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# Improvement of acoustoelastic coefficient for residual stress measurement by ultrasonic in low carbon steel

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**Abstract**

This research aimed to exhibit the effects of variation of grain size, hardness and ultrasonic energy input for improving the residual stress measurement by ultrasonic in low carbon steel. Low carbon steel (SS400) was used to vary its grain size and hardness by fully annealing with 6 different temperature levels. The grain size and hardness of each specimen were analyzed by the microscope and hardness testing machine. Then each specimen was applied static tension load below yield point. The load was increased at 25 N/mm$^2$ (MPa) in increment. Through transmission technique with probe 2 MHz and surface ultrasonic wave were used. Ultrasonic energy input generated from Pulser-Receiver was changed its Pulser Voltage (PV) and Pulse Repetition Frequency (PRF). Traveling time of ultrasonic surface wave was measured by using Pulser/Receiver and displayed by an oscilloscope to calculate the ultrasonic velocity. The average of acoustoelastic coefficient was calculated based on the correlation between ultrasonic velocity and tensile stress. The results showed that the speed of ultrasonic waves depended on grain size and hardness of material. The ultrasonic energy input affected to the residual stress measurement. Finally, the constant value for residual stress measurement was created to increase the accuracy of residual stress determination.

**Keywords:** Residual stress, Ultrasonic testing, Low carbon steel, Hardness, Pulser voltage, Pulse repetition frequency

## 1. Introduction

Residual stress is one of the main causes of premature failure in steel structures. Nowadays, an Ultrasonic Testing (UT) can be used to measure the residual stress in steel structures or materials based on the change of the velocity of ultrasonic wave. Its velocity in material is directly affected by the magnitude and direction of presented stress. However, the change in the velocity of ultrasonic waves is also affected by variation of other factors. Consequently the accuracy of residual stress determination by UT is reduced.

Many papers for residual stress measurement in carbon steel were reported. The comparison of contact and immersion waves used to measure residual stresses in weld joint by longitudinal critically refracted wave propagated was reported [1]. The ultrasonic computerized complex, software and finite element model were developed to measure the residual stress based on acoustoelasticity [2-3]. The relationship between velocity, direction of ultrasonic propagation and stress of pipe component were studied and calibrated specimen was built for using in the field [4]. The residual stress profiles estimated from X-ray diffraction and UT method exhibited good correlation between the two methods [5].

The purpose of this research is to study the effects of variation of grain size, hardness and ultrasonic energy input on the acoustoelastic coefficient for improving the residual stress measurement. The research benefits not only the operators in using the constant value but also in predicting it.

## 2. Experimental setup

### *2.1 Specimen preparation*

Low carbon steel (SS400), 0.17%C, 0.95%Mn, 0.025%P and 0.030%S by mass, was prepared as the tensile specimen according to JIS Z2201 (No.5) standard, 8 mm thickness, 25 mm width and 250 mm long. The annealing temperature was varied from 900 and 1150 $^{o}$C by increasing at 50 $^{o}$C in increment (6 levels) to vary its grain size and hardness. The holding time was 60 minutes and then cooled down in the furnace. The grain size was analyzed by polishing, etching the sample and evaluating the micrograph by microscope Zeiss-Axio vert 200M Mat and using Axio vision Rel 4.4 program according to American Society for Testing and Materials ; ASTM E1382. Furthermore, the hardness was determined by Vicker hardness testing machine, with 10 kgf loads.

### *2.2 Residual stress measurement by ultrasonic*

The ultrasonic surface wave velocity is dependent on the mechanical properties of material. The velocity of ultrasonic surface wave $V_S$ (m/s) can be determined by equation 1 [6].

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$$V_S = \frac{0.87 + 1.12\upsilon}{1-\upsilon}\sqrt{\frac{E}{2\rho(1+\upsilon)}} \quad (1)$$

Where $\upsilon$ is the Poisson's ratio of material, $E$ is the Yong's modulus of material (N/mm$^2$) and $\rho$ is the density of material (kg/m$^3$).

The residual stress measurement by ultrasonic is based on the acoustic-elasticity effect, according to which the velocity of wave propagation in materials is dependent on the mechanical properties. The change of surface wave velocity can convert to mechanical stress. The relationship between mechanical stress and surface wave velocity can be expressed by equation 2 [6].

$$K = \frac{1}{\sigma}\left(\frac{V_s - V_o}{V_o}\right) \quad (2)$$

Where $K$ is acoustoelastic coefficient (kg/m$^2$s x 10$^6$), $\sigma$ is the mechanical stress (N/mm$^2$), $V_S$ is the ultrasonic surface wave velocity obtained under stress conditions (m/s) and $V_0$ is the reference of ultrasonic surface wave velocity obtained under stress-free conditions (m/s).

In this research, the residual stress was simulated by pulling in the tensile testing machine below yield point. The load was increased at 25 N/mm$^2$ (MPa) in increment total 8 steps (200 MPa maximum). Through transmission technique with probe 2 MHz and surface ultrasonic wave was used. Ultrasonic energy input generated from Pulser-Receiver was varied its PV (100, 200, 300 and 400 volts) and PRF (100, 500 and 2000 Hz), 12 conditions. Other parameters of energy input were Transducer Frequency (MHz) = 2.00-2.25 and Gain (dB) = + 20. Then, time domain of each load was recorded to calculate the ultrasonic velocity by fixing the distance of ultrasonic probes (47 mm). Figure 1 is shown the diagram of experiment.

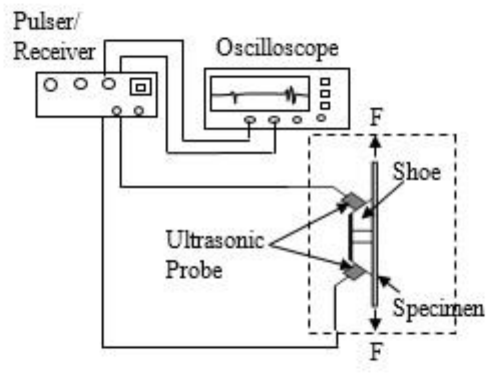


**Figure 1** Stress measurement from tension force

## 3. Results and discussions

### *3.1 Grain size and hardness*

The relationship between annealing temperature and grain size and annealing temperature and hardness are shown in Figure 2(a) and 2(b), respectively. The experimental result showed that annealing temperature had an effect on grain size and hardness. Apparently, the grain size was large (small grain size number) and hardness decreased as the annealing temperature increased. At high temperature, the internal energy of material was decreased so the grain size would be large and hardness would be decreased.

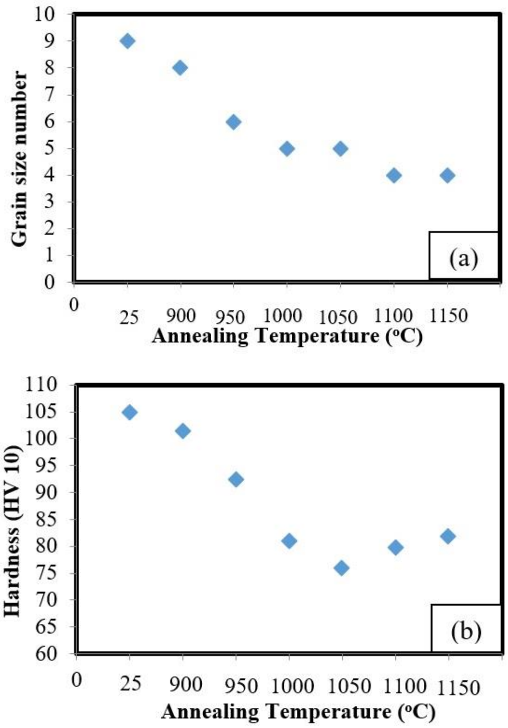


**Figure 2** (a) grain size number (b) hardness

### *3.2 Ultrasonic energy*

The example of time domain signal from tensile stress measurement for 150 MPa are shown in Figure 3(a) and 3(b). The time domain signal revealed that the amplitude of PV (100 and 400 volts) affected to sensitivity of stress measurement, whereas the PRF (100 and 2000 Hz) was found to be less significant. The amplitude of time domain signal (C point, 0.050 and 0.325 mVrms) would be increased when the PV increased. The traveling time ($T$) between two probes could be measured from A and B point to calculate the ultrasonic velocity.

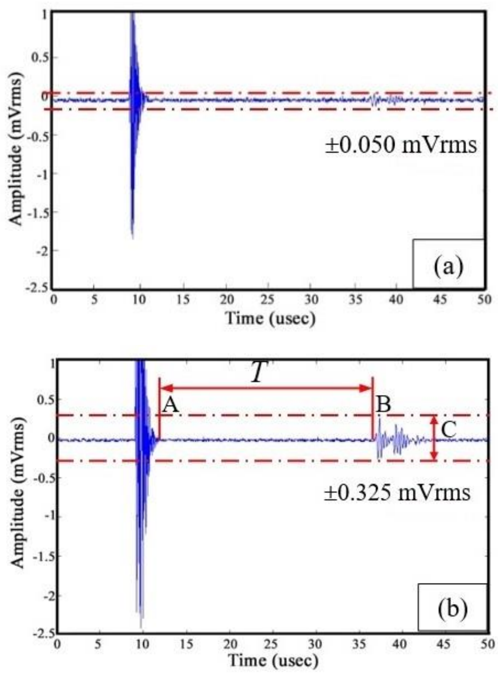


**Figure 3** (a) PRF 100 Hz, PV 100 volts (b) PRF 100 Hz, PV 400 volts

*3.3 Acoustoelastic coefficient*

The average of acoustoelastic coefficient ($K_{Ave}$) calculated from equation 2 is shown in Table 1. The average of acoustoelastic coefficient was related to the annealing temperature.

**Table 1** The average of acoustoelastic coefficient

| Annealing temperature (C°) | $K_{Ave}$ x $10^{-5}$ |
|---|---|
| 25 | 6.1128 |
| 900 | 5.1512 |
| 950 | 4.6439 |
| 1000 | 3.1677 |
| 1050 | 1.6838 |
| 1100 | 2.6399 |
| 1150 | 1.0591 |

The relationship between the average of acoustoelastic coefficient and grain size number and the average of acoustoelastic coefficient and hardness are shown in Figure 4(a) and 4(b), respectively.

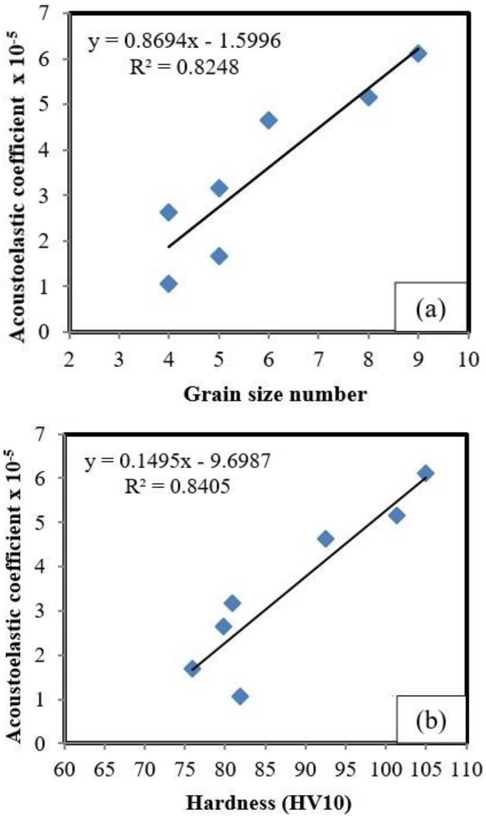


**Figure 4** (a) acoustoelastic coefficient versus grain size number (b) acoustoelastic coefficient versus hardness

The result showed that the acoustoelastic coefficient related to the grain size (see equation on Figure 4(a)) and hardness (see equation on Figure 4(b)) of material. This means that the grain size and hardness affected to the Poisson's ratio and Yong's modulus of material. From the equation 1, the ultrasonic velocity could be calculated in terms of Poisson's ratio and Yong's modulus of material. So the grain size and hardness of material would affect to the acoustoelastic coefficient. It could be utilized to increase the accuracy of the residual stress measurement by ultrasonic.

*3.4 Prediction error of tensile stress measurement*

To validate the influence of microstructure (grain size and hardness) on the acoustoelastic coefficient for stress measurement by ultrasonic, the tensile stress measurement in laboratory was calculated based on the average of acoustoelastic coefficient. The prediction error of tensile stress measurement calculated from equation 2 is shown in Table 2.

In Table 2, at 900°C if the average of acoustoelastic coefficient of 25°C condition was used in 900°C condition, the prediction error was -15.71% (error -15.71% if compared with the average of acoustoelastic coefficient of 900°C condition). For 1150°C condition, if used the average of acoustoelastic coefficient of 25°C condition for calculation, the prediction error was -82.65%.

**Table 2** Prediction error of laboratory tensile stress measurement

| | Prediction error (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **25** | **900** | **950** | **1000** | **1050** | **1100** | **1150** |
| **25** | - | | | | | | |
| **900** | -15.71 | - | | | | | |
| **950** | -24.06 | -9.90 | - | | | | |
| **1000** | -48.12 | -38.45 | -31.68 | - | | | |
| **1050** | -72.50 | -67.38 | -63.79 | -47.00 | - | | |
| **1100** | -56.79 | -48.74 | -43.10 | -16.72 | +57.14* | - | |
| **1150** | -82.65 | -79.42 | -77.16 | -66.56 | -36.90 | -59.85 | - |

* The average of acoustoelastic coefficient for 1050°C was more than 1100°C.

The results showed that the acoustoelastic coefficient depended on the microstructure of material. If used a single value of acoustoelastic coefficient, the accuracy of stress value determined by ultrasonic method was less than the actual value to calculate from acoustoelastic coefficient at the actual temperature.

## 4. Conclusions

The average of acoustoelastic coefficient was reduced as the grain size of material increased. The PRF exhibited insignificant effects but PV showed the effect on the sensitivity of residual stress measurement. The improvement of acoustoelastic coefficient can be utilized to increase the accuracy of the residual stress measurement by ultrasonic.

## 5. Acknowledgements

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