ABSTRACT

Majority of the core components for pressurized heavy water reactors and boiling water reactors, which are manufactured at Nuclear Fuel Complex (NFC) Hyderabad, are made of zirconium alloys. One of the quality control steps during fabrication of these components is the ultrasonic testing of zirconium alloy ingots and billets. Ultrasonic testing of zirconium alloy billets and ingots is carried out using normal beam technique with an aim to detect laminar flaws and inclusions. Ultrasonic simulation studies have been carried out using CIVA 9.2 with an aim to replace the conventional ultrasonic technique (carried out using single crystal normal beam probe) with a phased array technique using an annular phased array probe for examination of zirconium alloy ingot and billet. The study involved computation of the sound beam profile inside the component and then using this profile in the defect response module to assess the effectiveness of the sound beam to detect flaws of concern at various depths. The simulation study is carried out for both, the conventional probe (that is currently used) as well as the annular phased array probe. The results of defect response using both the probes are analyzed for uniformity in sensitivity throughout the inspected volume, lateral resolution and sizing accuracy. Based on the results of simulation studies a suitable annular phased array probe has been designed for ultrasonic phased array examination of zirconium alloy ingot and zircaloy billet.

INTRODUCTION

Zirconium alloys are widely used as a material of construction for nuclear core components. The starting product forms for manufacturing of these components are zircaloy billet and ingot. These are inspected by ultrasonic examination using normal beam technique to detect laminar defects and inclusions. Once acceptable, these ingots and billets are processed further by various fabrication routes such as extrusion, drawing, pilgering, etc. to manufacture components like fuel tubes, end plugs and pressure tubes. An ultrasonic simulation study was carried out with an aim to replace the conventional normal beam testing of billets and ingots with phased array. Phased array ultrasonic technique offers several benefits in terms of sensitivity, lateral resolution and defect sizing. Simulation studies were carried out using CIVA 9.2 NDE simulation package to arrive at the specifications of annular phased array probe for ultrasonic normal beam examination of billet and ingot.

The use of simulation finds important applications in Non Destructive Examination. The simulation studies helps in obtaining the inspection variables prior to taking up the actual inspection. The development of Phased Array Probe necessitates the use of simulation for design of the probe, computation of focal laws, and interpretation of experimental results. The CIVA software package, which supports ultrasonics, is a versatile simulation tool developed by CEA (French Atomic Energy Commission), France. This package allows computing the sound beam intensity within the material and interaction of the beam with the defects/reflectors present in the specimen (1-3). Many models are developed to simulate the radiation and propagation of the sound beam inside the material and diffraction of the beam, when it interacts with the defects (4-6). The experimental validation of these codes were done to increase the confidence level and good agreement were found between the values obtained by CIVA and the experiment, in terms of positioning and amplitude of echo (3,7).

During this study, ultrasonic simulation was carried out for three geometries: (a) Ingot of dia. 350 mm, (b) Solid billet of dia. 142 mm and (c) hollow billet of outside dia. 142 mm and 51 mm thickness. For all these configurations, beam computation and defect response behaviors were observed and analyzed using the conventional probe, which is currently used, and the annular phased array probe, which is designed as part of this study. For Phased array inspection, an annular phased array probe was selected, as it offers very good sensitivity for detecting small inclusions or other laminar defects due to its ability of sharp spherical focusing at various depths.
DESCRIPTION OF ZIRCALOY BILLETS AND INGOTS

Zircaloy finds application in nuclear industry as structural material due to its low neutron absorption cross-section. Variety of core components in the form of fuel tubes, end plugs and pressure tubes, which are made of zircalloys, are manufactured at Nuclear Fuel Complex, Hyderabad. These are extensively used in Indian pressurized heavy water reactors. The manufacturing of these components involves several thermo-mechanical processing steps starting from zircaloy ingot/billet. One of the quality control steps in the fabrication flowsheet of these components is the ultrasonic testing of zircaloy ingot/billet. The reference defect standard used is flat bottom hole of diameter 3.2 mm for ingot, 1 mm for hollow billet and 0.8 mm for solid billet. In this study, the annular phased array probe was designed using simulation studies for ultrasonic phased array inspection of three geometries: ingot of dia. 350 mm, solid billet of dia. 142 mm and hollow billet of outside dia. 142 mm and 51 mm thickness. Further, the results of simulation studies obtained using annular phased array probe are compared with the results obtained by conventional normal beam probe, which is currently used.

ULTRASONIC SIMULATION USING CIVA

CIVA follows the semi-analytical approach rather than numerical method (finite elements, finite differences), as it leads to short computation times without sacrificing on the accuracy of the results. The models were developed for i) radiation of ultrasonic beam from the transducer and propagation of field inside the inspection zone, ii) the interaction of ultrasonic field with the defects and iii) propagation of ultrasonic beam to the receiver (1,5 and 7). The ultrasonic testing (UT) Simulation consists of Beam Computation and Defect Response modules. The Beam Computation module gives the sound beam profile present inside the specimen and the defect response predicts the interaction of this beam with the defect and provides the result in the form of A-Scan, B-Scan, S-scan or C-scan.

The CIVA simulation studies start with defining the specimen geometry along with its material properties such as density, sound velocity and attenuation. During the present study, the attenuation of the material was measured at 2 MHz, 4 MHz and 5 MHz and its values were given as input during beam computation. Probe parameters such as probe type, size, frequency and wedge geometry (size, incident angle, velocity etc.) were defined. The probe was positioned at the required location and orientation. The computation zone was defined in the area of interest, and the beam profile was obtained in that area.

The computation of field radiated by the transducer is based on the Rayleigh integral. The Pencil method is used to predict the ultrasonic field radiated by the transducer. The emitting surface of the transducer is discretized into point sources and the field is calculated through the summation of all contributions from source points. The model considers the evolution of cone of rays between source point and observation point around the geometrical acoustic path. (4).

The beam computation provides the intensity variation in the beam profile in terms of colour coding. Using tools, it is possible to superimpose the result of beam computation on the component and find the location of maximum intensity of sound beam inside the component. Once the ultrasonic field is calculated, it is given as input to models of echo formation to simulate the whole inspection. Depending upon the type of flaw and the inspection technique, different classical approximations are followed. For prediction of response from volumetric flaws (side drilled holes, flat bottom holes etc.) and large voids, Kirchhoff approximation is used. The echo received at position (x, y) and at time t is given by

\[ E(x,y,t) = \int_{defect} Crl \Phi_0(t-(\Delta t + \Delta L))q(p_r, \theta_r, z_r)q(p_e, \theta_e, z_e)ds \]

\[ \Phi_0 \] denotes temporal convolution. The contribution of given surface element ds will depend upon its position relative to emission q(p_r, \theta_r, z_r) and reception q(p_e, \theta_e, z_e) and the response is obtained through summation of contribution from all surface elements ds. The Crl transfer function takes care of diffraction and reflection of the beam by defects (6). For cracks, diffraction from edges are calculated using GTD (Geometrical Theory of Diffraction) in pulse echo inspection. The interaction of field with inclusion is predicted using slightly modified form of Born Approximation (7-9). The field at reception is calculated by summing up all the scattered contributions. The model assumes the transmission-reception reciprocity principle based on Auld’s theorem (1,7). Finally the defect response results were obtained in terms of the relative amplitude of the reflected signals from flaws located at various depths.

RESULTS OF SIMULATION EXERCISE FOR ZIRCALOY INGOT & BILLETS

Beam Computation

The CIVA simulation was carried out on zircaloy ingot and billets using conventional and annular phased array probes. Various probe configurations used during the present study are given in Table 1.

For phased array inspection of solid billet and ingot, the focal laws were programmed in such a way that focused sound beam at depths starting from the center to the back surface is obtained (dynamic depth focusing technique). For hollow billet, the dynamic depth focusing range is defined from 10 mm below the top surface to the ID surface. The results of beam computation for various geometries using conventional and phased array probe are shown in Figure 1.

The results of beam computation indicate the following:

- With conventional probe, the maximum intensity of sound beam for ingot and billet is at the depth of 120 mm and 55 mm respectively. The sound intensity reduces drastically at the back surface, 8.7 dB lower than maximum for ingot and 7.8 dB lower than maximum for solid billet
- With conventional probe, for hollow billet, the sound beam intensity is uniform for the entire thickness
• With annular phased array probe the sound beam intensity is maximum and uniform in the region of interest for ingot and billets

**Defect Response**

The beam that was computed in beam computation module using both probe configurations was utilized in the defect response module. In order to study the defect response behavior, the flat bottom holes of dia 3.2 mm, 0.8 mm and 1 mm with 20 mm lateral separation were introduced at different depths starting from center to the back surface in ingot, solid billet and hollow billet respectively. Defect response behavior was computed using the above said parameter and the result obtained is shown in fig 2.

Based on the results of defect response, the following two parameters were evaluated for conventional probe and the annular phased array probe:

1. Amplitude variation in the echodynamics plot
2. Defect size by 2 dB drop method

The amplitude difference was calculated between the two defects, which show maximum and minimum amplitude in the echo-dynamic sequence. The differences in amplitude of signals from flat bottom holes (FBH) at various depths measured using the conventional probe are 9 dB, 6.4 dB and 1.1 dB for ingot, solid billet and hollow billet respectively. Using annular phased array probe, the figures are 1.7 dB, 3 dB, and 1.8 dB. The sizing of the defect was done using 2dB drop method. The results of defect sizing for hollow billet, solid billet and ingot are given in Table 3.

The defect size measured using annular phased array probe for hollow billet and ingot are within 0.2 mm of the size of standard reference defects, which were introduced at various depths in these geometries. For solid billet, defect sizing by phased array is observed to be within 0.4 to 0.8 mm of the

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**Table 1**: Probe configurations used for simulation of billets and ingot

<table>
<thead>
<tr>
<th>Component</th>
<th>Geometry</th>
<th>Conventional probe</th>
<th>Annular Phased Array probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingot</td>
<td>Dia: 350 mm</td>
<td></td>
<td>Dia: 50 mm, Number of Rings: 16, Frequency: 5 MHz</td>
</tr>
<tr>
<td></td>
<td>Dia: 24 mm, Frequency: 2 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Billet</td>
<td>Dia: 142 mm</td>
<td></td>
<td>Dia: 35 mm, Number of Rings: 16, Frequency: 4 MHz</td>
</tr>
<tr>
<td></td>
<td>Dia: 12.5 mm, Frequency: 4 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hollow Billet</td>
<td>Dia: 142 mm, Thickness: 51 mm</td>
<td></td>
<td>Dia: 14 mm, Number of Rings: 14, Element Gap: 0.1mm, Frequency: 5 MHz</td>
</tr>
<tr>
<td></td>
<td>Dia: 12.5 mm, Frequency: 4 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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[Fig. 1]: Beam computation results of (a) ingot-conventional UT probe, (b) ingot-annular phased array probe (c) solid billet-conventional UT probe (d) solid billet-phased array probe (e) hollow billet-conventional UT probe (f) hollow billet-phased array probe.
actual size of defects. However, sizing of defects by conventional normal beam probe show large variation when compared with the actual size for all the geometries. The result reveals that the annular phased array probe offers uniform sensitivity, excellent lateral resolution and very good sizing accuracy as compared to the conventional ultrasonic normal beam probe.

## CONCLUSION

CIVA simulation studies using conventional and phased array ultrasonic technique of ingot & billets (solid and hollow) were performed. The overall performances of the conventional as well as the phased array testing for billet and ingot were compared using beam computation and defect response modules of CIVA. While conventional UT could detect all the defects, it was observed that there was a huge variation in the amplitude of the signals from same size defects, which are at the center of the ingot/ solid billet and the ones which are near the back surface. It was also observed that the lateral resolution obtained by conventional UT is not very satisfactory which could lead to the condition wherein, two defects which are very close to each other may be interpreted as one big defect. The accuracy of defect sizing was also found to be inferior for conventional UT. On the contrary, phased array ultrasonic technique has shown much better results. There is a huge improvement in the lateral resolution as well as sizing capability. This is because of the fact that using phased array one can focus the sound beam at various depths using Dynamic Depth Focusing (DDF). DDF also ensures that one gets uniform sensitivity for detection of flaws throughout the thickness of billets and ingot. This study has helped in the design of annular phased array probe for inspection of zircaloy ingot and billets.

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**Table 3 : Defect Sizing by conventional and phased array probe**

<table>
<thead>
<tr>
<th>Geometry (True FBH dia.)</th>
<th>Defect Sizing by Conventional UT/ Phased array UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingot (3.2 mm)</td>
<td>9.3/3.4  11.2/3.3  12.2/3.4  13.6/3.2  14.8/3.2  17.6/3.4</td>
</tr>
<tr>
<td>Solid billet (0.8 mm)</td>
<td>4.1/1.5  4.5/1.2  4.8/1.5  4.9/1.4  6.0/1.5  6.6/1.6</td>
</tr>
<tr>
<td>Hollow billet (1 mm)</td>
<td>7.4/1.0  6.7/1.0  3.2/1.0  2.6/1.0  2.6/1.2</td>
</tr>
</tbody>
</table>

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**Fig. 2 :** Defect Response results obtained from (a) ingot using conventional UT probe, (b) ingot- Phased Array Ultrasonic probe (c) solid billet-conventional UT (d) solid billet- phased array UT (e) hollow billet- conventional UT and (f) hollow billet- phased array UT
REFERENCES


