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Ultrasonic field profile evaluation in acoustically inhomogeneous anisotropic materials using 2D ray tracing model: Numerical and experimental comparison

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ABSTRACT

Ultrasound propagation in inhomogeneous anisotropic materials is difficult to examine because of the directional dependency of elastic properties. Simulation tools play an important role in developing advanced reliable ultrasonic non destructive testing techniques for the inspection of anisotropic materials particularly austenitic cladded materials, austenitic welds and dissimilar welds. In this contribution we present an adapted 2D ray tracing model for evaluating ultrasonic wave fields quantitatively in inhomogeneous anisotropic materials. Inhomogeneity in the anisotropic material is represented by discretizing into several homogeneous layers. According to ray tracing model, ultrasonic ray paths are traced during its energy propagation through various discretized layers of the material and at each interface the problem of reflection and transmission is solved. The presented algorithm evaluates the transducer excited ultrasonic fields accurately by taking into account the directivity of the transducer, divergence of the ray bundle, density of rays and phase relations as well as transmission coefficients. The ray tracing model is able to calculate the ultrasonic wave fields generated by a point source as well as a finite dimension transducer. The ray tracing model results are validated quantitatively with the results obtained from 2D Elastodynamic Finite Integration Technique (EFIT) on several configurations generally occurring in the ultrasonic non destructive testing of anisotropic materials. Finally, the quantitative comparison of ray tracing model results with experiments on 32 mm thick austenitic weld material and 62 mm thick austenitic cladded material is discussed.

1. Introduction

Austenitic cladded materials, austenitic welds and dissimilar welds are extensively used in primary circuit pipes and pressure vessels in nuclear power plants and chemical industries because of their high fracture toughness and resistance to corrosion. It is very important to evaluate the structural integrity of these components. Ultrasonic non destructive inspection of austenitic cladded and welded components is complicated because of anisotropic columnar grain structure leading to beam splitting and beam deflection [1–4]. Simulation tools play an important role in developing advanced reliable ultrasonic testing techniques and optimizing experimental parameters for inspection of anisotropic materials.

Motivation of the present work is due to the fact that, quantitative evaluation of accurate ultrasonic wave fields in inhomogeneous austenitic welds and dissimilar weld components are of general importance in optimizing the experimental parameters such as optimum angle of incidence, frequency and mode of excitation during the ultrasonic non destructive inspection of these anisotropic materials. In this contribution an attempt has been made to determine the ultrasonic field profiles in inhomogeneous anisotropic materials using 2D ray tracing method (includes directivity of the excitation ray source) and successfully validated the ray tracing predictions with 2D EFIT [5–7] results and experiments on real life austenitic weld materials.

In the early 1990s, Johnson et al. [8] presented the first ray tracing approach to calculate ultrasonic transducer fields in homogeneous isotropic solids. Ray tracing models are numerical methods, where the complete wave propagation phenomena are evaluated based on the analytical expressions resulting from elastic plane wave theory [9,10] and calculations such as reflection and transmission involved only at the interfaces between different layers. This drastically reduces computational time as compared to the finite element [11] and finite difference [12] techniques. RAYTRAIM a commercially available ray tracing software package developed by Ogilvy [13–16] and it is used to understand the

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ultrasound propagation in inhomogeneous austenitic weld materials. The algorithm is primarily proposed for evaluation of ray paths, propagation times in inhomogeneous austenitic welds. Ogilvy [13] determined the virtual grain boundary between two adjacent columnar grains with in the inhomogeneous weld by vector representing half of the difference between two adjacent crystal orientations. Later, Ogilvy [14] modified the definition of grain boundary with in the weld material and selected the interface between the layers to be parallel to the local directions of constant ray group velocity magnitude. Based on the first order Bessel functions, the approximated spherical point source beam profiles in homogeneous austenitic materials were also presented by Ogilvy [17]. Combining the ray tracing principles and Kirchhoff theory, the approximated ray amplitudes in austenitic weld materials were presented by Hawker et al. [18]. A computer model for evaluating ultrasound ray paths in complex orthotropic textured materials was discussed by Silk [19]. Schmitz et al. [20] presented the 3D-ray-SAFT algorithm to calculate the direction of the ultrasound beam and deformation of the transmitted sound field in inhomogeneous weld material and discussed the qualitative comparison with experiments on unidirectional weld structure. The 3D-ray-SAFT algorithm does not evaluate the ray amplitude information. Computationally efficient Gaussian beam superposition approach to calculate the transducer fields in layered materials, immersed components and inhomogeneous anisotropic materials have been presented by Spies [21–23]. Gengembre and Lhemery [24] computed the ultrasonic fields in homogeneous and heterogeneous materials based on the pencil method. They used approximated Rayleigh integrals to describe the transducer effects. Commercially available ultrasonic modeling software tool such as CIVA model [25,26] which is also able to compute the ultrasonic beam fields in homogeneous and heterogeneous material where ultrasonic beam is evaluated based on the semi analytical solutions. Apfel et al. [27] presented the MINA model to calculate the local grain direction of the weld material and they coupled the MINA model with ATHENA finite element simulation tool to predict the ultrasound propagation in austenitic welds. A numerical simulation tool Elastodynamic Finite Integration Technique (EFIT) for the elastic wave propagation in austenitic welds was presented by Langenberg et al. [28]. Recently synthetic aperture focusing technique for defect imaging in anisotropic and inhomogeneous weld materials was discussed by Spies et al. [29] and Shlivinski and Langenberg [30]. Connolly et al. [31] presented the application of Fermat's principle in imaging inhomogeneous austenitic weld materials and compared the ray path behavior in the presence of vertical crack in austenitic welds using finite element simulations [32]. A 2D ray tracing model in anisotropic austenitic welds which includes a probe model based on Fourier integral method in an isotropic half space was presented by Liu and Wirdelius [33]. Halkjaer et al. [34] used the Ogilvy's [13] empirical relation for grain structure model and compared the experimental normal beam amplitude profiles with the numerical EFIT simulation results.

In the present research work we evaluate the point source as well as finite dimension transducer generated ultrasonic fields in inhomogeneous austenitic welds using ray tracing method accurately by taking into account all the physical aspects of ray such as ray directivity in the isotropic base material, anisotropic weld material and ray divergence variation at a boundary separated by two dissimilar materials, ray transmission coefficients, phase relations and finally ray amplitudes represented in terms of density of rays. Apart from that a reliable weld model is considered which accounts the spatial variation of grain orientation in the macrograph of real life austenitic weld materials. These important aspects improve the reliability of the ray tracing predictions and helps in optimization and defect assessment during the ultrasonic inspection of inhomogeneous weld material. The accuracy of the ray tracing results is verified quantitatively based on numerical 2D Elastodynamic Finite Integration Technique (EFIT) simulation results on several configurations generally occurring in the ultrasonic non destructive testing of anisotropic weld and cladded materials. Experiments were conducted on real life Cr–Ni based inhomogeneous V-butt austenitic weld material (X6 CrNi 18 11) and compared the ray tracing results quantitatively with the experiments. The present research work is carried in the frame of German nuclear reactor safety research program to develop a complete analytical, efficient and accurate ray tracing method for quantitative evaluation of ultrasonic fields in inhomogeneous austenitic welds. The present ray tracing model is primarily designed for the inhouse research work.

The extensive metallographic investigations on microstructure of the austenitic weld materials were carried and concluded that austenitic weld metal is polycrystalline and can be assumed as transverse isotropic [35]. Using surface acoustic wave technique, Curtis and Ibrahim [36] conducted the texture studies in austenitic weld materials and suggested that the austenitic welds exhibit transverse isotropic symmetry. Generally in austenitic weld material three wave modes will exist in which one with quasi longitudinal wave character (*qP*), one with quasi shear wave character (*qSV*) and one pure shear wave (SH). Pure shear horizontal wave (SH) polarizes exactly perpendicular to the plane of wave propagation, i.e. in the plane of isotropy so that polarization direction of this mode always perpendicular to the wave vector direction.

The aim of the present paper is threefold. First, we present the theoretical description of the ultrasound field evaluation for point sources and finite dimension transducers in inhomogeneous anisotropic materials using a ray tracing model. Explicit analytical expressions for evaluating ray energy velocities and directions in general anisotropic material are presented. Second, we validate the ultrasound fields predicted on acoustically anisotropic austenitic cladded and weld materials from the ray tracing model quantitatively by 2D Elastodynamic Finite Integration Technique (EFIT) model calculations. Third, the ray tracing model results are compared quantitatively with experiments on thick austenitic weld, cladded materials and reasons for discrepancies are discussed.

2. Theory: Ray tracing model for inhomogeneous layered anisotropic materials

2.1. Modeling of material inhomogenity

Fig. 1 shows macrograph of the Cr–Ni based V-butt austenitic weld which is subjected to the experimental investigation. The filler layers in the austenitic weld metal were made using multipass Manual Metal Arc (MMA) welding and the root pass was carried out using Tungsten Inert Gas (TIG) welding. It can be recognized from Fig. 1, thus the austenitic weld materials exhibit epitaxial grain growth start from weld root and weld fusion face up to the weld crown, which results spatial variation of columnar grain orientation with in the weld metal.

Based on the several investigations on macrographs of the V-butt austenitic welds, Ogilvy [13] developed a mathematical empirical relation to describe the local columnar grain structure of the inhomogeneous austenitic weld material. Its form is given as

$$\tan\theta = \begin{cases} \frac{-T(D+z\tan\alpha)}{x^{\eta}}, & x \geqslant 0 \\ \frac{T(D+z\tan\alpha)}{(-x)^{\eta}}, & x < 0 \end{cases}, \tag{1}$$

where θ is the columnar grain orientation obtained with respect to the reference *x*-axis, *T* is measure of 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 angle of the weld preparation and η is a parameter