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Prediction of grain orientation in dissimilar metal weld using ultrasonic response of numerical simulation from deliberated scatterers

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ABSTRACT

Ultrasonic nondestructive testing plays an important role in structural integrity monitoring of dissimilar metal weld (DMW) structures in pressure vessels and piping of nuclear power plants. Inspection of DMW components is too complicated due to its anisotropic behavior to ultrasonic beam propagation. Many researchers are working rigorously to model the grain orientation and ultrasonic beam skewing in DMW structures but still not completely resolved yet. This paper is intended to estimate the grain orientation with the help of numerical simulation for a given asymmetric DMW component with specified scatterers. The DMW is fabricated from austenite stainless steel and carbon steel base metals with austenite stainless steel filler metal using Gas Tungsten-Arc Welding. To study this research a finite element method (FEM) based numerical simulation has been used to exactly evaluate the grain structure. This model mainly depends on the elasticity matrix which is a function of the grain orientation and attenuation of ultrasonic energy of the weld. Iterative measurement of grain orientation using macrograph of the etched weldment with 5 × 5mm mesh size was carried out then the attenuated elasticity matrix was fed into the FEM COMSOL software model as input parameter. Result obtained from numerical simulation (time of flight and amplitude) are validated with the experimental result and good agreement (above 0.8 correlation coefficient) have been observed at higher iterations. This macro-graphic information based numerical model shows the potential to predict the grain orientation of DMW.

1. Introduction

DMW is a typical joint of two or more different metals, often found in Inconel alloys. DMW components are qualitatively required to improve the mechanical properties of structures [1]. Generally, DMW joints between SA508Gr.3cl.1 ferritic steel and SS304LN pipes were prepared using Inconel 82/182 and Inconel 52/152 consumables. The joints of these structures requires periodical inspection for its structural integrity. Nowadays, the interest towards the investigation of DMW structures is radically increasing, especially in nuclear power plant structures such as [2] water reactor piping, pressure vessels and nozzles, steam generators and pressurized systems of process industries [3]. Metallurgical characterization and fracture toughness studies of weldment regions have been carried out to determine the effect of microstructure on fracture toughness in weldment regions. According to [4], microstructural and mechanical properties of weldment depends on the kind of filler material used and the method used for welding, observations showed that there was no evidence of possible cracking in the weldments achieved by nickel-base filler materials. Though the weldment materials of the specimen in this research is differ from others, the previous studies shows that the grain structure is the root cause for structural and mechanical properties and many researchers trying to model the grain structure finds it difficult in weldment including buttering section [5] helpful for the nondestructive evaluation of weldments.

Ultrasonic testing has wide spread application in safety and micro structural integrity of industrial components such as DMW joints and other heterogeneous anisotropic solids. Especially, in pressure vessels, piping and nozzle systems ultrasonic testing has more advantage and also its future direction shows an absolute valuable application over the other NDT inspection technique. But, this technique also suffers from a demerit that the scattering of wave propagation by the grain structure of weldment. High ultrasonic energy loss owing to the anisotropy of grain structure indicates that the wave propagation is totally dependent on the grain orientation and center frequency. DMW has been identified as a difficult component to test using ultrasonic techniques, primarily

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due to the anisotropic nature of the weldments and large grain size [6]. Especially, attenuation of high frequency ultrasound, backscattering noise associated with grain boundary reflections, and beam redirection in weld materials and solidification boundaries are major causes of difficulties in the ultrasonic testing. Thus, ultrasonic inspection of dissimilar metal welds is still a challenge due to the different acoustic impedances across the interfaces between parent metals, welded, buttering or cladded regions. The parent metals shows isotropic behavior, on the other hand weld exhibits anisotropic nature that attributes to columnar grained texture resulting from high thermal inputs during welding and solidification process. Research efforts to model the grain orientation and ultrasonic beam penetration in DMW have been excelled in the recent times, the basis for the ultrasonic plane wave displacement in anisotropic solids has been stated earlier [7]. A mathematical expression modeled by Ogilvy has been widely used for modeling the crystalline structures of such austenitic DMW weldments [8]. Moysan et al., presented the ultrasonic beam attenuation in weld grain orientation and Ye Jing et al., had modeled the crystallographic orientation of austenite stainless steel weldment for a normal beam incidence [9,10]. This model is appropriate for symmetric and normal ultrasonic incidence. To determine the ultrasonic field profiles in inhomogeneous anisotropic materials 2D ray tracing method was used [11]. In the early 1990s, Johnson et al. [12] presented the first ray tracing approach to calculate ultrasonic transducer fields in homogeneous isotropic solids, later it helped to study transversely isotropic inhomogeneous material. In another case, a model of material anisotropy without the need for macrographs was proposed [13]. However, this system of study failed to convince the researchers compared with a thoroughly developed macro-graphic modeling of grain orientation. Though there are many research reports on DMW, but most of them are dealt with symmetric geometry and normal ultrasonic beam incidence. In the present work the upper surface of the specimen is inclined at 19°, then the incidence angle is not normal to the surface. As it has been discussed about incidence direction above, there is 19° shifting in attenuation value to both sides from the center of weld. Therefore, according to the researches discussed above related to DMW, grain orientation and buttering, this research has find wider gap in modeling of grain orientation and ultrasonic beam propagation.

The present study dealt with inclined incidence of ultrasonic beam and asymmetric geometry of the specimen, but it works for all DMW structures. Since, DMW depends on welding condition, it is necessary to have an accurate general model that includes mechanical, structural and acoustic properties to determine how accurately model the grain orientation on dissimilar metal weld apart from carful grain orientation measurement technique. The more the angle between grain orientation and ultrasonic energy propagation direction, (closer to 90^0) the more will be the ultrasonic energy scattering. This study gives a potential solution to find an accurate model of grain orientation in DMW structures based on the material properties. Numerical simulation approach was presented and validated by experimentally measured values. The present study can be applied for any DMW specimen.

2. Materials and methods

This paper dealt with two approaches, experimental and numerical modeling, and also each method has its own detail way of implementation. A comprehensive integrated study by experimental and numerical analysis method provides a concrete valuable result.

The experimental measurement served as a reference and boundary for the numerical evaluation based on the factual specifications of the specimen under study. This method controls the research flow. The numerical simulation is provided as an iterative analysis approach to study this research according to experimental measurement result. Under the numerical study there are also proposed study techniques, which are the measurement of grain orientation and measurement of attenuation coefficient. Fig. 1, shows the overall study approach by relating the experimental and numerical simulation procedures. The process of validation serves as a bridge to interrelate both the experiment and simulation process. This is an illustrated short description of the study method in an iterative numerical simulation in correlation with the experiment.

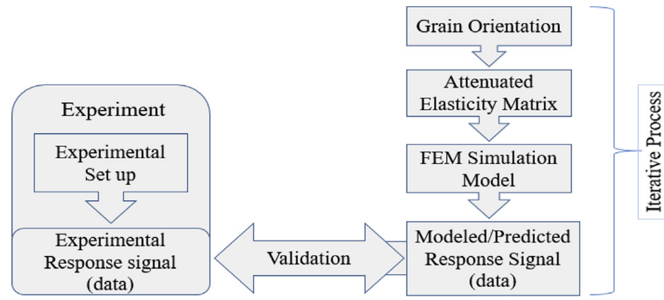

Fig. 1. Shows the overall experiment to simulation and vice versa to validate, approach used to estimate the grain orientation.

2.1. Experimental set up

Ultrasonic investigation of heterogeneous anisotropic solid materials is a big challenge because of the ultrasonic beam skewing in DMW part, a precised experimental set up is required considering the attenuation of sound energy and signal to noise ratio. A typical pulse-echo contact ultrasonic inspection technique was used for this experiment. Because of different acoustic impedances across the interfaces between parent metals, welded, butter or cladded regions, contact ultrasonic testing to be an appropriate choice to clearly inspect the specimen.

Fig. 2a, shows the geometry and plane view of the specimen used for this study. The specimen does not have perfectly v-shaped welded region, it can be clearly observed in the geometry of weldment. The specimen is composed of austenite stainless steel (SA240 TP304) and mild steel (SA508 Gr.3) as base metals, filler material is austenite stainless steel ERNiCr-3(Alloy 82). Three side-drilled-hole (SDH) scatterers (uniformly spaced at 25 mm with 1 mm diameter) machined on the weldment surface are considered as the defects in weldment. Shielded metal arc welding (SMAW) process well known for carbon steel, stainless steel welding was used to form a groove picking the welding position at 1G (Flat). From the surface view of the specimen, the right side weldment edge inclined at 10.12^0 from vertical axis and the left side edge makes 18.47^0 inclination from the vertical axis. The inclined surface at 19^0 is tilted from a height of 80 mm horizontal reference, the weld root and weld thickness are approximately 11 mm and 25 mm respectively. The weld also embodies a buttering part in between the weld (austenitic steel) and mild steel. From this welding process, it was assumed that the material properties like grain structure to be transversely isotropic throughout the thickness of weldment [14] though the asymmetry of weldment geometry has its own difficult effects on the grain orientation during welding process and solidification. A formal experimentation procedure using ultrasonic testing machine was used in our laboratory. Fig. 2b, shows the ultrasonic measurement machine setup in experimental system, the basic building blocks of this system are; a 1 MHz contact transducer with 25.4 mm diameter, a pulser/receiver integrated with a band pass filter of frequency range 1 KHz-20 MHz, a power amplifier to drive transducer, a wave runner oscilloscope and a computer connected with DAQ software to control and log the data automatically. ULTRAGEL II (it facilitates the transmission of ultrasonic energy) was used as a coupling agent between transducer and specimen for experimental purpose. The application of couplant during experiment is thoroughly done to remove the complication regarding the ultrasonic energy transmission during the inspection [15].

The measurement process was done by moving the transducer on

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