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Development of an Ultrasonic Ray Model for Phased Array Ultrasonic Testing in Austenitic Weldments

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Abstract

Austenitic stainless steel is widely used in nuclear industry due to its high corrosive resistance and excellent creep properties over a range of temperature. However, inspection of austenitic material weldments using phased array ultrasound is not easy at all, because crystalline structure of austenitic stainless steel weldments cause deviation and splitting of the ultrasonic beams. Thus, to focusing and/or steering phased array beams in the austenitic weldments, proper time delays based on ray tracing in the anisotropic and inhomogeneous medium is needed. In this paper, we applied modified Oglivy's model to describe the crystallized structure of real austenitic steel weldmens. And then, a ray tracing model is used to calculate the proper time delay and proper incident angle of linear phased array in the anisotropic and inhomogeneous material for focusing and/or steering phased array ultrasonic beams on the desired position in the weldments.

Keywords: austenitic weldments, ray model, phased array, time delay

1. Introduction

Austenitic weldments are used throughout nuclear power plants wherever a ferritic material is joined to an austenitic material such as reactor vessel safe end welds, control rod drive mechanism vessels and etc. Austenitic weldments typically consists of a stainless steel filer material, such as a high temperature Ni-Cr butter layer applied to the carbon steel interface, surrounded by carbon steel and stainless steel base materials. Austenitic weldments have long been identified as a difficult component to test using ultrasonic techniques, due primarily to the anisotropic nature of the weldments and large grain size [1]. Especially, attenuation of high frequency ultrasound, backscattering noise associated with grain boundary reflections and beam redirection of the sound wave as it propagates through the weld materials and solidification boundaries are major cause of difficulties in ultrasonic testing. In order to address such difficulty in ultrasonic inspection of austenitic steel weldments, research works have been carried out for describing the material properties and its effects on ultrasonic wave propagation [1,2,3,5].

Recently, ultrasonic phased array testing are increasingly adopted for inspection of austenitic weldments, since it can improve probability of detections (PODs) and sensitivity in locating defects in attenuative media and specimens with complex curvatures[4].

However, to apply phased ultrasonic testing for inspection of austenitic weldments, proper time delays for focusing and/or steering ultrasonic beams on the desired position through anisotropic and inhomogeneous medium should be determined.

So, in this study, to determine proper time delays for fousing and/or steering ultrasonic beams, we developed a ray model for phased array ultrasonic testing in austenitic weldments including a model for describing crystallized structures of austenitic weld structures by modification of the Ogilvy model [2] based on the real crystalline structures of austenitic weldments. Then, modified crystallized structure model and ray tracing procedure are briefly discussed. And, using the developed model, optimal time delays for focusing and/or steering ultrasonic beams in the austenitic weldments radiated from a linear phased array ultrasonic transducer are presented.

2. Crystallized structure modeling

Several models for modeling crystallized structures were proposed by previous researchers. And, most of the models developed under an assumption that is the crystallized structure is symmetric with respect to center line of the weldments. Among the models, A mathematical function proposed by Ogilvy's was widely used for modeling the crystallized structure of austenitic weldments[1].

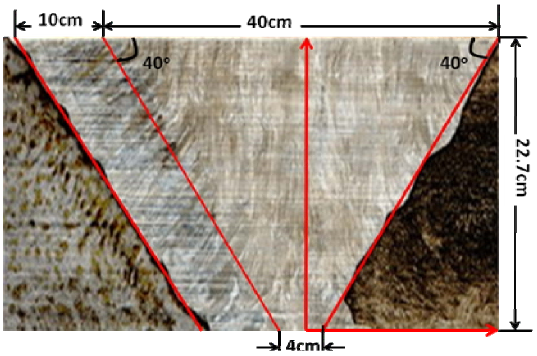


Fig.1 Macro-photo of austenitic steel weldments

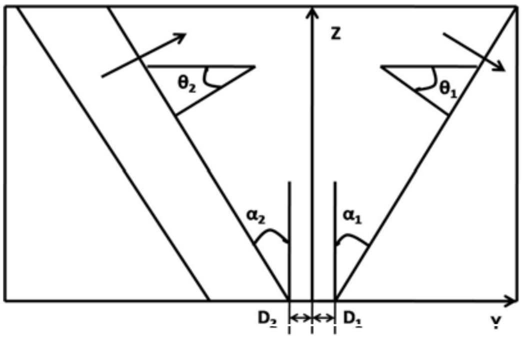


Fig.2 Definition of parameters used to describe the grain structure within a V-butt weld in Oglivy's model

Figure 1 shows a macro-photo of austenitic steel weldments, which consists of four parts: carbon steel part, buttering layer, austenitic steel weld part, and stainless steel part. Also, as shown in Fig. 1, crystallized structure of real austenitic steel weldments are non- symmetric with respect to center line of the weldments. Thus, the left part and right part of the crystallized structure of the austenitic steel welds should be treated separately. To take account of this non-symmetric nature, we modified the Ogilvy's model, since their model is based on a piecewise-defined function to model crystallized structures of weldments. In their model, to predict crystallized structure of austenitic steel weldments, they used T1, T2, and η parameters. So, in this study, we modified the Ogilvy's model by modifying the parameters T_1, T_2 and splitting η into η_1 and η_2 where the parameter T_1 and T_2 are proportional to the tangents of the grain axes at the sloping edges; the parameter η varies between 0 and 1, and η_1 stands for the right part of measure of how fast the crystallized structure falls with an increase in y, while η_2 represents the left part. Figure 2 shows the definition of parameters used to describe the crystallized structure of a V-butt weld. Eq. (1) is the modified model for calculating crystallized structure of austenitic steel wedments.

$$F(y,z)=\begin{cases}\tan\theta_1=\dfrac{T_1(D_1+z\tan\alpha_1)}{y^{\eta_1}} & y>0\\ \tan\theta_2=\dfrac{T_2\,|(D_2+z\tan\alpha_2)|}{|y|^{\eta_2}} & y<0\end{cases}\qquad(1)$$

As defined in Eq. (1), to model crystallized structure of the real austenitic weldments, optimized parameters for T1, T2, η1 and η2 are needed. So, in this study, we have adopted nonlinear regression method to find the optimal parameters.

To get the information of real structure of weldment, as shown in Fig. 1, we draw the crystallized orientation in every grid based on the original picture and apply edge detection, dilating imfilling, and skeleton method to get rough crystallized structure of the specimens and link the edge pixel to straight line, then interpolate between the two dots of one line given the information of location, and calculate the slope as well. And then, fill every grid with the value of slope to get crystallized structure of the specimens in detail. Figure 3 shows crystallized structure of the weldment obtained from the Fig. 1.

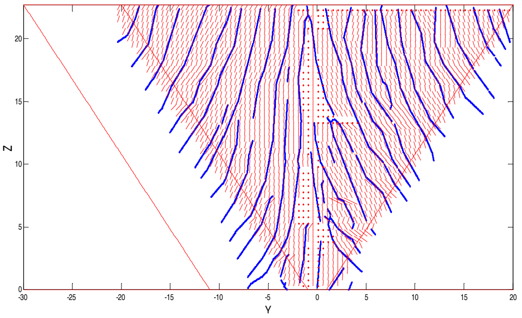


Fig.3 Crystallized structure after image processing from the macrograph

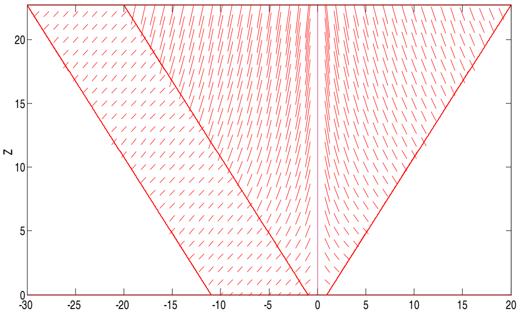


Fig.4 Crystallized structure of modified model with optimal parameters

Based on the crystallized structures obtained from the macro-photo, the nonlinear regression method to get the optimal T_1, T_2, η_1 and η_2 is adopted. In the nonlinear regression, observational data (y_i,z_i,F_i) ,for i=1,2…,m are modeled by equation (1) which is a nonlinear combination of the model parameters T_1, η_1, T_2, and η_2 for two piecewise-defined function. So the model function can be written as $F_j=f(y_i, z_i, T_j, \eta_j)$, where j=1,2. It is desired to find parameters T_j, η_j such that the best curve fits of the given data in the least squares method, that is, the sum of squares is minimized, where the residuals r_i are given by $r_i = F_i - f(y_i, z_i, T_j, \eta_j)$, for i=1,2,…,m, and j=1,2. The minimum value of S occurs when the gradient is zero, where

$$\frac{\partial S}{\partial \eta_j}=2\sum_i r_i\frac{\partial r_i}{\partial \eta_j}=0,\ \frac{\partial S}{\partial T_j}=2\sum_i r_i\frac{\partial r_i}{\partial T_j}=0\qquad(2)$$

Using the Eq. (2), calculated optimal parameters for modeling crystallized structure of the specimen are $T_1=-0.38$, $\eta_1=0.283$, $T_2=0.3782$ and $\eta_2=0.4782$. Here, η_2 is bigger than η_1 crystallized line falls faster in the right part than that in the left part, which can be seen from the Fig. 1. Fig 4 shows modeled crystallized structure of the specimen using the optimal parameters.

3. Ultrasonic ray tracing in austenitic weldments

Ray theory are often used for calculating propagation of ultrasonic waves in the austenitic weldments [2,5]. Ray properties such as direction and phase are described by the eikonal equation for the system, and the ray amplitudes are determined by the transport equations. Most of ray tracing methods were developed for predict ultrasonic ray paths for anisotropic homogeneous materials. However, in the case of austenitic weldments are anisotropic inhomogeneous materials. So, in this study, to take care of the austenitic weldments, we applied layered model for ray tracing[5]. In this model an inhomogeneous material is assumed as layered medium, each layer consider as homogeneous (but anisotropic) and adjacent layers having slightly different material properties. So, using the layered model, we could handle anisotropic inhomogeneous materials. Figure 5 shows the process of successive ray refraction occurs at the interfaces between layers, leading to curved ray paths. We choose the layer to be parallel to lines of constant ray group velocity for the analytical solution to be reproduced by the discrete ray tracing technique[5]. Figure 6 shows the two dimensional construction used to determine the local variation in ray group velocity, from which we can find the lines of constant ray group velocity and define the normal **n** to the local interface between homogeneous layers.

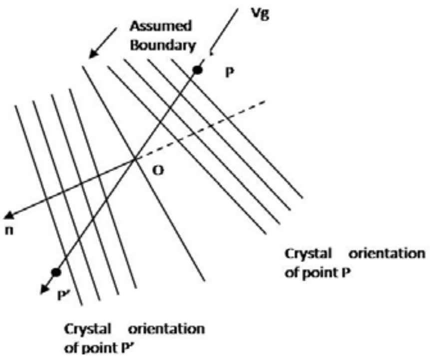


Fig.5 determination of assumed boundary for determination in inhomogeneous media

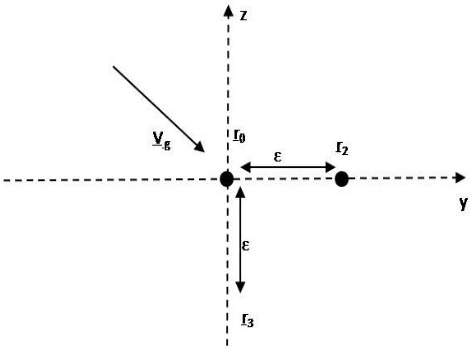


Fig.6 determination of the local variation in ray group velocity

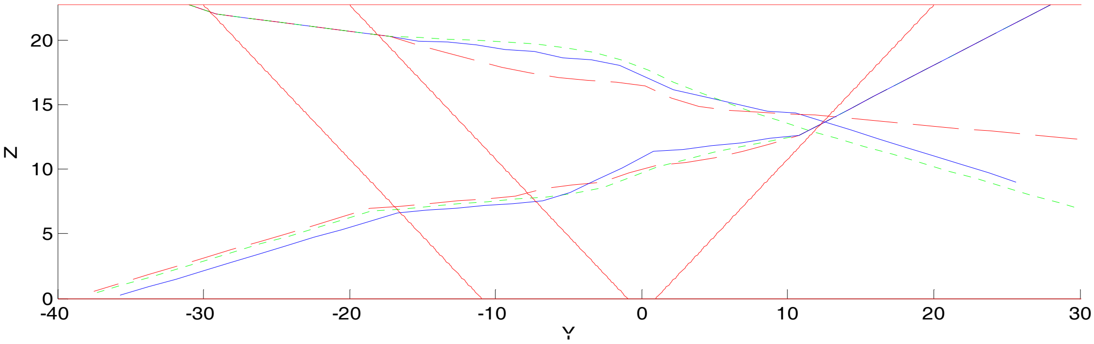


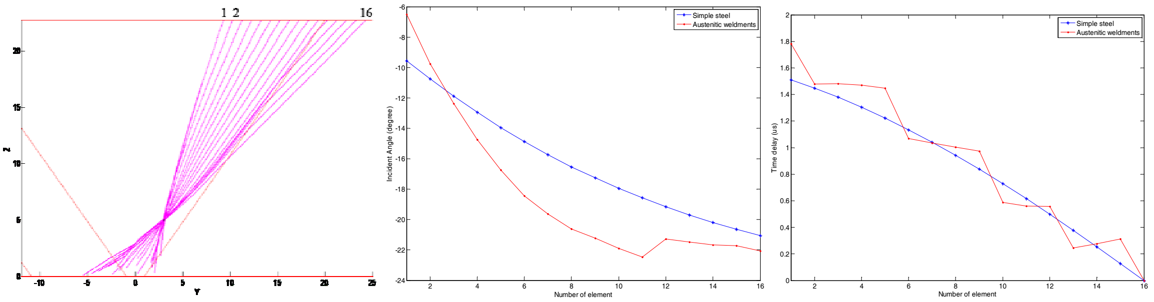
Fig.7 Calculated ray paths of qP wave for the austenitic steel weldments using Oglivy's model (dashed line), modified crystallized structure model with optimal parameters (dotted line) and the real structure based on the macro-photo (solid line).

Using the ray model described above, we calculate the ray paths in the austenitic weldments radiated from a planar transducer placed on a Lucite wedge. Figure 7 shows predicted ray paths of qP wave using three different types of crystallized structures: Oglivy's model with published parameters, modified model with optimal parameters and the structure based on the macrograph. Position of transducer and angle of incident for left side and right side are x_1 = (-31mm, 22.7 mm), θ_1 = 25 degree and x_2 = (28 mm, 22.7 mm), θ_2 = -26 degree, respectively. As shown in Fig. 7, the ray paths for the three crystallized structure are similar when ultrasonic beam propagating from the right part to left part. However, rays from the left part to right part shows discrepancy between each other. From the Fig. 7, the ray path using the modified model is similar to the ray path calculated using the structure based on the macro-photo, while the ray path using Oglivy's model with published parameters shows big discrepancy with other two results, due mainly to the non-symmetric character of the austenitic weldments.

4. Time Delay for Focusing Ultrasonic Phased Array Beams

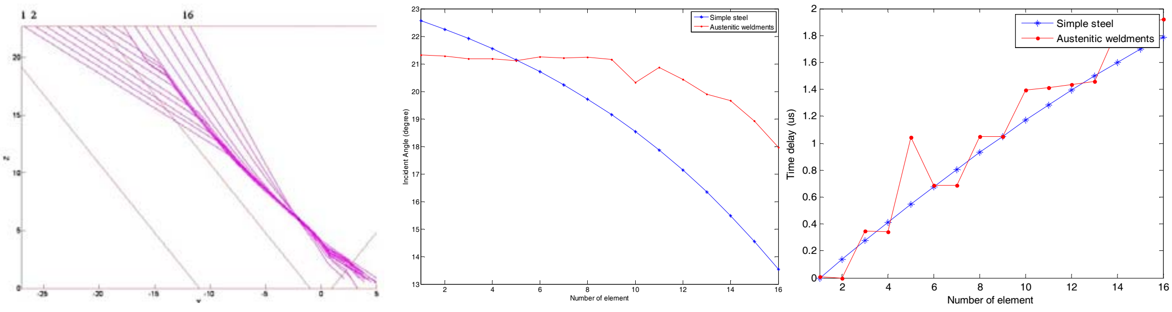
For the phased array in inhomogeneous anisotropic material, proper time delay and incident angle to focus all the rays on one desired point are strongly needed. So, in this study, to get proper time delay, we search the incident angle that can propagate to desired point using following procedures:

Firstly, let desired focal point is (y_f,z_f), incident point is (y_0,z_0) and the initial assumed incident angle θ_r is $\arctan(\frac{y_0 - y_f}{x_0 - x_f})$, then calculating the assumed initial incident angle θ_i by applying transmission equation. Secondly, using θ_i , we perform ray tracing in the weldments, find the smallest distance from the focal point to the ray and judge whether the supposed incident angle is too big or too small , if it' s too big, treat this θ_i as the maximum value of incident angle θ_{max}, and decrease θ_i until θ_i becomes small enough that the ray goes to other side of the focal point then set θ_i as the minimum value of incident angle θ_{min}. Thirdly, applying bisection method on the interval [θ_{min} θ_{max}] to find the optimal incident angle whose ray passes through the focal position. Finally, repeat previous steps for all the elements of a phased array transducer.



(a) (b) (c)

Fig.8 calculated (a) ray paths, (b) incident angle, (c) time delay for a linear phased array transducer



(a) (b) (c)

Fig.9 calculated (a) ray paths, (b) incident angle, (c) time delay for a linear phased array transducer

Using the determined optimal incident angle, we have calculated time delay for focusing and/or steering ultrasonic beams on the desired point. In the austenitic steel weldments, time delays are not proportional to ray path lengths because of the continuous changing in group velocity in inhomogeneous anisotropic material. So, in this study, time delay was calculated by summing all the time of flight of all the layers based on ray path of each propagated ray and their the group velocities.

Fig.8(a) and Fig.9(a) show the ray tracing results for focusing on a point (3 mm, 5 mm) and a point (-2 mm, 6 mm) respectively. And Fig. 8 (b) and Fig. 9 (b) show the calculated incident angle of all the 16 elements to focusing ultrasonic beams on the desired points based on the ray tracing results for austenitic steel weldments (solid lines) and assumed as ordinary mild steel (solid line with stars). From the ray tracing results, time delay for focusing ultrasonic beam on the desired points are calculated. As shown in Fig.8(c) and Fig.9(c), we can find that there are big discrepancies in time delays in austenitic weldments and in ordinary mild steel, so time delay for focusing ultrasonic beam strongly depends on the its crystallized structure.

5. Conclusion

To find optimal time delay for phased array ultrasonic testing in austenitic weldments, we modified the Oglivy's model as a non-symmetric one and find the optimal parameters based on the real structure of the macro-photo and regarded the inhomogeneous anisotropic material as layered homogeneous anisotropic material. Then ray tracing method with the modified crystallized structure model was applied to calculate ray paths in the austenitic weldments. The ray tracing results of the real structure based on the macro-photo and modified crystallized structures model agrees very well. Using the ray model, optimal time delays for focusing and/or steering ultrasonic beam on desired position in the austenitic weldments was calculated. Thus, the developed ray model can be a useful tool for determination of optimal inspection setup of phased array ultrasonic testing system in austenitic weldments.

Acknowledgement

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