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Material Characterization of Weld-Zone Using Poisson's Ratio Distribution

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Abstract Poisson’s ratio, one of elastic constants of elastic solids, has not attracted attention due to its narrow range and difficult measurement. Transverse wave velocity as well as longitudinal wave velocity should be measured for nondestructive measurement of Poisson’s ratio. Rigid couplants for transverse wave is one of obstacle for scanning over specimen. In the present work, a novel measurement of Poisson’s ratio distribution was applied. Immersion method was employed for the scanning over the specimen. Echo signals of normal beam longitudinal wave were collected, and transverse wave modes generated by mode conversion were identified. From transit time of longitudinal and transverse waves, Poisson’s ratio was determined without the information of specimen thickness. Poisson's ratio distribution of the carbon steel weldment was mapped. Heat affected zone of the weldment was clearly distinguished from base and filler metals.

Keywords: Poisson's Ratio, Heat Affected Zone(HAZ), Mu-Scan, Immersion Ultrasonic Testing, Mode Conversion

1. Introduction

Welding has been widely used for jointing parts and members in metal structures. The heat during welding causes residual stress, micro-structural changes and degradation of the base material. Heat affected zone(HAZ) is the area where microstructure and elastic properties altered by the weld. The metal in this area is often weaker than both the base material and weld zone. Efforts are taken to relax the residual stress found in HAZ. Flaws such as cracks, inclusions, and voids could also be present in HAZ. Therefore welded joints are very sensitive to fracture. HAZ should be inspected in order to retain the structural integrity.

Typical material characterization of weldment involves microscopic analysis of material texture and microhardness test. In nondestructive testing (NDT), ultrasonic wave speeds and attenuation of the sample are measured. Poisson's ratio, the ratio of lateral contraction to longitudinal extension, is another elastic parameter that can be used for material characterization. One of the advantages using Poisson's ratio is that it is a dimensionless parameter. Its value thus does not depend on the units.

Poisson's ratio has not received much attention owing to its narrow range of value and difficult measurement. However, Poisson's ratio can tell the material's microstructure. Softer materials tend to have larger Poisson's ratios. It has been reported that Poisson's ratio is closely related to the bonding forces and ultrasonic wave speeds in the material(Kumar et. al., 2003). Cyclic-softening of high-strength steel resulted in Poisson's ratio close to 0.5(Matsuoka et. al., 1987). Auxetic property of polymer foams causes

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negative Poisson's ratio(Lakes, 1987).

Poisson's ratio can be, by definition, obtained from the tensile test by measuring axial and transverse strains. Or else, nondestructive contact method is in common. Longitudinal and transverse mode transducers are coupled with the specimen and measure ultrasonic wave speeds (Roth et. al., 1993). Use of piezoelectric PVDF (poly-vinylidene fluoride) film was suggested in order to avoid such burdensome process(Vargas et. al., 2009). Depending on frequency, the film vibrates in thickness or radial mode, creating longitudinal or transverse wave. Noncontact method, such as immersion ultrasonic testing carries great advantages.

We propose a genuine nondestructive evaluation(NDE) method of characterizing weld-zone using Poisson's ratio distribution. It was found that immersion ultrasonic testing can measure longitudinal and transverse wave speeds simultaneously(Kim et. al., 2003). Having no couplants makes free scan possible over large surface area. Moreover, velocity ratio can be obtained without prior knowledge of specimen thickness. Poisson's ratio can be calculated from this velocity ratio using the relationship below.

$$\mu = \frac{1-2\alpha^2}{2-2\alpha^2} = \frac{\tau_t^2 - 2\tau_1^2}{2\tau_t^2 - 2\tau_1^2} \tag{1}$$

where $\alpha = \frac{c_t}{c_1}$ is the ratio of transverse and longitudinal wave velocity, and τ_t and τ_1 are the transit times of transverse and longitudinal wave, respectively.

Nondestructive measurement of Poisson's ratio has been a challenging job, since bulk and shear moduli, or longitudinal and transverse wave velocities should be measured. Possibility of Poisson's ratio mapping (*μ-scanning*) using longitudinal wave mode transducer immersed in water has been suggested through a series of works. It was reported that transverse wave can be generated by mode conversion of normal incident longitudinal wave(Kim et. al., 2003). Simultaneous measurement of longitudinal and transverse wave speeds by using immersion ultrasonic testing was reported(Shin et. al., 2007). Poisson's ratio mapping without the prior information on specimen thickness was also demonstrated(Oh et. al., 2008).

In the present work, weldment of carbon steel specimen was tested. Ultrasonic pulse-echo signals were acquired in the immersion testing and the mode converted signals were identified. Time of flight of longitudinal wave and mode-converted transverse wave was used to obtain Poisson's ratio. Heat affected zone of the specimen was clearly distinguished from the Poisson's ratio distribution.

2. Experimental

Double V-groove welded carbon steel plates were fabricated. The specimen was of 30 mm thickness and of 24 mm width. Specimen was cut out from the weldment using water jet to avoid change in microstructure due to thermal effects during cutting the specimen.

The echo signals were captured using the normal-beam transducer of longitudinal-wave mode, of which diameter and a center frequency were 12.7 mm and 5 MHz, respectively. Ultrasonic pulser/receiver(Panametrics 5800) and A/D converter module(NI PXI-5124) were used for generation, reception and acquisition of ultrasonic signals. Sampling rate was 100 Ms/s, so that the time resolution was 10 ns.

Cross-section of specimen was scanned in water tank in order to obtain distribution of Poisson’s ratio, and water distance between transducer and top surface of specimen was approximately 30 mm. Scan area was 50 mm x 50 mm with 0.5 mm step in both width and length.

Echo signals from the C-scan were post-processed. Noises were successfully suppressed by Gaussian filtering. The longitudinal and the transverse wave speeds could be simultaneously determined from the large echo signals of longitudinal wave modes and mode converted echo with small amplitude. By knowing the ratio of the two ultrasonic speeds, Poisson's ratio could be determined without the knowledge of specimen thickness. Large-echo 2P, 4P peaks were determined by an appropriate threshold value. Small-echo 3P1S peak was designated to the largest peak between the two large-echo 2P and 4P signals. The numbers in the front of P and S represent the number of wave modes involved in the multiple reflections in the plate. Arrival times of 2P, 4P, and 3P1S signals were used to calculate the ratio of longitudinal and transverse wave speed. Poisson's ratios were obtained by using eqn. (1).

3. Results and Discussions

Fig. 1 shows the measured pulse-echo signals at a specific point of the specimen. The first, second, and third large-echo signals corresponded to 2P, 4P, and 6P, respectively. Small mode-converted echoes between 2P, 4P, and 6P were designated 1P1S, 3P1S, and etc. in time order. Generally, 3P1S peak can be easily identified compared to 1P1S, thus this signal was chosen to be used to obtain transverse-wave speed.

At each point, Poisson's ratio was obtained using the eqn. (1). Fig. 2(a) shows the distribution of measured Poisson's ratio over the specimen. Fig. 2(b) shows the photograph of the specimen. *Mu-scan* resembled photograph in pattern. The color pattern of the specimen in the photograph was caused by natural stain. Light-colored area of the weldment was distinguished from the dark-colored area of base metal region, since Poisson's ratio of the filler metal was higher than that of the base metal.

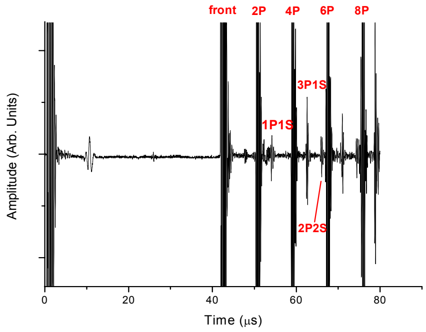


Fig. 1 Typical example of full RF pulse-echo signal

In Fig. 2(c), Poisson's ratio distribution along the line segment in Fig. 2(b) was profiled. For reference, part of Fig. 2(b) was reproduced in Fig. 2(c) with adjusted color contrast. Poisson's ratio of the heat affected zone(HAZ) was smaller

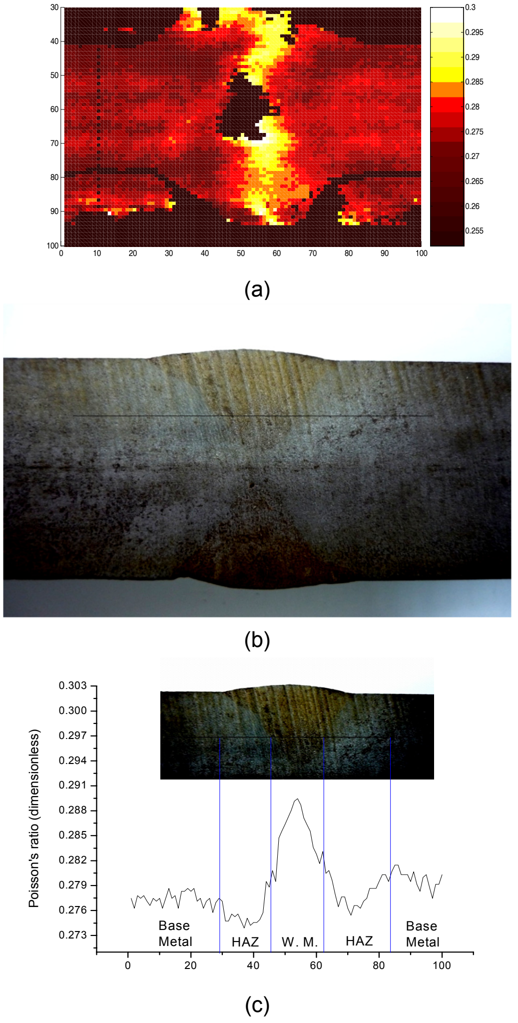
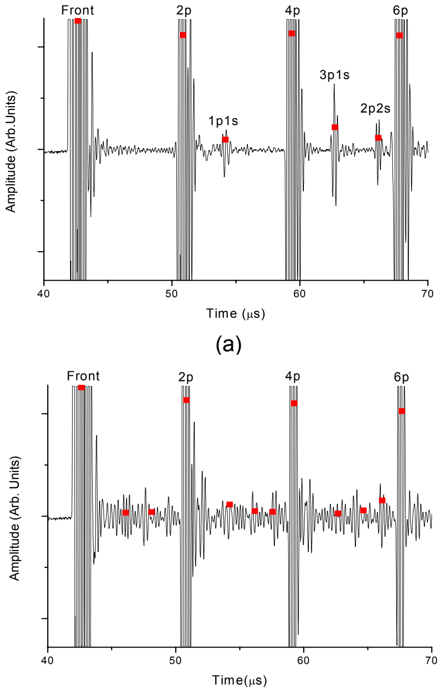


Fig. 2 (a) μ-scan of weldment of carbon steel, (b) photograph of weldment and (c) linear profile of μ-scan data than those of base metal and filler metal. Decrease in Poisson's ratio at HAZ is thought to be caused by hardening of the HAZ during welding.

For the abnormal region such as void region in the middle of Fig. 2(a), where the mode-converted signal was weak or had Poisson's ratio beyond the range 0.2~0.5, Poisson's ratio was not plotted. Such anomalies occur when identification of 3P1S signal failed. It may be caused by multi-path ultrasound due to heterogeneous or anisotropic medium, existence of flaw and high attenuation. Fig. 3(a) shows typical normal pulse-echo signal in which red dots indicate identified peaks corresponding to 2P, 1P1S, 4P and so on. Whereas abnormal signal in Fig. 3(b) shows dots which failed to identify each mode.

Width of the specimen measured from Poisson's ratio scan (Fig. 2(a)) is about 10mm broader than its real width (Fig. 2(b)), because of the size-effect of transducer. It implies that the obtained value at each point is average value over a certain area corresponding to the diameter of the transducer. Therefore, in order to obtain a high-resolution Poisson's ratio scan, focused transducer is strongly recommended.



(a)

(b)

Fig. 3 (a) Echo signals at a normal point and (b) echo signals at an anomaly point

4. Conclusions

In the present work, heat affected zone (HAZ) of welded carbon steel specimen was distinguished from the measured Poisson's ratio distribution. Longitudinal and transverse wave speeds were determined from the transit times of mode converted echoes in pulse-echo signal of ultrasonic immersion testing. 3P1S echo signals were more efficient in determining transit time compared to 1P1S. Poisson's ratio distribution was obtained through the probe scanning of the immersion testing. Poisson's ratio of the filler metal was larger than that of the base metal. Owing to the microstructural variation and hardening due to heat during welding, Poisson's ratio decreased at the HAZ. For further investigation, microscopic analysis and microhardness test at the HAZ will be performed.

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