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Evaluation of near-surface stress distributions in dissimilar welded joint by scanning acoustic microscopy

Dong Ryul Kwak [a], Sanichiro Yoshida [c], Tomohiro Sasaki [d], Judith A. Todd [e], Ik Keun Park [b,*]

[a] Graduate School of NID Fusion Technology, Seoul National University of Science and Technology, Seoul, Republic of Korea
[b] Dept. of Mechanical & Automotive Engineering, Seoul National University of Science and Technology, Seoul, Republic of Korea
[c] Dept. of Chemistry and Physics, Southeastern Louisiana University, Hammond, LA 70402, USA
[d] Dept. of Mechanical Engineering, Niigata University, Niigata, Japan
[e] Dept. of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16801, USA

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ABSTRACT

This paper presents the results from a set of experiments designed to ultrasonically measure the near surface stresses distributed within a dissimilar metal welded plate. A scanning acoustic microscope (SAM), with a tone-burst ultrasonic wave frequency of 200 MHz, was used for the measurement of near surface stresses in the dissimilar welded plate between 304 stainless steel and low carbon steel. For quantitative data acquisition such as leaky surface acoustic wave (leaky SAW) velocity measurement, a point focus acoustic lens of frequency 200 MHz was used and the leaky SAW velocities within the specimen were precisely measured. The distributions of the surface acoustic wave velocities change according to the near-surface stresses within the joint. A three dimensional (3D) finite element simulation was carried out to predict numerically the stress distributions and compare with the experimental results. The experiment and FE simulation results for the dissimilar welded plate showed good agreement. This research demonstrates that a combination of FE simulation and ultrasonic stress measurements using SAW velocity distributions appear promising for determining welding residual stresses in dissimilar material joints.

1. Introduction

Laser welding, among the metal joining techniques, is widely used in automotive industries to assemble many parts due to its advantages such as reduced weight, cost savings, high precision, and enhanced structural performance. The welding process induces undesired residual stresses or plastic deformation of welded structural components, especially in thin plates of dissimilar materials. These factors can significantly affect the mechanical properties of materials and lead to changes in the surface and near-surface stresses.

Residual stresses can be measured by conventional destructive methods such as hole drilling, saw cutting, and layer removal. In the destructive method, a part of the stressed body is damaged after testing. These methods may be difficult to analyze theoretically and unable to detect micro-stresses [1].

On the other hand, the nondestructive methods can be classified into three basic types including X-ray or neutron diffraction method, magnetic method, and ultrasonic method. The X-ray diffraction method is the most common nondestructive method for measuring residual stresses. It is based on lattice strains and depends on the changes in the spacing of the atomic planes in materials. The neutron diffraction method is very similar to the X-ray diffraction and its advantage is the large penetration depth [2,3]. The magnetic method is based on the concept of magneto-elastic interaction between magnetic domain and elastic stresses. The measurement method is simple, but it can be used only for ferromagnetic materials [4]. The ultrasonic method for stress measurement uses the fact that the velocity of elastic wave propagation in a solid depends on the mechanical stress. It is well-known as the acousto-elastic effect [5]. The surface acoustic wave (SAW) velocity changes in accordance with the amount of stress within a material. The ultrasonic stress measurement techniques have been developed to evaluate the integrity of a dissimilar metal weld. This technique can be applied to visualize surface and near-surface stresses within a material, and map the stresses using precisely measured SAW velocities [5–8]. A scanning acoustic microscope (SAM) with an acoustic lens can focus an ultrasonic wave to a micron-scale spot. Using the $V(z)$ curve technique [9–11], the SAW velocity change induced by surface stresses can be precisely measured.

* Corresponding author.

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In this study, scanning acoustic microscopy was used to investigate the development of surface stresses in dissimilar metal welded plates. The scanning acoustic microscopy technique allows the measurements of the small area in the boundary between weld metal and heat affected zone. Considering the high attenuation of these materials, a circular point focus lens with a frequency of 200 MHz was used to measure the leaky SAW velocities. A three dimensional (3D) finite element simulation by commercial software (ANSYS) was performed for the numerical predictions of the stress distributions.

2. Scanning acoustic microscopy

2.1. Image principle

Fig. 1 presents a schematic diagram of a SAM, capable of generating tone-burst waves in the frequency range 100 MHz to 1.5 GHz. In this study, the SAM was operated at a frequency of 200 MHz for the SAW velocity measurement, and 400 MHz for acoustic imaging. The parameters of the acoustic lens are shown in Table 1.

An electrical signal is generated by an RF tone-burst source and transmitted to a piezoelectric transducer located on the top of a buffer rod through a circulator. The electrical signal is converted to an acoustic signal (i.e. ultrasonic plane wave) at the transducer. The ultrasonic plane wave travels through the buffer rod to a spherical recess (hereinafter called simply the "lens") located at the bottom of the buffer rod. The lens is coated by an acoustic impedance matching layer or acoustic anti-reflection coating (AARC). The lens converts the ultrasonic plane wave to an ultrasonic spherical wave (i.e. ultrasonic beam). The spherical wave is focused within the specimen and then reflected back to the lens. Distilled water is usually used as the coupling medium. The reflected ultrasonic beam, which carries acoustic information from the specimen, is again converted to an ultrasonic plane wave by the lens. The ultrasonic plane wave returns to the transducer through the buffer rod and is converted again to an electric signal at the transducer. The voltage of the electric signal ranges from 300 mV to 1 V. When the operating frequencies ranged from 100 MHz to 1 GHz, the corresponding insertion loss is approximately 30 dB–80 dB, requiring the electric signal to be amplified by 30–80 dB at the receiver. Furthermore, the electric signal is compromised by transmission leaks, internal reflections from the interface between the lens and the AARC, and reflections from the specimen. Therefore, the reflections have to be selected by a rectangular wave from a double balanced mixer (DBM), known as the first gate. The peak of the electric signal amplitude is detected by a circuit, which includes a diode and a capacitor (i.e. the peak detection technique). The gate noise is removed using a second gate within the first gate (i.e. blanking technique). The peak-detected signal is stored into a memory through an analog-to-digital (A/D) signal converter. The stored signal is converted again into an analog signal by a digital-to-analog (D/A) signal converter. Consequently, information collected from each location on the specimen corresponds to a specific intensity value on the TV display. In order to form a two dimensional acoustic image, the acoustic lens mechanically scans across a given area of the specimen, which is positioned on an X–Y stage. The acoustic lens is translated axially along the z direction to vary the distance between the specimen and the lens for sub-surface visualization. That is, when visualizing the surface of the specimen, the acoustic lens is focused at the specimen surface (denoted as $z = 0$), and when visualizing the subsurface, the acoustic lens is mechanically defocused toward the specimen (denoted as $z = -z$), where z is the defocused distance.

Table 1
Parameters of the acoustic lens.

Frequency	Aperture angle	Focal distance	Curvature radius	Working distance
200 MHz	120°	577.5 μm	500 μm	310 μm

2.2. V(z) curve technique

Fig. 2 shows a schematic diagram of the SAW propagation between the acoustic lens and the specimen via a coupling medium (e.g. distilled water).

In theory, the oscillations of the received signal can be explained by the interference between a reflected longitudinal wave (path 1; E-O-E) and a surface wave (path 2; A-B-O-C-D) in Fig. 2. The SAW can be generated at the liquid–solid interface if the half aperture angle of the acoustic lens is larger than the critical angle to the surface. The SAW can propagate along the interface between the sample surface and the liquid, and radiate energy continuously at the critical angle. Since the energy leaks into the liquid as soon as it is generated, this surface wave is called a leaky surface acoustic wave (Leaky SAW). The leaky SAW interferes with the reflected longitudinal wave and produces a voltage change at the transducer. The plot of transducer voltage amplitude with changes in the distance between the specimen surface and the focus of the acoustic lens is known as the $V(z)$ curve.

Eq. (1) can be used to calculate the leaky SAW velocity. This equation from the ray optics theory [10] allows quantitative

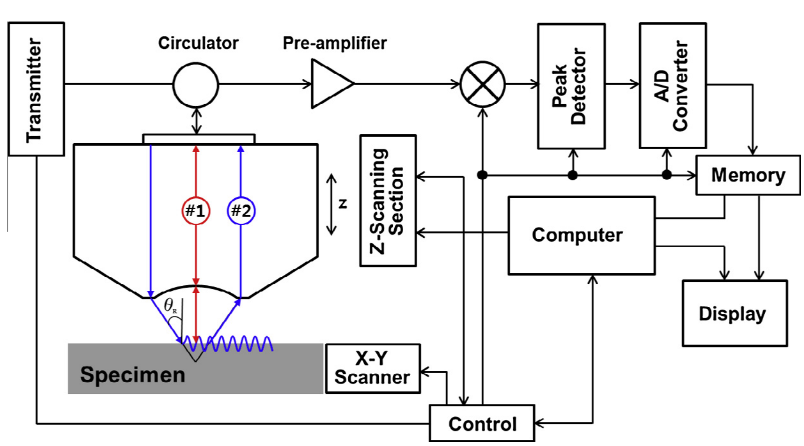

Fig. 1. Schematic diagram of SAM.