Phased Array Ultrasonic Testing of Dissimilar Metal Welds using Geometric based Referencing Delay Law Technique

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Abstract
Phased array ultrasonic testing (PAUT) techniques are widely used for the non-destructive testing (NDT) of austenitic welds to find defects like cracks. However, the propagation of ultrasound waves through the austenitic material is intricate due to its inhomogeneous and anisotropic nature. Such a characteristic leads beam path distorted which causes the signal to be misinterpreted. By employing a reference block which is cutout from the mockup of which the structure is a dissimilar metal weld (DMW), a new method of PAUT named as Referencing Delay Law Technique (RDLT) is introduced. With the RDLT, full matrix capture (FMC) was used for data acquisition. To reconstruct the images, total focusing method (TFM) was used. After the focal laws were calculated, PAUT was then performed. As a result, the flaws are more precisely positioned with significantly increased signal-to-noise ratio (SNR).

Keywords: dissimilar metal weld (DMW), phased array ultrasonic testing (PAUT), full matrix capture (FMC), total focusing method (TFM), referencing delay law technique (RDLT), probability of detection (POD)

1. Introduction

Ultrasonic testing techniques are widely used for the non-destructive testing (NDT) of austenitic welds to find defects like cracks. The use of austenitic materials is demanded both by the mechanical and by environmental, i.e. high temperature or corrosive, circumstances of nuclear power plants. The designing dissimilar metal welds (DMW’s), in particular, is well adopted due to its’ higher sustainability in nuclear power plants [1]. However, a high nickel content in stainless steel retains this phase on cooling to room temperatures. The fast cooling rates and channels yield what is termed dendritic epitaxial grain growth over successive weld deposits leading to the coarse and elongated grain structure characteristic of austenitic welds [2]. The solidified weld shows strong anisotropy, i.e. it indicates differing elastic properties depending on the direction in which it is stressed [3]. For these reasons, the propagation of ultrasound waves through the austenitic material is intricate due to its inhomogeneous and anisotropic nature. Such a characteristic yields considerable limitations of (1) decreased signal-to-noise ratio (SNR) or increased backscattered energy [4], (2) increased attenuation of the propagating sound waves which limits the range of inspection [5], and (3) increased distortion in the propagation of sound waves [6]. Hence, the inspection of austenitic welds, particularly in thick section welding can be difficult to locate the defect. Due to the problems described above, it becomes often the controversial issue for NDT engineers that the individual differences of skill are inevitable which is also degrading reliability of testing results. Particularly, compared to the other NDT methods, the results of ultrasonic testing depend on individual skills, types of equipment and procedures. M. Beth and J. L. Monjaret [7] reported the problematic points based on the results of round robin test for locating inter-
granular stress corrosion cracking (IGSCC) signals in pipe lines in the nuclear power plants. It was found that there were problems not only with capability of locating the cracks but also with the reliability of the ultrasonic testing during pre- and in-service inspection [8]. Hence, in order to improve the reliability for the testing results, the need for performance demonstration (PD) of DMW’s for ultrasonic testing system in accordance with the ASME Code, Section XI was brought to the fore. For the PD, mockups or reference blocks with the artificially induced defects which are similar to the real flaws being generated are produced using the same material and dimension. Hence, the main aim of this study is to overcome the individual skill deviation by using a reference block with artificial flaws based on a phased array ultrasonic testing combined with full matrix capture (FMC) and total focusing method (TFM) which is called referencing delay law technique (RDLT) in this study.

2. **Dissimilar metal weld specimen and artificial flaws**

Two pieces of DMW were cut out from the mockup as shown in Figure 1. One piece was used for characterization of the weld, e.g. chemical metallography and electron back scattered diffraction (EBSD) and the other piece was used for wave visualization by scanning laser vibrometry (SLV) and for phased array ultrasonic testing (PAUT).

![Figure 1. Image of mockup for performance demonstration (left), reference block with composition of different material media (middle) and sample for weld characterization (right)](image)

The most difficult location to detect cracks is the place behind the weld mainly due to the high attenuation. Therefore, the location of the sound reflector as a target flaw was determined in that place which is called as “Notch B”. The type of the artificial flaw is electron discharge machined (EDM) notch and two identical notches were produced through the whole thickness.

![Figure 2. Dimension of specimen (left) and geometric information on EDM notches (right)](image)
Figure 2 shows the dimension and the geometric information of the specimen and the notches. In this study, the key idea is to make use of a reference data obtained from Notch A in the specimen. It is assumed that the wave propagation passing through the transversely isotropic media, i.e., austenite steel region, may render no significant variation in the beam direction since the microstructure in that media does not vary evidently as the wave runs [9]. This assumption was checked by RDLT technique in the experiment of this study.

3. Structural analysis methods of specimen

3.1 Grain structures by electron backscatter diffraction (EBSD) technique in comparison with chemical metallography

EBSD is a scanning electron microscope (SEM) based technique for material crystallography. EBSD is a powerful tool to provide quantitative data for modeling a complicated weld structure. In order to save time and cost, only six pieces of samples were chosen for EBSD measurements as shown in Figure 3. The weld in EBSD image represents a strong fibre with the vertical direction which is consistent with the observed solidification growth. In terms of size of the grain, the major grains are in the range of 2 to 4mm and are tilted from the vertical axis by up to 45°. The grains in the buttering are mostly horizontally laid. Compared to the metallography results, the EBSD provides minor size of grain orientations clearly.

3.2 Wave visualization by scanning laser vibrometry with ultrasonic transmitting technique

To visualize beam propagation, ultrasonic transmitting technique as a vibrating source of longitudinal wave was implemented with the SLV. This method has already been demonstrated for NDT applications by [10]. When the pulsed longitudinal waves start to
stimulate the grains in the material, the SLV starts to scan the surface point by point. Four pieces of main screen snapshots gained by the measurements are shown in the Figure 4. When the P-wave front passes through the boundary between the transversely isotropic and the weld region, the wave scattering and absorption are remarkably intensified and it becomes deformed as shown in Figure (a). When the P-wave keeps propagating into the buttering region, the wave front becomes squashed until it passes out of the region as shown in Figure (b). Once the P-wave passes through the ferrite material region, it becomes back to undeformed wave as shown in Figure (c). In the (c) image the weak S-wave propagating is found. The strong scattering signals are found in the overall weld area as shown in Figure (d). In the transversely isotropic region, relatively weak scattering is occurred and in the ferrite material region little scattering is found. The black dots appeared in the filtering and feature extraction process when the time of wave propagation could not be found in noise signals.

Figure 4. Propagating waves passing through the lower part of the welds [unit: μs]

4. Referencing delay law technique

4.1 Principle of full matrix capture (FMC) combined with total focusing method (TFM)

Full matrix capture (FMC) is a specific technique to acquire signal data using phased array ultrasonic probes. This technique provides a complete time domain signal set which is received from every element of an array probe. This technique was introduced by Holmes et al in 2005 [11]. In the FMC technique, one element shots while the other elements are receiving and this procedure is repeated until all elements are shot, in which FMC does not need to define the steering condition and focal laws before the testing. The output is usually a
huge matrix, e.g., $n \times n$ for an array of $n$ elements. Such a huge amount of data set can be a disadvantage on processing speed. Practically FMC needs image reconstruction methods which are typically performed by total focusing method (TFM). Nevertheless such a sufficient data allows ultrasonic testing to acquire all possible data. In addition, FMC has a great advantage of avoiding grating lobes because it does not need to focus [12].

When FMC is combined with TFM for image reconstruction, the data obtained from the complete transmitting-receiving process is stored in a matrix, $S_f$. Figure 5 shows the principle of FMC-TFM combination technique. The size of matrix is determined by “number of transmitting elements ($n_{tx}$) $\times$ number of receiving elements ($n_{rx}$) $\times$ number of samplings in each signal ($n_s$)”$. Delay laws can be different from one focal point to other focal point in the grid. The size of the matrix for the whole region of interest (ROI) is determined by “number of focal points in x-axis ($n_{px}$) $\times$ number of focal points in z-axis ($n_{pz}$) $\times$ number of probe elements ($n_e$)”. Assuming that the matrix $S_f (i,j)$ is $1 \leq i \leq n_e$ and $1 \leq j \leq n_e$, the array is focused to produce an image matrix $I(x,z)$ as below:

$$I(x,z) = \sum_{i=1}^{n_{tx}} \sum_{j=1}^{n_{rx}} S_{tx,rx} \left( \sqrt{(x_{tx,x}-x)^2 + (z_{tx,z} - z)^2} + \sqrt{(x_{rx,x}-x)^2 + (z_{rx,z} - z)^2} \right)$$

where $x_{tx}$, $z_{tx}$ locations of transmit element, $x_{rx}$, $z_{rx}$ locations of receive element, $c$ is sound wave velocity in the material

4.2 Application of referencing delay law technique

Considering the wave behavior within a structure composed of an anisotropic inhomogeneous and a transversely isotropic homogeneous media, the idea was formulated to correct the transversely isotropic region as an isotropic homogeneous region where the waves propagate along straight lines with constant wave speed. For this, it is necessary to determine the sound velocities at least two different directions of the wave propagation. In this study, a practical approach to measure the velocities directly from the specimen with the aid of Notch A was applied by using FMC-TFM technique. Once the transversely isotropic region is corrected, the time delay values for the anisotropic inhomogeneous region, e.g., Notch B, can be calculated by referencing the region. Thus one would take RDLT for correcting the distorted region where the complex waves pass varying velocities into a simple geometry where the waves travel in simple path with constant velocity.
4.2.1 Sound velocity measurements for 0 degree angle in Z-axis ($c_z$)

The values of sound velocity in 0 degree were acquired based on the basic data set gained from scanning position $P_1$ to $P_{35}$ as shown in Figure 6. By using the pre-known data of the beam path distance at each scanning position and its corresponding time of flight value, the velocities were calculated. The lowest velocity is 5,606m/sec, the highest one is 5,618.1m/sec, the average velocity is 5,612.6m/sec and the standard deviation is 3.4m/sec.

![Figure 6. Schematic diagram of scanning for measurements of direct sound velocity in zero degree and the overall distribution of the velocities gained from scanning position 1 to 35](image)

4.2.2 Sound velocity measurements for 90 degree angle in X-axis ($c_x$)

At the velocity measurement of Z-axis, a height of Notch A with maximum amplitude was determined. It was assumed that the wave path direction is perpendicular to the bottom line as shown in Figure 7. Under this scheme, the probe was placed at the scan position 37 ($P_{37}$), referring the center index of the linear array probe which only the 9th element was activated for signal transmitting and receiving. The height of the notch was precisely identified and the horizontal line indicating the height of the notch was used for adjusting the beam paths gained from other scan positions. Based on the scanning path from $P_{37}$ to $P_{20}$, the moving distance of the probe in horizontal line is defined as $X_l$. The $d_l$ lined in red is the distance of the beam path to be gained as an ideal measurement, e.g. in case of the sound velocity is fitted with the beam path. The beam path in blue marked as $d_R$ is the reconstructed image providing the image of the notch tip and root-edge signals. It was assumed that when the wave ($d_R$) passes into the specimen in Z-axis at the $P_{37}$, there would be no component of the sound speed in X-direction. Under the same assumption, the beam ($d_R$) generated at $P_{20}$ would arrive at the reflector in the sound velocity in Z-axis, e.g. $c_z$. Then, the time of flight of $d_l$ is the same as $d_R$ of which each beam arrives at the same height of the notch, but only the sound velocity of $d_l$ ($c_l$) and $d_R$ ($c_R$) is different. In order to obtain the value of $c_x$, it was assumed that when a reconstruction is processed by the value of $c_z$, the signals of Notch A should be appeared in front of its real position in space as shown in Figure 7. As a result, the distance difference between $d_l$ and $d_R$, e.g. $\Delta X$, becomes the function for calculation of the sound speed in X-axis. Since we know the coordinates of Notch A from the geometric data, by using such a data $\Delta X$ is determined and hence the sound velocity of $c_x$ at a certain scan position is calculated as the following equation:
\[ c_X = c_2 \frac{x_i}{x_i - \Delta x} \]  

Through the calculation gained from each scan position from \( P_{16} \) to \( P_{28} \), the individual sound speed was determined as shown in the graph in Figure 7. The standard deviation is 11.1 m/sec and the average velocity is 5,713.4 m/sec.

![Figure 7](image.png)

Figure 7. Schematic diagram of gaining sound speed in X-axis and graph of overall distribution of sound velocity gained from scanning point 16 to 28

4.2.3 Adjusting Z-axis based on Notch A

For the image reconstruction by TFM, the average sound velocity of the transversely isotropic region in X-axis was input. Then the images were adjusted to the Z-axis. As a result, the signals of Notch A are in positioned as shown in Figure 8 (a).

![Figure 8](image.png)

Figure 8. Image gained by TFM for Notch A representing missizing of the notch height before the correction of the mother material (a) and after the correction (b)
Since the sound velocity was set to the value of $c_X$, the wave propagating in Z-axis arrives at the sound reflectors as longer as the sound velocities in X- and Z-axis is different. As a result, the signals appeared 1mm longer than the real height of Notch A. In order to fit the height of the notch, time delay value of each element was calculated by using the sound velocity obtained. The time delay values determined were then applied to compensate the error of the height of Notch A. Figure 8 (b) represents the corresponding results of TFM gained at Notch A. The tip notch and the root-edge signals are both in horizontally and vertically well located.

4.2.4 Geometric based computation and compensation of error in austenitic weld region

The weld region still remains to be processed more complicatedly. When the sound velocity is simply different from the material, the velocity values can be obtained by the method applied for the transversely isotropic region. However, in the case of the austenitic weld, the wave skew should be considered. Figure 9 (a) shows that the height of Notch B is 0.8mm higher than the original dimension. This result was obtained when the Notch A in Z-axis was adjusted. Unlike the signals obtained from the transversely isotropic media, the signals gained through the anisotropic media contain bottom-wall reflected signals due to the beam skew. In addition, at the image reconstruction it was interesting to notice that all the elements foam the wave signal in a circular arc shape and it generates the noise like signals. These complicated signals would hinder the evaluation and cause to misinterpret.

![Figure 9. Image gained by TFM for Notch B after the correction of the transversely isotropic region (a), after the correction of height of Notch B (b), and after the correction of mislocation in X-axis (c)](image)

To determine the time delay between two different signals, cross correlation method was used. By using the pre-known geometry of the Notch B, the time of flight values were calculated. Although the error of the height is compensated, the reconstruction result still shows 4.4mm mislocated from the original location in X-axis as shown in Figure 9 (b). This is mainly caused by the wave skew in the weld. Locating Notch B signal can be determined by using the distance between the center of Notch A and Notch B. Hence, the delay laws can be determined by referring both the geometric location of Notch B and the location of the signal acquired by the cross correlation method. By this RDLT, the signals of Notch B including the notch tip are more precisely located as shown in Figure 9 (c).

4.2.5 Validation by phased array ultrasonic testing by sector scan mode

Figure 10 (a) shows sector scan images without compensation of the time of flight in the weld. The signals highlighted in a square line contain the coordinate data (steered angle to the sound
reflector, \( \theta_f \), and beam path distance to the sound reflector, \( d_{p} \) which identify the location where the signal is reflected. Before the compensation, the signals gained from both notches represent the mislocation. Apart from the signals from the notches, a signal reflected inside the weld was found in the middle area of the weld. This suspected signal has not been successfully investigated yet. The signal cannot be identified by digital X-ray CT due to the strong absorption of the weld. Such a sound reflector in heavy wall austenitic weld can be identified by a gamma-ray CT.

Figure 10. Sector scan images with coordinated identification of target signals before compensation of time delay values (a) and after compensation with calculated time delay values (b)
The focal laws of Notch A and B for compensation were determined by RDLT. Then the time delay values were inserted on the platform of PcusPro® Array, phased array ultrasonic testing system and the sector scan measurements were performed by the same parameters at the same scan position. Figure 10 (b) shows the sector scan images focused at each target focal point except the suspected inner signal. All the signals in spectral scale show the higher SNR with the enhanced amplitude in comparison with the signals before compensation. It was also noticed that the signals are more precisely located representing improved probability of detection (POD).

5. Conclusions

The objective of this study has been to investigate the wave propagation through the DMW with the aim of the improvement of POD and the reducing significantly the individual skill difference of sizing flaws by the RDLT. Through the RDLT, the reliable sound velocity values were directly determined and the time of flight values were then obtained. By inserting the time delay values into the platform of Pcuspro®, the signals mislocated were more precisely positioned with improved SNR and POD. For the future work, RDLT should be validated for real flaws, e.g. inter granular stress corrosion cracks (IGSCCs) in the DMWs.

References