waves, bring out the capability of L (0, 2) and T (0, 1) modes to detect the lack of bonding in IPW joints. This study covers the response of various configurations of lack of bonding in IPW viz., through thickness, part thickness, part circumferential etc. This paper also discusses the possibility of a guided wave based screening method for the IPW joints.

Key words: Induction Pressure Welding, Lack of bonding, Ultrasonic Testing, Guided wave UT, torsional mode, longitudinal mode, finite element analysis, reflection coefficient, mode conversion.

1. Introduction

Induction Pressure Welding (IPW) (Fig. 1a) is a tube joining process wherein tube ends are clamped and aligned together and then heated by an electrical induction coil, and concurrently the hot ends are brought against each other with a precise and automatically controlled hydraulic pressure [1]. Due to the high productivity of this process, it is extensively used in boiler manufacturing industry for the fabrication of tubular products in Steel such as economiser, superheater, re-heater etc. (Fig. 1b). Being a solid state welding process, this process is free from defects such as pores, incomplete penetration, lack of fusion etc.

Lack of bonding is the common defect in solid state butt welds such as IPW and this is detected by Ultrasonic Testing (UT) using manual pulse echo contact technique (Fig. 1c), besides sample based evaluation based on destructive testing methods such as cold impact test and bend test. However, since conventional UT involves manual scanning of the transducer, at the region adjacent to the weld, around the circumference, it is slow, cumbersome, and operator skill dependent. Moreover, since this method requires access to the weld, it cannot be performed unless the joint gets sufficiently cooled.

2. Guided Wave Ultrasonic Testing

Low frequency ultrasound propagating in thin structures when travel as guided waves, their velocity depends upon thickness of the wave travel path and wave frequency, in addition to material properties [2]. By virtue of the ability to cover full volume of the thin structural components such as plates, tubes, pipes etc. and the long range propagation capability, guided wave UT is a popular choice for long range UT in several industrial applications. Three types of cylindrical guided wave modes, which occur in a number of orders, are Longitudinal, Torsional and Flexural modes. Amongst these, the fundamental modes, viz., Longitudinal L(0,2) and Torsional T(0,1) are commonly used in industry, due their axi-symmetry, non-dispersive behavior and easiness to excite [3, 4]. Extensive workshave been done on the applications of guided wave UT using these modes for the inspection of cylindrical structures.[5-7]. However, the effect of interaction of these modes with the defects in tubular butt welds is a relatively less explored area.
3. Guided wave UT for solid state welding of tubes

The modes considered for this work are L(0,2) and T(0,1) modes. In order to choose the operating frequency, the dispersion curves, which indicate the relationships between velocities (phase velocity and group velocity) of various modes and the frequency were plotted [8]. Representing the typical dimensions of IPW tubes, Outer Diameter (OD) values 45 mm and 51 mm, and thickness values 3.6 mm, 6 mm, 6.6 mm and 7 mm were considered. As shown in figure 2, the phase velocity dispersion curves for a carbon steel tube of OD 51 mm and thickness 6.6 mm indicate the possible modes in guided wave regime. T (0, 1) and L (0, 2) modes show non-dispersive behaviour when compared to other modes. As noted from the dispersion curve that very low frequencies and very high frequencies pose dispersion and clustering problems respectively, 100 kHz was chosen as an optimum frequency for this study.

4. Finite Element Modeling of IPW Joints

Lack of bonding, which is typically an oxide or inert gas layer having width less than 100 microns, presents itself as a break in the IPW joint [1]. They could occupy part or entire portion of the circumference/thickness, and can exist in continuous or intermittent form. Although analytical approach is quite effective in conventional UT, due to the possibility of myriads of modes, this is quite complex in the case of guided wave UT. Moreover, preparation of weld specimens with lack of bonding at the desired location with the desired height, orientation and circumferential extent is extremely challenging. Finite Element Method (FEM) is one of the numerical methods, wherein the physical system is viewed as an integration of finite sized volumetric elements, of which each element is connected to its neighborhood element at their boundaries [9]. The wave equation for a complex structure is solved by dividing the continuum into simple regular shaped finite elements and solving in terms of field variables at nodal point of these elements.

FE simulations of propagation of T (0, 1) mode and L (0, 2) mode in 3-D models of tubes with IPW having various configurations of defect were performed using the package ABAQUS / Explicit 6.12 [10]. Typical length of the tubes modeled is 2 m, wherein the IPW joint is centrally located.
Spatial discretization was done by structured linear order hexahedral brick elements (C3D8R) with global element size of 0.001m. Similarly the discretization in time domain was done by giving a time step of 10 nano-seconds, for a propagation time period of 1000 micro-seconds. The parameters of FE studies are shown in table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
<th>Longitudinal velocity of sound</th>
<th>5920 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7932 kg/m$^3$</td>
<td>Shear velocity of sound</td>
<td>3260 m/s</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>200 GPa</td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>

IPW profile in the center of the tube was modeled by adding layers of elements, of maximum reinforcement of 4 mm each on outer and inner sides of the tube. Lack of bonding was modeled as thin notches along the weld bonding line, by removing, one or multiple radial layers of elements. Various configurations of lack of bonding such as axial extents, circumferential extents, and radial extent, were modeled to study the response of each of these features.

A five cycle Hanning windowed tone burst pulse having central frequency of 100 kHz was used for excitation. The spacing between the excitation points conforms to the Nyquist-Shannon criteria [11]. L (0, 1) and T(0,1) modes were generated in the respective models by giving the directions of excitation parallel to the axis of the tube, and tangential to the axis of the tube respectively [9]. The response of the weld and defects to ultrasound was studied by analyzing the displacement magnitudes of the reflected, with respect to that of the incident signals. This is quantified as Reflection Coefficient (RC), as shown in equation 1, where $u(j)_i$, $u(j)_r$, are the displacement magnitudes of the $j^{th}$ monitoring node of the incident and reflected signals respectively. For this purpose, all these signals were monitored at ncircumferential locations on the reflection side.

\[
RC = \frac{\sum_{j=1}^{n} u(j)_R}{\sum_{j=1}^{n} u(j)_I}
\]

5. **FE simulation results and discussions**

Figure 3. Comparison of the snapshots of the contours of total displacement magnitudes of a good IPW joint vis-à-vis defective joint.

FE simulation results show that, the weld causes partial reflection and transmission of the incident guided wave mode. In the case of IPW without defect, the amplitude of the signal is uniform around the circumference, since it acts as an axially symmetric reflector. However, when there is a defect in the joint, which is part circumferential, this axially symmetric reflection pattern gets disturbed and in turn results in the variation of signal amplitude around the circumference, both on the reflection and transmission sides. Figure 3 shows, a comparison of snap shots of the contours of total displacement magnitudes of reflected as well as transmitted waves for T (0, 1) mode incident case, from an IPW joint without and with defect, on a tube having OD 51 mm, thickness 3.6 mm, and the defect circumferential extent 25%. Similar pattern was observed in the case of L (0, 2) mode also. It was also noted that, in the case of defective welds, a portion of the incident wave gets trapped.
within the weld and propagates along the circumference. In the case of weld, it is the increase in the area of the weld with respect to the plain tube region which results in the acoustic impedance mismatch and in turn the reflection, whereas in the case of defective region in the weld, it is the combined effect of difference of area as well as the air-solid interface in the defect which causes the acoustic impedance mismatch. Therefore the latter case results in more complex interactions, which depends upon the extent of the defect in the radial as well as circumferential directions.

5.1. Reflection Coefficient

![Figure 4. Total Reflection coefficient vs. circumferential extent of the defect for different configurations of the defect, for T (0, 1) mode incidence.](image)

Extensive studies on Reflection Coefficients (RC) were done for various defect configurations, and it was observed that RC is strongly influenced by the circumferential and radial extents of the lack of bonding, and also the height of the weld cap. Figure 4 presents the consolidated results of RC vs. Circumferential Extent (CE) for T (0, 1) mode. There is a notable change in the RC vs. CE pattern, among the welds with defects of through thickness, part thickness and embedded type. In the case of through thickness defects, the relationship is quite similar to that of the well-studied plain tube defects [12-13]. But the interference with the reflection and transmission from the weld becomes significantly large and reduces the total RC, in the case of part-thickness as well as embedded type defects, resulting in, (i) initially increasing and then increasing behaviour of total RC with respect to CE, and (ii) a relatively lower total RC than through thickness defects. Similar observations were made in the case of L (0, 2) also.

5.2. Mode conversion

Another important observation made from the FE simulations is the presence of mode converted signals in the reflected as well as transmitted signals from the part circumferential as well as embedded defects in IPW. Calculations of group velocity showed that the primary reflected / transmitted modes are L (0, 2) and T (0, 1) in their respective incidence cases. Typical A-scan plots deductible from FE simulations, as shown in figure 5, give information about the magnitude as well as velocity of mode converted signals. It can be seen that, in the case of L (0, 2) incidence, mode converted signals are trailing behind the main waves, as they are slower than L (0, 2) mode. Analysis of the group velocities and mode shapes revealed that these new modes are F(1,2) and F(1,3) in the case of L(0,2) and T(0,1) incidence respectively[9].
6. Experimental validation

Experimental validations were conducted on IPW specimens using a guided wave UT system consisting of pulser-receiver, Cathode Ray Tube (CRT) display system, and piezoelectric crystal probes having a central frequency 100 kHz along with cables and connectors, with an appropriate probe mounting mechanism. In order to excite pure T (0, 1) mode and L (0, 2) mode, the probes were placed in tangential direction and axial direction respectively. Preliminary trials in the lab were done with IPW specimens with artificial notches (machined with Electro-Discharge Machining process) to simulate the FE models and later done with IPW joints having natural defects. Scatter diagram of Reflection Coefficients, shown in figure 6, shows the difference in response of good and defective IPW joints in terms of RC values. This shows that total RC of good joints, fall within a range of 0.4-0.6, whereas, in the case of lack of bonding the total RC is either lower than 0.4 or higher than 0.6. This confirms that the FE simulations results can be used as a basis for screening of IPW joints. The rare possibility of lack of defective joints wherein the total falls within 0.4-0.6 can be addressed by studying the circumferential variation of nodal RC, by capturing the signals from each probe separately. Both in the case of L (0, 2) and T (0, 1) mode this was confirmed.
7. Conclusions
This work shows that, contrary to the case of conventional UT, the response to guided wave UT, using L (0, 2) and T (0, 1) modes, from a defect present in a tube butt weld, is different from that of a plain tube defect of identical properties. The total reflection coefficient of an IPW with defect is influenced by the circumferential extent and radial extent of the defect, in addition to the weld-tube thickness mismatch. Non-axisymmetric defect also causes circumferential variation of the total displacement magnitude, mode converted signals, on both reflection and transmission sides of the weld. The difference in the reflection coefficients, obtained from good and defective joints, along with the circumferential variation in the reflection coefficient can be used as basis of defect detection. However, fine tuning with respect to the inspection system such as, development of the scanner which can mount larger number of smaller sized piezo-electric crystals, use of multi-channel signal capturing technique, etc. will be required, in order to develop a robust system for qualification of IPW and other similar solid state butt welded joints in tubes, in the case of industrial applications.

8. Acknowledgement
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9. References