3D Ray Tracing Model for Ultrasound Field Evaluation in Inhomogeneous Anisotropic Materials: Model and Experimental Validation

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Abstract

In this contribution a 3D ray tracing model for ultrasonic field evaluation in inhomogeneous anisotropic materials such as austenitic welds is presented. The inhomogenity of austenitic weld material is represented as several homogeneous layers. The general problem of energy reflection and transmission at the boundaries of the layers are solved resulting 3D amplitude and energy reflection and transmission coefficients. The directivity factor for the ray in general arbitrary oriented austenitic weld material (including lay back orientation) is determined based on Lamb's reciprocity theorem. The transducer excited ultrasonic fields are accurately evaluated by employing ray directivity factor, transmission coefficients, divergence of the ray bundle and density of rays. Finally, the comparison between theoretical and experimental results will be described.

Introduction

Ultrasonic non destructive inspection of austenitic weld material is complicated because of anisotropic grain structure leading to beam splitting and beam deflection [1]. Modeling tools play an important role in developing new reliable ultrasonic testing techniques and optimization of testing parameters for inspection of anisotropic materials. Modeling of accurate ultrasonic fields in inhomogeneous austenitic welds is a challenging task for non-destructive evaluation. The aim of the paper is to determine the ultrasonic field profiles in 3D representation of austenitic welds based on ray tracing model and the comparison of the ray tracing model results with experiments.

Theoretical Background

Modeling of Material Inhomgenity

The locally inhomogeneous grain structure of the austenitic weld material is modelled by the empirical relation given in [2]. It is expressed in terms of weld parameters and is given as follows

$$\tan\theta = \begin{cases} \dfrac{-T\left(D + z\tan\alpha\right)}{x^{\eta}}, & x \geq 0 \\[2ex] \dfrac{T\left(D + z\tan\alpha\right)}{(-x)^{\eta}}, & x < 0 \end{cases} \qquad (1)$$

where θ is the grain orientation, T is the slope of the columnar grain axis at the fusion faces, D is the half width of the gap between root faces, α is the weld preparation angle and η measures the change of the grain orientation as a function of the distance x from the weld centre line.

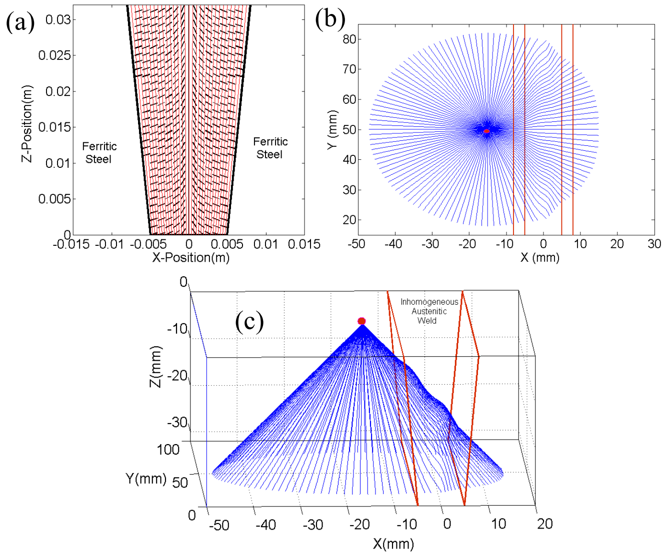

Figure 1: (a) Layered representation of the inhomogeneous austenitic weld. 45º longitudinal cone of rays propagation into the austenitic weld material (b) ray pattern in XY plane, (c) 3D view of the ray pattern. Weld thickness = 32 mm. D = 5mm, α =5.36º, T= 0.54 and η =1 in Eq.(1).

The inhomogeneous region of the austenitic weld material is discretized into several homogeneous layers and the boundary between two adjacent grains is assumed along the lines of constant crystal orientation. Fig. 1(a) shows layered representation of inhomogeneous austenitic weld material. The elastic parameters of the austenitic weld material and ferritic steel material are taken from [3]. Fig. 1(b) shows 45º longitudinal cone of ray pattern along the XY plane and Fig. 1(c) shows 3D view of the ray pattern. It is apparent from the Fig. 1(b) and Fig. 1(c) thus the ray paths are affected by the anisotropy of the austenitic weld material.

Ultrasonic Field Evaluation in Inhomogeneous Austenitic Weld Material

A diverged ray bundle is considered at each source position in the finite dimension transducer and it is allowed to propagate from isotropic ferritic steel material into the austenitic weld material. The incident ray directivity factor in isotropic medium or in general anisotropic medium is determined based on the Lamb's reciprocity theorem [4][5]. The ray travel through the layers of the inhomogeneous austenitic weld material. If the material properties changes during ray propagation, the problem of reflection and transmission at the interface is solved three dimensionally resulting reflection and transmission coefficients. Reflected rays from the layer boundaries are neglected. By taking into account only transmitted ray coefficient and directivity factor the ultrasound fields are modified. For the present model we terminate the ray when it becomes evanescent and assume it carries no energy. The procedure is repeated till the ray reaches the back wall or a receiver surface. The constructive and destructive interference phenomena are achieved by superposition of ray contributions from each source point in the finite dimension transducer at the observation region. At the end, the ray amplitudes at the region of interest in the material are obtained by incorporating the exact inverse distance factors. The final ray amplitudes are expressed in terms of density of rays and their amplitudes.

Comparison of the Results between Experiments and Model

The test specimen of a 32 mm thick inhomogeneous austenitic weld was used for the comparison between ray tracing model and experimental results. A 34° longitudinal beam transducer of 2.25MHz center frequency and 12mm in length was used to excite an ultrasonic pulse on the ferritic base material into the austenitic weld material. The transducer is situated 14 mm away from the weld centre line. The ultrasound field profiles are measured along the back wall surface using an electro dynamical probe.

Optimization of Weld Model

Weld parameters are optimized in the empirical relation given in Eq. (1) to match with the real micrograph of the austenitic weld specimen. Fig. 2(a) shows the optimized weld model for the transversely isotropic weld sample used for the theoretical evaluation of ultrasonic fields.

The lay back orientation (i.e. grain orientation along weld run direction) is uniform through out the weld material so that one can reduce the 3D problem into 2D by considering a

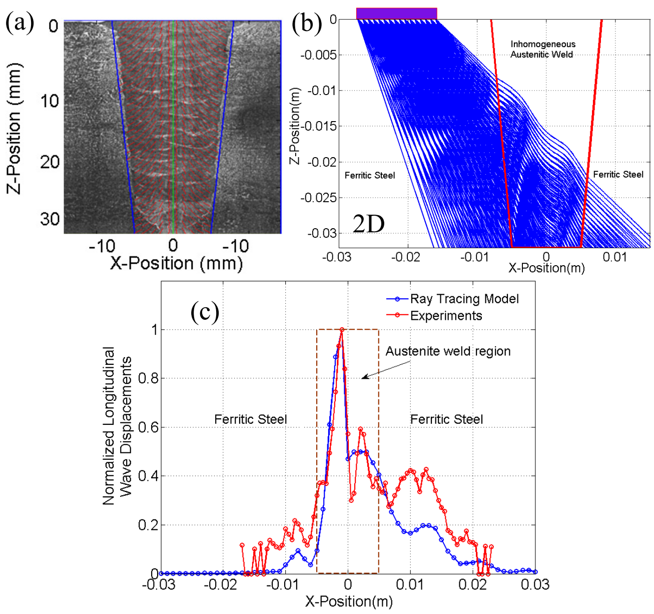

Figure 2: (a) Optimized weld structure. (b) 34° longitudinal array transducer 2D ray pattern (XZ plane) in inhomogeneous weld specimen. (c) Comparison of ray tracing model and experimental results. Weld thickness = 32 mm. D = 5mm, α =5.36°, T= 0.55 and η =1 in Eq.(1)

slice of the 3D geometry of the weld material. This consideration reduces the computational time of ray tracing model calculations significantly. Fig. 2(b) shows 34° array transducer 2D ray pattern in the XZ plane. It can be seen from the Fig. 2(b) thus the rays are not uniformly distributed along the receiver surface. Fig. 2(c) shows comparison of normal component of longitudinal wave displacement profile along the back wall of austenitic weld material calculated using ray model with that of experimental results. A good quantitative agreement between model and experiments is achieved.

The location of the maximum amplitude and main lobe pattern predicted from theory shows good agreement with experiments. Minor differences are observed in the side lobe formation.

Discussion

Following are the reasons for minor deviations from theory and experiments.

Elastic constants for austenitic weld are taken from the literature and these data is not exactly same for the test block. The grain structure evaluated based on Eq. (1) is not based on the principles of solidification mechanics. Ultrasound field attenuation at the grain boundaries of weld region is not included in the ray theory. Ray model assumes monofrequency calculations whereas pulses are used in the experiments. The above important physical aspects should be employed in the theory for further improving the ray tracing model predictions.

Conclusions

A 3D ray tracing model for ultrasonic field evaluation in inhomogeneous austenitic weld material is presented. By employing ray transmission coeffients, directivity factor, divergence of the ray bundle and density of rays the ultrasonic field are accurately evaluated. Theoretical predictions are compared with the experiments and shows good quantitative agreement. Ultrasonic scattered sound field evaluation based on ray theory and its experimental comparison is planned for the future work.

Acknowledgements

This research work is financially supported by BMWi under the grant 1501365 which is gratefully acknowledged.

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