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EVALUATION OF ACOUSTIC NONLINEARITY OF HEAT-TREATED SPECIMENS USING A PULSE-ECHO METHOD

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ABSTRACT

In this paper, an experimental study is conducted to accurately measure the absolute nonlinear parameter (β) of damaged solid samples in the pulse-echo setup and the results are presented. Artificially aged Al 6061 specimens are used as the damaged specimen. In order to improve the amplitude of the second harmonic wave received in the pulse-echo mode with the stress-free boundary to a measurable level, we develop a dual element transducer in which the transmitter and receiver are separated. For the measurement of absolute β, the transfer function is obtained from the calibration experiment of the receiving transducer, and the diffraction and attenuation corrections are taken into account. The results of β measurement are presented as a function of the aging time, and the change of β are found to well represent the change in the microstructure of the material due to the change of precipitate.

Keywords: Nonlinearity, pulse-echo, heat treatment

1. INTRODUCTION

The second harmonic generation (SHG) and the nonlinear ultrasonic evaluation techniques using it are known to be sensitive to the microstructural characteristics of materials. It has been attracting attention as a technique that can evaluate the degree of damage of materials such as deterioration, plastic deformation, and closed cracks which are difficult to evaluate by conventional linear ultrasonic techniques [1,2]. When a finite amplitude acoustic wave having a single frequency propagates in the nonlinear medium, harmonic waves corresponding to integer multiples of the incident fundamental wave frequency are generated and are called nonlinear acoustic waves. Particularly, material damage such as fatigue, deterioration, and creep changes the nonlinearity of the material by changing the microstructural characteristics such as anharmonicity, dislocation or precipitation of the crystal lattice, thereby affecting the generation of harmonics. SHG is most widely measured among these harmonics to assess the acoustic nonlinear parameter, β, which is a collective and quantitative measure of microstructural changes and damage state [3-6]. The nonlinear parameter of a material is defined by the amplitude ratio of the second harmonic to the square of the fundamental wave.

At present, the through-transmission (T-T) method using longitudinal waves is widely employed for the measurement of β, and it is not easy to apply due to problems such as the availability of both sides of the specimen and the alignment of transducers. In many cases, the application is very limited because it measures the nonlinear parameter in a relative manner, ignoring diffraction and attenuation effects. For this reason, it is necessary to develop a new method for the absolute measurement of β that eliminates the limitations of existing measurement and has general and practical applicability.

For practical applications, pulse-echo measurements are preferred, which allow single-side access of test components with stress-free surfaces. The problem of using a single-element probe in the pulse-echo setup with the stress-free boundary is that such a boundary destructively alters the SHG process. Therefore, the amplitude of the received second harmonic is too small to be measured and it is difficult to obtain reliable results of β. In the pure plane wave case, the second harmonic generated during forward propagation will diminish to zero on returning to its origin after reflection from the stress-free boundary [7,8]. For this reason, the pulse-echo method could not be used up to now to measure the nonlinear parameters of solid samples. In order to solve this problem, we have developed a dual-element transducer with separate transmitter and receiver, which was found to greatly improve the SHG in the pulse-echo setup. The β values were measured in the pulse-echo mode for undamaged aluminum specimens using the dual-element probe and its validity was verified by comparison with the T-T test results [9].

In this paper, the absolute nonlinear parameter β of artificially aged aluminum specimens is measured by the pulse-echo method using the dual-element probe, and the test results clearly demonstrate the correlation between the microstructural change of the material due to the generation, evolution and extinction of the precipitate by the annealing time.

2. MATERIALS AND METHODS

2.1 Material

The heat treatment changes the microstructure of the material and therefore changes the mechanical properties. As a representative example, the aluminum alloy is strengthened by aging precipitation of an intermetallic compound. Precipitation is known to affect the strength and hardness of the material depending on the quenching conditions and the heat treatment conditions (time, temperature) [10,11].

Al 6061 specimens of 4 cm thick were prepared for the heat treatment. The heat treatment process was similar to that of T6 heat treatment, which is mainly used for strength enhancement in Al 6061. As shown in Fig. 1, the solution treatment was first performed at 540℃ for 4 hours, followed by water-quenching treatment for 2 hours. After water-quenching, artificial aging treatment was carried out at 220℃ for different times. A total of 14 specimens were prepared with artificial aging. The details of the artificial aging specimens are shown in Table 1.

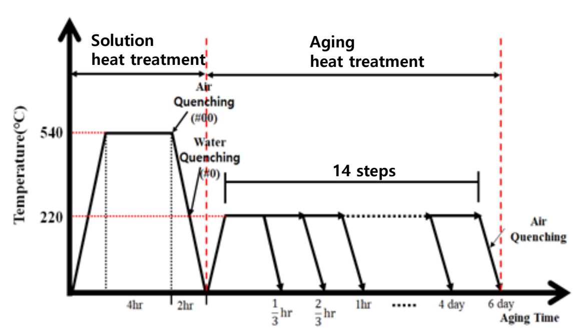

FIGURE 1: HEAT TREATMENT CYCLE

TABLE 1: DETAILS OF HEAT-TREATED AL6061 SAMPLES

No.	Time (min)	No.	Time (min)
1	20	8	360 (6 hr)
2	40	9	480 (8 hr)
3	60 (1 hr)	10	960 (16 hr)
4	90 (1.5 hr)	11	1440 (24 hr)
5	120 (2 hr)	12	2880 (48 hr)
6	180 (3 hr)	13	5760 (96 hr)
7	240 (4 hr)	14	8640 (144 hr)

2.2 Experimental

In the β measurement, the surface state (parallelness, surface roughness, etc.) of the specimen is known to affect the measured value [12]. Especially, the surface condition of the stress-free boundary is very important because the pulse-echo method receives and uses the reflected signal from the boundary. When the surface is rough, the amplitude of the received signal decreases due to the scattering of the ultrasonic waves at the surface, thus directly affecting the measurement results. For accurate measurements, it is necessary to match the surface condition of all the specimens as much as possible. In this study, the upper and lower surfaces were machined parallel to each other, and the surface roughness was kept as constant as possible by polishing with a metal abrasive.

In SHG measurements, the bandwidth of the receive probe should be wide enough to receive both fundamental and second harmonic components from the output signal. In addition, high voltage excitation is necessary to generate second harmonic, and it is not easy to select a piezoelectric material satisfying both high voltage and wide band characteristics. One possible solution to this problem is to use a separate transmitter and receiver. That is, a broadband receiver is located at the center and a ring-type transmitter is located outside the receiver to produce a finite amplitude sound beam in a solid specimen. The final configuration of the dual element transducer for pulse-echo SHG measurements consists of an outer transmitter and a central receiver, as shown in Fig. 2. The transmitter uses a $LiNbO_3$ piezoelectric element with the center frequency of 5 MHz, the inner diameter of 0.5 inches and the outer diameter of 1.1 inches. The central receiver is a broadband commercial probe of 10 MHz center frequency and the 0.25 inch diameter.

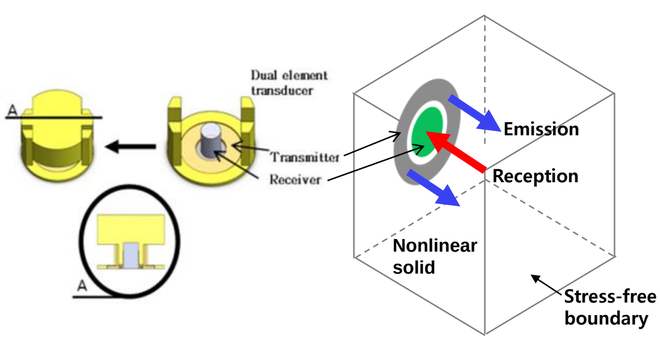

FIGURE 2: SCHEMATIC OF A DUAL ELEMENT TRANSDUCER

3. RESULTS AND DISCUSSION

Fig. 3 shows the measurement results of nonlinear parameters as a function of aging time. Fig. 3(a) is the result of the relative nonlinear parameter β' without corrections made for diffraction and attenuation, and the error bars shown here represent the standard deviation of the values of β' obtained from a series of input voltages. The maximum error over the mean value over the entire period does not exceed 2%. Fig. 3(b) is the result of the absolute nonlinear parameter β corrected for diffraction and attenuation, and is obtained from β' by multiplying the total correction value of about 6.4. In Fig. 3, the artificially aged Al 6061 specimen shows the maximum value of β at the aging time of 2 hours. As a result, the β value tends to increase and decrease slightly with the aging time at the beginning of artificial aging. After reaching the minimum value, it shows a rapid increase at 2 hours and then shows a rapid decrease and a gradual increase.

This tendency can be explained by the microstructural change of the material due to the generation, evolution, and extinction of the precipitate inside the specimen due to the artificial aging heat treatment time [13-15].

At the beginning of the heat treatment, a GP (Guinier-Preston) zone precipitation phase (Mg_2Si) is initially formed. The formation of this coherence precipitate causes a regular lattice strain between the aluminum matrix and the precipitate. The β value is increased by distorting the ultrasonic waves propagating inside the specimen. Therefore, β increases with increasing aging time and a weak peak of β occurs at 20 min.

When the heat treatment is continued, the GP zone precipitation phase, which has caused lattice distortion due to the lattice warping between the aluminum matrix and the precipitate, shows a matching relationship and is transformed into a stable precipitate and shows a relationship with the lattice mismatch. As a result, β is decreased from 20 minutes to 1 hour in heat treatment time.

On the other hand, the growth of the precipitates delays dislocation formation in the material, and as the heat treatment continues, the number of precipitates decreases and the size grows. Coarse precipitates contribute to the increase and migration of dislocations, so β increases sharply and has a maximum at 2 hours.

After 2 hours, the GP zone phase, which had been dissolved in the aluminum matrix, begins to be replaced by a finer β_p'' phase and β decreases relatively rapidly until 10 hours. As the aging continues, the density of β_p'' decreases and the β_p' phase begins to appear, resulting in a very gradual increase of β.

The change of β with the change of heat treatment time is due to the change of precipitate. The microstructural properties of the precipitates are known to have a direct effect on the mechanical properties such as yield strength and hardness of the material. From this correlation, the heat treatment time showing the maximum mechanical properties in the age hardening heat treatment of Al 6061 can be determined. For this purpose, measurement of mechanical properties and microstructure analysis of the specimens used in this study are underway.

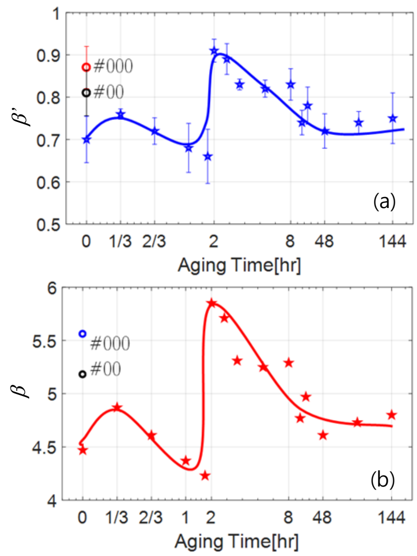

FIGURE 3: MEASUREMENT RESULTS (A) β' AND (B) β

4. CONCLUSION

In this paper, an experimental study was conducted to accurately measure the absolute nonlinear parameter (β) of a damaged solid specimen by the pulse-echo method, and the results are presented. An artificially aged Al 6061 specimen was used as the damaged specimen. In order to improve the amplitude of the second harmonics received in the pulse-echo mode with the stress free boundary, a dual element transducer separated from the transmitter and receiver was fabricated and used. The results of β measurement according to aging time are presented, and the change of β represents well the change of microstructure of material due to the change of precipitate. The properties of the precipitates are known to have a direct effect on the mechanical properties of the materials. From the correlation between β-microstructure-mechanical properties, it will be possible to determine the heat treatment time which shows the maximum mechanical properties.

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