



Article FEA-Based Ultrasonic Focusing Method in Anisotropic Media for Phased Array Systems

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Abstract: Traditional ultrasonic imaging methods have a low accuracy in the localization of defects in austenitic welds because the anisotropy and inhomogeneity of the welds cause distortion of the ultrasonic wave propagation paths in anisotropic media. The distribution of the grain orientation in the welds influences the ultrasonic wave velocity and ultrasonic wave propagation paths. To overcome this issue, a finite element analysis (FEA)-based ultrasonic imaging methodology for austenitic welds is proposed in this study. The proposed ultrasonic imaging method uses a wave propagation database to synthetically focus the inter-element signal recorded with a phased array system using a delay-and-sum strategy. The wave propagation database was constructed using FEA considering the grain orientation distribution and the anisotropic elastic constants in the welds. The grain orientation was extracted from a macrograph obtained from a dissimilar metal weld specimen, after which the elastic constants were optimized using FEA with grain orientation information. FEA was performed to calculate a full matrix of time-domain signals for all combinations of the transmitting and receiving elements in the phased array system. The proposed approach was assessed for an FEA-based simulated model embedded in a defect. The simulation results proved that the newly proposed ultrasonic imaging method can be used for defect localization in austenitic welds.

Keywords: austenitic welds; finite element analysis; ultrasonic wave; phased array

1. Introduction

Dissimilar metal welds (DMWs) of ferritic steel and austenitic stainless steel are widely used in nuclear power plants [1], where primary water stress corrosion cracks have been found in DMW areas between the pressure vessels and piping [2]. Therefore, it is necessary to ensure the structural integrity of structures by using nondestructive evaluation (NDE). Recently, the use of ultrasonic phased array systems has drastically increased in the field of NDE. The advantage of using ultrasonic phased array systems is that they provide two-dimensional B-scan images, which can help analyze the defect sizes and locations.

The probability of defect detection is relatively low when ultrasonic nondestructive testing is applied to austenitic weldments. During the welding process, coarse columnar grains grow [3], and the microstructure becomes anisotropic. The coarse grain size causes signal scattering and energy attenuation, and the anisotropic material properties of columnar grains result in a change in grain orientation in the welds, distorting the ultrasonic wave propagation paths [4]. Because traditional basic ultrasonic phased array systems use a straight wave propagation path and time in isotropic media for imaging defects, defect localization in austenitic welds is inaccurate. Thus, for practical applications of phased array systems in welds, information on grain orientation distribution, anisotropic material properties, and precise simulation of ultrasonic wave propagation behavior are



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). required. As a result, many studies have been conducted to determine the distribution of grain orientation [1,3,5] and the elastic constants [6–8] in austenitic welds. In addition, several studies have applied ultrasonic array data to NDEs for austenitic welds [3,6,9–17]. However, there is no reliable and practical ultrasonic imaging method that can be applied to defects in austenitic welds.

In a previous study, the authors proposed a grain orientation prediction methodology in a nondestructive manner [5]. In the present study, a finite element analysis (FEA)based ultrasonic imaging methodology for austenitic welds is proposed for practical applications of ultrasonic imaging. The proposed ultrasonic imaging method uses the total focusing method (TFM) and a wave propagation database, which was constructed using FEA that considered the grain orientation and anisotropic material properties of the welds. The grain orientation was extracted from a macrograph obtained from a dissimilar metal weld specimen, and the anisotropic elastic constant was iteratively optimized by minimizing the ultrasonic wave propagation velocity difference between the test and simulation results. A full matrix of time-domain signals for all combinations of transmitting and receiving elements in the phased array system was calculated through a series of finite element analyses. Subsequently, the TFM was applied to build a defect image in the finite element (FE) model.

2. TFM in Anisotropic Material

2.1. TFM Algorithm in Isotropic Material

The full matrix capture (FMC) approach uses the complete set of time-domain data (A-scans) from all combinations of transmitting and receiving elements. During an FMC inspection process, ultrasonic waves are transmitted from one array element, and all array elements capture the reflected signals, which is repeated to cover every combination of all transmitting and receiving elements. For an array system consisting of *N* elements, an FMC signal matrix is composed of $N \times N$ A-scan signals. The TFM imaging algorithm uses an FMC matrix [18]. Figure 1 illustrates the concept of the TFM algorithm. The position of a single point reflector within the media is defined in terms of the *x*- and *z*-coordinates, (*x*, *z*). The wave propagation distance, d_{ik} , from transmitter *i* to the reflector and back to receiver *k*, is calculated for each possible combination of *i* and *k* using Equation (1).

Figure 1. Schematic representing the basic concept of phased array imaging and the geometry of the phased array system.

The propagation time, t_{ij} , is determined by dividing the propagation distance by the velocity of the longitudinal wave *c* in media. In the TFM, the ultrasonic beam is focused at any target point (*x*, *z*). The TFM algorithm first discretizes the target region into a grid. The signals from all the elements in the array are then delayed and summed to focus on the target point in the grid. The intensity of the grids I(x, z) at every point in the grid is expressed as follows:

$$I(x, z) = \left| \sum_{i}^{N} \sum_{j}^{N} h_{ij} \left(\frac{d_{ij}}{c} \right) \right|$$
(2)

where h_{ij} is the analytical signal associated with the signal recorded by element *j* as element *i* transmits, and *N* is the element number.

In general, the TFM is used to image point-like reflectors in isotropic media, in which the ultrasonic beam propagates in a straight line. However, in austenitic welds, the anisotropic material properties and the distribution of the grain orientation associated with the position cause skewing and splitting of the ultrasonic beam. Therefore, it is necessary to accurately calculate the ultrasonic beam propagation path in austenitic welds for TFM applications.

2.2. TFM Imaging in Anisotropic Material

The focus of the ultrasonic waves is realized by means of time delays, meaning that the transmitted pulses arrive in phase at the target region, which produces high-intensity focal points. In isotropic materials, the time delays can be determined using the longitudinal wave velocity and the relative position between elements *i* and *j* within the aperture and the target point; however, in anisotropic materials, this information is insufficient to determine the time delays because the propagation path of the ultrasonic wave is distorted, and does not maintain straightness. Precisely calculating the ultrasonic wave propagation path in austenitic welds is difficult because the complex grain structure and anisotropic material property cause skewing of the ultrasonic waves. For wave propagation simulation, information on the distribution of grain orientation and the anisotropic elastic constants is essential.

In this section, an FEA-based ultrasonic beam focusing methodology for austenitic welds to determine time delays for the TFM is provided. Figure 2 shows a schematic procedure of TFM imaging in the welds. First, the grain orientation distribution and the anisotropic elastic constants, which are the major parameters for determining the ultrasonic wave propagation behavior, should be obtained (Step 1). Then, FEA is performed based on the information on the grain orientation distribution and the elastic constants of the welds (Step 2). From the FEA result, the ultrasonic wave propagation time database is extracted (Step 3). The DB contains the wave propagation time from every element within the aperture and every scanning target point in the grid for TFM imaging. Using the database, the time delays can be determined, and a TFM image can be formed in anisotropic material.



Figure 2. Schematic procedure of TFM imaging in austenitic welds.

To implement the proposed FEA-based ultrasonic beam focusing methodology for typical nondestructive testing in sites, the information or database of the grain orientation distribution and the anisotropic elastic constants should be given in advance. There are two practical ways to obtain this information. The first is to predict the material properties of a nondestructive method in advance, which the authors proposed in previous studies [5].

The second is to database the material properties in a destructive way for specimens made according to welding procedure specifications in advance. However, additional research should be conducted to minimize the difference of the material properties between a nondestructive test target and information obtained in advance, and to quantify the effect of material property uncertainties on the wave propagation behavior.

3. Measurement of Grain Orientation Distribution and Anisotropic Elastic Constants 3.1. Distribution of Grain Orientation

To simulate the ultrasonic wave propagation behavior, it is necessary to model the distribution of the grain orientation, which is the macroscopic pattern of the grain orientation in austenitic welds. For the simulation, grain orientation obtained from micrographs can generally be used [3,5,9]. In a previous study, the authors proposed a grain orientation prediction methodology based on computational mechanics and an optimization technique [5]. In this study, a micrograph was used to determine the distribution of grain orientation in austenitic welds. Figure 3a shows the schematic of the DMW specimen and the coordinate system, and Figure 3b shows the weld section of the DMW specimen fabricated for this study. The thickness, top width, and weld root of the welded zone were 30.0 mm, 39.7 mm, and 5.1 mm, respectively. The base materials were carbon steel (SA508 Gr.3) and stainless steel (STS304). This weld included a buttering part between the austenitic weld and the carbon steel parts, and the material of the welding and buttering part was alloy 152M.



(a) Schematic of the DMW specimen.



(b) Macrograph of the DMW showing grain orientation pattern.

Figure 3. DMW specimen.

To model the grain orientation of the DMWs, the specimen was thoroughly etched, and the grain orientations were characterized using scanning electron microscopy (SEM). The macrographs of the weldment section were meshed with a 2 mm \times 2 mm size mesh [12], after which the grain orientations were carefully marked in the macrographs (yellow lines in Figure 4a). The measured grain orientations from each meshed area were used to interpolate the grain orientations in any position. The interpolated grain orientations, as shown in Figure 4b via red lines, were used as input information for the FEA.



(a) Measured grain orientations (yellow lines).



(**b**) Interpolated grain orientations (red lines).

Figure 4. Grain orientations extracted from macrograph in weld region.

3.2. Anisotropic Elastic Constants

In the austenitic weldment, the material properties along the welding pass (*y*-axis) were assumed to be isotropic; however, in the other directions, to be anisotropic [9,10]. The material behavior can be properly simulated well with a transversely isotropic material, for which the elastic constants are expressed as follows:

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & & 0 & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & & 0 & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & & C_{44} & 0 & & 0 \\ 0 & 0 & 0 & 0 & & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}(C_{44} - C_{12}) \end{bmatrix}$$
(3)

The prediction of the elastic constants can be formulated as an inverse problem in which the objective is to find an optimal set of the elastic constants with which wave propagation behavior in austenitic welds can be simulated with minimal error. In general, the behavior is measured using a set of sensors attached on the welds. The inverse problems can be solved by a trial-and-error method: guessing the unknown information, solving the forward problem, and then updating the guessed information in the forward data [19–21]. A user-defined error function describing the discrepancy between the measured wave velocity and the predicted one is minimized during the process.

The objective function is defined as the difference between the measured and calculated wave velocities, and the design variable is the five elastic constants in the transversely isotropic materials, C_{11} , C_{12} , C_{13} , C_{33} , and C_{44} . The details of the FEA are described in Section 4.

Figure 5 shows the schematic for the wave propagation test setup for the measurement of anisotropic elastic constants in the welding and buttering parts. A transmitter was placed on the top surface of the welds, and three receivers were attached on the bottom surface. The input load represented in Figure 6 was excited by a transmitter, of which the center frequency was 2.25 MHz, after which the response was stored by the three receivers at a sampling rate of 100 MHz. Figure 7 represents the stored signal by the receivers.



Figure 5. Position of a transmitter and three receivers for wave propagation response.



Time, µsec

Figure 6. Excited signal from transmitter.



Figure 7. Wave propagation response measured on bottom surface.

The test and simulation signals were filtered to extract the time signals containing an interesting frequency, after which the wave velocity could be well observed. The signals were used to optimize the elastic constants by minimizing the difference between the wave velocities of the test and the simulation. Figure 8, calculated using the optimized elastic constants, shows the normalized filtering signals with a 2nd order band-pass filter for measured signals and simulated signals, of which the upper and lower limits were 2.0 and 2.5 MHz, respectively. As shown in Figure 8, which demonstrates the response on the basement, weld, and buttering regions, the simulated wave propagation time from the transmitter to the receivers showed a good agreement with the tested one; the differences between simulated wave propagation times from the transmitter to receivers 1, 2, and 3, compared with the tested one, were -11, 1, and 0 µsec, respectively. The density of the welding and buttering parts was assumed to be 8190 kg/m³, and the elastic constants of the welding and buttering parts were optimized as follows:

Γ	226.5 131.0 115.6		0 0 0]
	131.0 226.5 115.6		0 0 0		
	115.6 115.6 250.0		0 0 0		CBs for the such ding root
	0 0 0	111.0	0	0	Gra for the weiding part,
	0 0 0	0	111.0	0	
L	0 0 0	0	0	47.8	
Γ	202.7 119.4 115.6		0 0 0		1
	119.4 202.7 115.6		0 0 0		
	115.6 115.6 246.0		0 0 0		GPa for the buttering part.
	0 0 0	101.8		0	
	0 0 0	0	101.8	0	
L	0 0 0	0		41.4	



(c) Receiver 3.

Figure 8. Comparison between measured and simulated signals.

4. Construction of Wave Propagation Time Database

It is impossible to determine the time delays in the austenitic welds using the basic TFM algorithm because the ultrasonic waves in the welds are distorted. This section describes the methodology used to construct the wave propagation time database, *S*, which consists of three parameters: coordinates of elements within aperture (x_i, z_i) or (x_j, z_j) , coordinates of any target scanning points (x, z), and the wave propagation time from the elements to scanning points, t_i or t_j . The wave propagation time can be calculated through FEA for a sufficiently rich set of phased array element positions on the surface of the DMW specimen, after which the wave propagation time can be extracted at the scanning points. The elements in the database are the coordinates of the phased array elements, scanning points, and the corresponding wave propagation time. The database can be expressed as follows:

$$S = \{ (x_i, z_i) \text{ or } (x_i, z_j), (x, z), t_i \text{ or } t_j; x_i, x_j, x \in X, z_i, z_j, z \in Z \}$$
(4)

The wave propagation behavior in the austenitic welds was calculated using elastic FEA. The FEA was performed using the implicit solver in ABAQUS [22]. Figure 3a depicts the schematic of the DMW specimen used in the simulation. Within the x-y-plane, the medium appears isotropic; however, in other directions outside the plane, the medium exhibits anisotropic features. The FE model was assumed to have two dimensions, meaning that energy only propagated in the x-z plane. The mesh (Figure 9) was constructed using eight-node reduced integration plane strain elements, CPE8R in ABAQUS. The finite element size was 0.25 mm, to ensure that there would be at least seven nodes per wavelength in the spatial domain [13]. The simulation method using FEA was used to verify the longitudinal velocity in the transversely isotropic medium without changing the grain orientation. The longitudinal wave velocity in the x- and z-directions was calculated as $V_{xx} = \sqrt{C_{11}}/\rho$ and $V_{zz} = \sqrt{C_{33}}/\rho$, obtained from the Christoffel equation for transversely isotropic media. In a previous study [5], the velocities calculated by FEA were well matched with the theoretical solution within 1%. The measured grain orientation distribution described in Section 3 was used as the simulation input describing the grain structures in the austenitic welds, as shown in Figure 9.



Figure 9. FE mesh for calculating wave propagation time in austenitic welds and schematic representation for phased array element position.

The array parameters with a linear array transducer with equispaced elements are presented in Table 1. The transmitted load from the phased array elements was simulated as the pressure at which the signal was modeled in the form of a sine function, $A_0/2 \cdot (\sin(2\pi f(t - \lambda/4)) + 1)$ for $(0 \le t \le \lambda)$, as shown in Figure 10. A_0 is the amplitude of the input load, f is the center frequency, and λ is the wavelength in the time domain. The acceleration data were stored at a sampling rate of 200 MHz.

Table 1. Simulated array parameters.

Array Parameter	Value	
Number of Elements	16	
Element Width	0.5 mm	
Element Pitch	0.75 mm	
Center Frequency	2 MHz	



Figure 10. Input load transmitted to medium.

Figure 11 shows the change in the displacement field with time after the first phased array element located at x = -5.75, y = 0.0 was excited. Instead of pure longitudinal and shear waves, quasi-longitudinal and quasi-shear waves were generated in the anisotropic medium, as shown in Figure 11. Figure 12 shows the displacement as time increased at the points presented in Figure 11a (6.0, 16.0), and the method used to identify the wave propagation time. In the FE model, all of the nodes can be the potential scanning point; therefore, the database *S* contained the wave propagation time for all of the potential nodes per excited loading point (phased array element position).



Figure 11. Cont.



(c) 5 µs.

Figure 11. Change of displacement field with increase in time.



Figure 12. Definition of wave propagation time form an element of aperture to any scanning point.

5. Implementation of TFM Imaging Algorithm in Anisotropic Material

Using the wave propagation time database described in the previous section, the time delays can be determined in anisotropic media, after which the TFM image can be formed. This section describes the implementation of the TFM imaging algorithm for visualizing defects in austenitic welds.

An FEA-based simulation was performed to calculate the FMC signal matrix, S(t), which represents the full matrix of time-domain impulse response signals for all transmitting and receiving combinations. The finite element model described in Section 4 was used, but the model had a notch at x = 5.25, z = 13 mm with a width of 0.5 mm and a length of 4.5 mm, which corresponded to approximately 1.5 λ , as shown in Figure 13. Each transmitting element was excited with the impulse defined in Section 4, and the response signals were calculated in the position of all the receiving elements. Thus, 256 time signals were generated for all combinations of transmitting and receiving elements (16 \times 16). Figure 14 shows an example of a set of 16 A-scan signals, which were calculated for all the receiving elements (elements 1–16) when element 1 was excited. All reflected signals did not arrive in phase because of the difference in propagation distance.



Figure 13. Simulation model with a notch.



Figure 14. Simulated A-scan signals at element 1–16 under excitation of element 1.

The TFM imaging algorithm is performed by first discretizing the target region (in the x-z-plane within the medium) into the grid. The FMC matrix **S**(t) is delayed to produce a high intensity by aligning the reflected signals, and summed to synthesize a focus on every point in the grid. The intensity of the image I(x, z) at any target scanning point can be calculated using the propagation time database of the austenitic welds. Figure 15 shows the simulated A-scan signals at elements 1–16 under the excitation of elements 1–16, and the reflected signals from the notch. In addition, Figure 15 shows the delayed reflected signals from the center of the notch using the wave propagation database proposed in this study, using the basic traditional TFM method; the wave propagation time is also represented in the detailed figure. When the wave propagation time database was used to delay the A-scan signals, the signals arrived in phase at the target scanning point (notch center). However, when the wave propagation time calculated using the traditional TFM method was used, the A-scan signals were not aligned at the target point. This resulted in errors in the positioning of the defect.

Figure 16 shows the method used to calculate the intensity using Equation (2) at the scanning point of the notch center. In the graph, the line indicates the *function h* in Equation (2), and t_{ij} is the wave propagation time from the transmitting element to the receiving element. Figure 17 shows the TFM imaging results for the scanning area (as shown in Figure 13) from the starting point of x = -10, z = 0 mm to the ending point of x = 10, z = 20 mm. The imaging results of the basic TFM and the proposed TFM are displayed in Figure 16, in which the known locations of the defects are marked by red dotted lines. The proposed database-based method accurately estimated the defect position, but the traditional method incorrectly predicted the defect location by an error of approximately

3.2 mm. The error was caused by the wrong information of the wave propagation time, which was calculated using the basic TFM algorithm.

It can be concluded from the comparisons in Figure 13 that the proposed TFM imaging results have a significant improvement in the performance of defect localization accuracy compared with basic TFM imaging results, and the usefulness of the proposed TFM imaging methodology in this study is validated. Therefore, if the wave propagation database of the austenitic welds is used, the proposed TFM imaging methodology can be applied to the NDE of the DMWs at the site. However, it should be noted that the grain orientation distribution and the elastic constants should be determined in a nondestructive manner before the evaluation.



Figure 15. Simulated A-scan signals at element 1–16 under excitation of element 1–16.



Figure 16. Intensity in TFM image at target scanning point.



Figure 17. Defect images by (a) proposed TFM method and (b) traditional basic TFM method.

6. Conclusions

A new FEA-based ultrasonic imaging methodology for austenitic welds is proposed in this paper. The methodology is composed of four steps: (1) measurement or prediction of grain orientation distribution and the anisotropic elastic constants; (2) simulation of wave propagation behavior; (3) construction of a wave propagation time database; and (4) computation of TFM intensity and TFM imaging. In this study, the grain orientation distribution was measured by a macrograph of the DMW specimen, and a new measurement method of the elastic constants was proposed using the measured grain orientation information and an optimization technique. The ultrasonic wave propagation behavior was calculated through FEA using the grain orientation and elastic constant information, after which the ultrasonic wave propagation time database was extracted. Finally, an FMC matrix in the phased array system was calculated through a series of finite element analyses for the simulated model embedded in a defect, and a TFM image was generated. The proposed TFM imaging results have a significant improvement in the performance of defect localization accuracy compared with basic TFM imaging results, and the usefulness of the proposed TFM imaging methodology in this study is validated.

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