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Variation of Acoustoelastic Effect in Al6061-T6 according to Heat Treatment Time

Chang-Soo Kim*, Jongbeom Kim**†, Dong-Gi Song* and Kyung-Young Jhang**†

Abstract The acoustoelastic effect is a phenomenon where the elastic wave velocity varies slightly because of changes in the density or microstructure of the material depending on the variation of tensile or compressive stress. In this paper, we apply the acoustoelastic effect to evaluate the micro-structural changes caused by heat treatment. For this purpose, Al6061-T6 specimens were heat-treated at a constant temperature of 220°C for the seven different heat-treated times. The stress-dependent coefficients were then measured and compared with the variation of the yield strength. The stress-dependent coefficient quantitatively represents the relationship between the variation rate of the ultrasonic wave velocity and applied stress. The ultrasonic wave velocities were measured under the compressive stress state and the time-of-flight(TOF) obtained through the autocorrelation process. The experimental results showed that the heat treatment time at which significant changes in stress-dependent coefficients occurred coincided with the heat treatment time at which a significant change in yield strength occurred. Consequently, it is expected that the variation of yield strength due to heat treatment can be estimated through the acoustoelastic effect.

Keywords: Elastic wave velocity, Acoustoelastic effect, stress-dependent coefficient, Heat treatment, Yield strength

1. Introduction

The acoustoelastic effect describes the slight changes in ultrasonic propagation velocity according to the stress, which is caused by changes in the density or micro-structure of the material depending on the variation of tensile or compressive stress [1,2]. This acoustoelastic effect has a similar relation to the ultrasonic nonlinear characteristics in that the propagation velocity depends on the applied stress [3].

As the ultrasonic nonlinear characteristics is sensitive to changes in micro-structures such as precipitate, dislocation and void in micrometer -scale material, it is recognized as useful for evaluating the degradation of material [4,5]. However, unlike the nonlinear ultrasonic technique (NUT) that uses the harmonic generation [4-6], the acoustoelastic technique utilizes the variation of ultrasonic propagation velocity caused by applied stress and has been mainly used to evaluate the residual stress or measure axial stress [7-9].

Nevertheless, since acoustoelasticity is related to acoustic nonlinearity, it can be expected that the acoustoelastic technique might be used to evaluate material degradation like the NUT. However, only a few studies have conducted to evaluate the material degradation using acoustoelastic effect. There is a case study to evaluate fatigue degradation [10,11].

Thus, this study attemped to use the acoustoelastic effect in the evaluation of heat treatment-related variation of yield strength. For this purpose, seven Al6061-T6 specimens were prepared that were heat-treated for different time (0, 20, 40, 60, 120, 600, and 6000 min) at 220°C. Compressive stress was applied as an

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[Received: March 16, 2018, Revised: April 11, 2018, Accepted: April 18, 2018] *Department of Mechanical Convergence Engineering, Graduate School, Hanyang University, Seoul 04763, Korea, **School of Mechanical Engineering, Hanyang University, Seoul 04763, Korea, †Corresponding Author: kyjhang@hanyang.ac.kr

external force, and ultrasonic time-of-flight (TOF) was obtained using the auto-correlation function of ultrasonic signals received by the pulse-echo technique. The variation rate of TOF according to variation of stress were used to calculate a stress-dependent coefficient, which indicated the relationship between the variations of wave propagation velocity and applied stress, thereby quantifying the acoustoelastic effect. After the ultrasonic test, the tensile test was conducted to obtain yield strength. Finally, the relationship between yield strength and the stress-dependent coefficient was analyzed according to heat treatment time.

2. Acoustoelastic effect

In order to measure the acoustoelastic effect, stress-dependent coefficient is used, which is the variation rate of TOF according to the compressive stress applied to the specimen. That is, when uniaxial compressive stress σ is applied, the elastic wave velocity can be defined as [12,13]

$$V_L = V_{0,L}\left(1+\alpha_L \cdot \frac{\sigma}{E}\right) \tag{1}$$

$$V_T = V_{0,T}\left(1+\alpha_T \cdot \frac{\sigma}{E}\right) \tag{2}$$

where $V_{0,L}$ and $V_{0,T}$ are the velocities of the longitudinal and transverse waves, respectively, in the initial state where no stress is applied. α_L and α_T are stress-dependent coefficients in the longitudinal and transverse waves, respectively. E is the elastic modulus. The above Eqs. (1) and (2) can be rearranged by t_L and t_T, respectively, each of which is the TOF of longitudinal and transverse waves, respectively, as follows [13],

$$t_L = \frac{W(1-\sigma/E)}{V_{0,L}(1-\alpha_L \cdot \sigma/E)} \tag{3}$$

$$t_T = \frac{W(1-\sigma/E)}{V_{0,T}(1-\alpha_T \cdot \sigma/E)} \tag{4}$$

where, W is the distance of propagation. If we express, TOFs of longitudinal and transverse waves there is no stress as $t_{0,L}(=W/V_{0,L})$ and $t_{0,T}(=W/V_{0,T})$, respectively, then the variations in TOFs of longitudinal and transverse waves can be described as $\triangle t_L(=t_L-t_{0,L})$ and $\triangle t_T(=t_T-t_{0,T})$, respectively. If these variations are substituted into Eqs. (3) and (4), then Eqs. (5) and (6) can be derived [12].

$$\alpha_L = 1+\frac{E}{\sigma}\left(\frac{\triangle t_L}{t_{0,L}}\right) \tag{5}$$

$$\alpha_T = 1+\frac{E}{\sigma}\left(\frac{\triangle t_T}{t_{0,T}}\right) \tag{6}$$

In order to quantify the acoustoelastic effect, the stress-dependent coefficients of longitudinal and transverse waves under the uniaxial stress condition were defined. When tensile stress is applied to a material, the sign of the stress in the Eqs. (1) and (2) become minus, but the value of the stress-dependent coefficient does not change irrespective of stress direction.

This study utilized the variation of the stress-dependent coefficient to identify the change in acoustoelastic effect according to heat treatment time.

3. Experiment

3.1 Experimental setup

The pulse-echo technique was applied to measure TOFs of longitudinal and transverse waves, as shown in Fig. 1, and seven Al6061-T6 specimens with dimensions of 40 mm × 38 mm × 20 mm (width × length × thickness) were prepared. Al6061-T6 has tensile strength of 120-290 MPa [14,15]. As it has good machinability, high resistance of corrosion, and is also inexpensive, it is widely used in the automobile, construction, and aerospace industries [16,17]. After the specimens were annealed for 240 min at 540°C to form a super-saturated solid solution [18], the quenching was performed for 60 min to maintain the super-saturated solid solution. Then, to increase the strength according to growth of precipitate, the specimens were heat treated for different time periods (0, 20, 40, 60, 120, 600, and 6000 min) at 220°C [18].

A hydraulic system was used to apply compressive stress to the specimens and the variation of propagation velocity was measured according to compressive stress. The hydraulic system was located on top of a jig, and a load cell was placed under the specimen to monitor the compressive stress in real time. The compressive load that was applied ranged from 500 kg(≒4 MPa) to 4500 kg (≒39 MPa) at increments of 500 kg. For the purpose of transmission and reception of ultrasonic pulse signals, a pulser/receiver (Panametrics, PR5072) was used. Piezo-electric longitudinal/transverse wave transducers with center frequency of 5 MHz was used to transmit and receive ultrasonic signals. As shown in Fig. 1, both longitudinal and transverse waves propagated in the x-direction. The particles movement of longitudinal waves oscillated in the x-direction, while those of transverse waves oscillated in the y-direction. Received signals were obtained by an oscilloscope (Lecroy, WS452) with 0.5 ns time resolution. The experiment was repeated three times for each specimen.

3.2. Signal processing

Fig. 2(a) and 2(b) illustrate signals of longitudinal and transverse waves, respectively, which were received under 4 MPa stress load. The autocorrelation function for the received signals was calculated to obtain TOFs under each stress. Fig. 3(a) and 3(b) show the autocorrelation functions for the received signals of longitudinal and transverse waves. TOF is the peak lag between the first and second echoes.

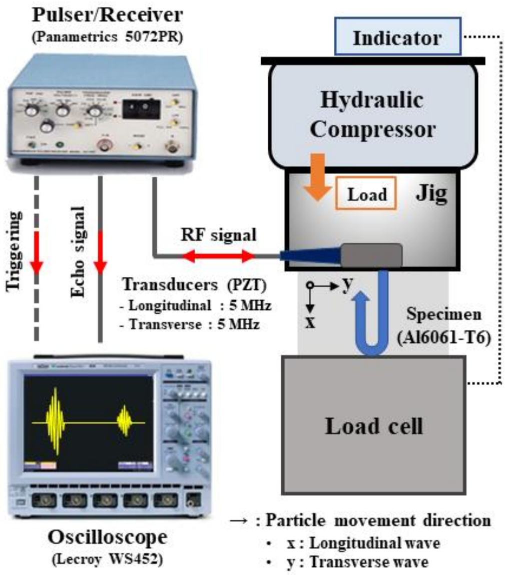
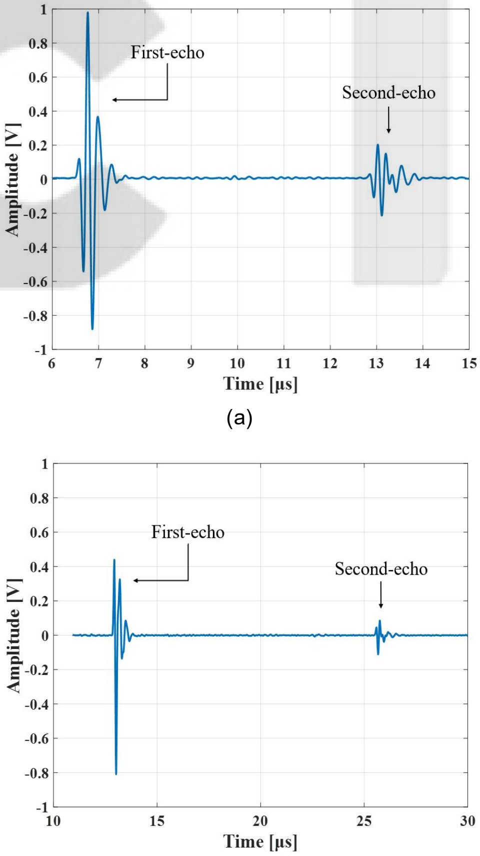


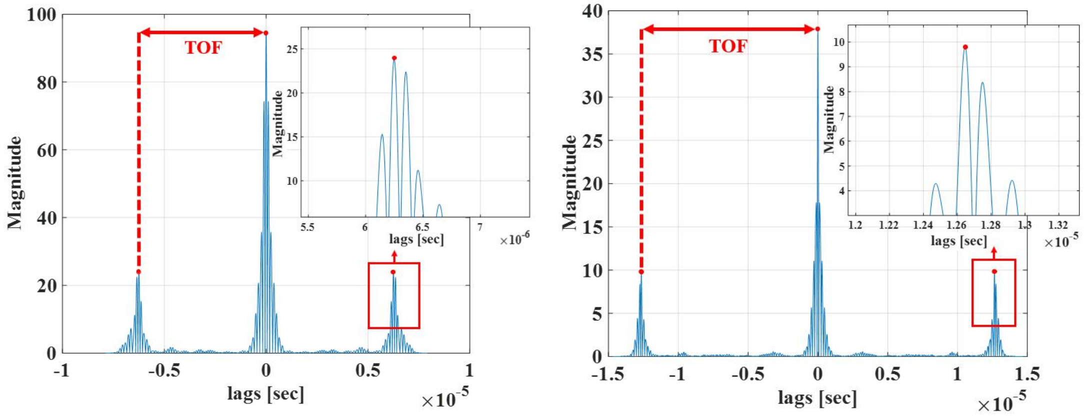
Fig. 1 Experimental setup for pulse-echo signals measurement



(a)

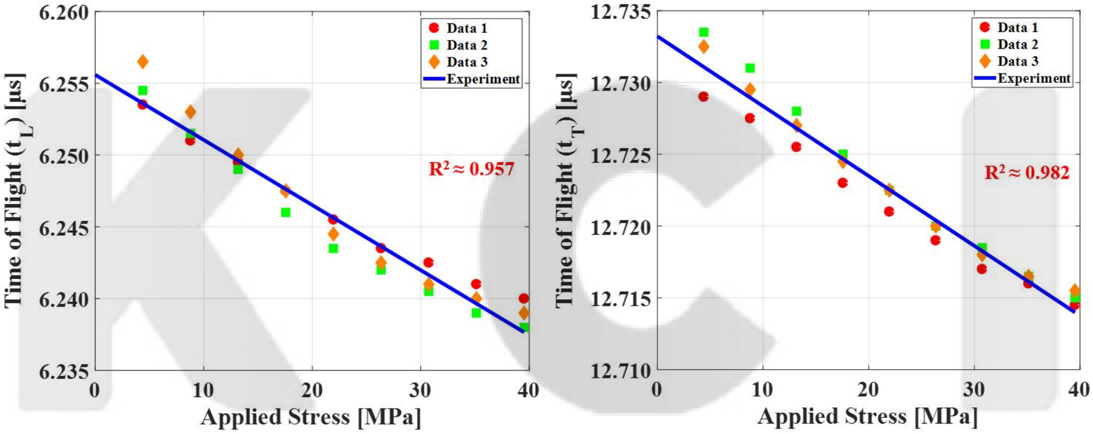
(b)

Fig. 2 Pulse-echo signals of (a) longitudinal wave and (b) transverse wave in 4 MPa



(a) (b)

Fig. 3 Auto-correlation results of received (a)longitudinal wave and (b)transverse wave



(a) (b)

Fig. 4 Time-of-flight differences in (a)longitudinal wave and (b)transverse wave

During the autocorrelation procedure, when the positive peak value was less than the negative one, negative peak was used to determine TOF. This process prevents phase inversion effect that might lead to the use of incorrect peak for TOF measurement. Besides, after the acoustoelastic effect on the heat-treated specimens was measured, a tensile test was conducted to obtain yield strength using an universal tester (Instron, MTS793).

4. Experimental results

4.1. TOF variation according to the compressive stress

Fig. 4(a) and 4(b) display the TOF variations of longitudinal and transverse waves in the 0 min specimen under increasing compressive stress. The R^2 value of the longitudinal wave was approximately 0.957 while that of the transverse wave was approximately 0.982. As the compressive stress increased, TOF changed linearly. When the compressive stress increased from approximately 4 MPa to 39 MPa, TOF of the longitudinal and transverse waves changed by approximately 15 ns and 16 ns, respectively. TOF changed in a similar way in both types of waves. The gradient of Fig. 4 indicates the TOF variation rate according to compressive stress, from which the stress-dependent coefficients were calculated by using Eqs. (5) and (6). The same condition and method were applied to obtain stress-dependent coefficients for the longitudinal and transverse waves in the other specimens.

4.2. Variations of stress-dependent coefficient and yield strength

Fig. 5 presents stress-strain curves obtained from the tensile test for Al6061-T6 heat-treated specimens. Yield strength was acquired by applying 0.2% offset to the curves.

Fig. 6 shows the variation of stress-dependent coefficients of longitudinal and transverse waves in accordance with heat treatment time. When the uniaxial compressive stress was applied, the velocity of ultrasonic waves increased, which resulted in the decrease of TOF. Thus the sign of the stress-dependent coefficient is negative. The pattern of variation shows two peaks in both for the longitudinal and transverse waves, a down peak and an upward peak. Note that the heat-treated time of those peaks were also similar for both of the longitudinal and transverse waves; the down peak was appeared at around 40 min and the upward peak was at 120 min. The width between two peak values was also similar for longitudinal and transverse waves; the variation widths were approximately 1.38 and 1.28 in longitudinal and transverse waves, respectively.

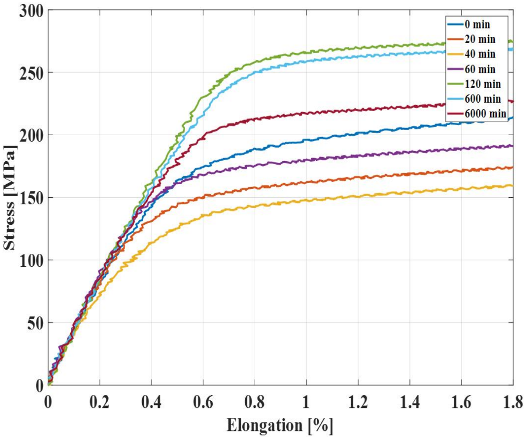


Fig. 5 Tensile test results of Al6061-T6 with respect to the heat treatment specimens

As shown in Fig. 6, the longitudinal wave showed larger absolute values of stress-dependent coefficients than the transverse wave. This seems to be because the deformation of the lattice structure in the loading direction, which is the same direction with the particle movements of longitudinal wave, was greater than that in the particle movements direction of transverse wave.

Fig. 7 illustrates the variation of yield strength according to heat treatment time. The yield strength was maximized at 120 min and

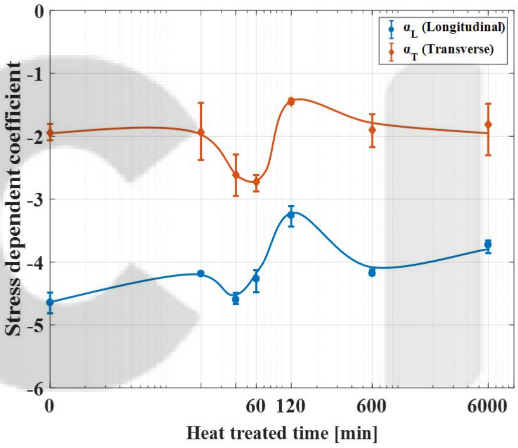


Fig. 6 stress-dependent coefficients in accordance with the heat-treated time variation

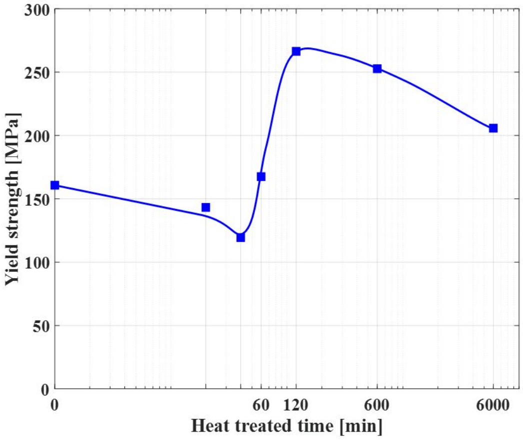


Fig. 7 Yield stength in accordance with the heat-treated time variation

minimized at 40 min. These results correspond to the above heat treatment times where the longitudinal and transverse stress-dependent coefficients showed peaks.

Such variations of yield strength according to the heat treatment for Al6061-T6 specimens are attributed to the coarsening of the precipitate [19]. Generally, from 0 to 120 min, which is the initial phase of heat treatment, the precipitate gradually coarsens and its density increases, which again increases the yield strength [19]. The number of precipitates reached its peak in 120 min and the yield strength was maximized [20]. The yield strength decreased from 20 min to 40 min when the heat-treated Al6061-T6 specimens were exposed to room temperature for a long time; thus, the internal structure of the material stabilized due to the natural aging effect [18,21]. Later, from 120 min to 6000 min, the coarsening of precipitates decreased their density, which reduced yield strength [22]. Consequently, the variation of yield strength according to the heat treatment time was attributed to the change in precipitates, which changed the acoustoelastic effect. Based on the above relationship, the heat treatment time where Al6061-T6 has maximum strength during the age-hardening process can be determined by the acoustoelastic effect.

5. Conclusions

This study focused on the acoustoelastic effect to evaluate the variation of the elasticity of Al6061-T6 due to micro-structural changes during heat treatment. For this purpose, seven Al6061- T6 specimens were heat-treated for the different time (0, 20, 40, 60, 120, 600, and 6000 min) at 220°C. TOF of each specimen was measured under increasing compressive stress. Stress-dependent coefficients were used, which are parameters expressing TOF variations of longitudinal and transverse waves in relation to strain. Based on the stress-dependent coefficients, the acoustoelastic effect of materials can be quantified. The acoustoelastic effects obtained were compared with yield strengths, which were measured in the tensile test. As a result of the experiments, the heat treatment time, in which the longitudinal and transverse modulus changes were largest, coincided with the heat treatment time where the change in the yield strength was largest. This relationship confirms that the acoustoelastic effect can be used to determine the heat treatment time where Al6061-T6 has the maximum strength during the age-hardening process. Thus, the correlation between acoustoelastic effect and yield strength seems to allow the use of acoustoelastic effect to evaluate the variation of yield strength of materials during heat treatment process.

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