Change in Ultrasonic Waveform during Tensile Deformation of Aluminum Alloy and Copper Alloy

Hiroshi KATO[*] and Hani SYAZWANA B.Z.[**].

Aluminum alloy A2024-T3 and copper alloy C2200-P plates were subjected to the tensile testing and the off-line and in-process ultrasonic measurements to obtain ultrasonic parameters, such as the relative peak intensity of Fourier spectrum of the bottom echo (RPI) and the average gradient of the transfer function (AGTF). The ultrasonic parameters (RPI and AGTF) obtained by the off-line and in-process measurements decreased with increasing plastic strain normalized by the maximum strain with the same rates for both alloys. The ultrasonic parameters measured with the water container showed the same tendency as those measured with the water bag, but decreased with the plastic strain with smaller fluctuation than those measured with the water bag.

Key words: Nondestructive testing, Ultrasonic measurement, Aluminum alloy, Copper alloy, Tensile deformation, Waveform analysis

1. Introduction

For maintenance of machineries, nondestructive evaluation of damage in components is very important, and lots of studies have been carried out. There are several kinds of nondestructive methods to evaluate damages in the material, such as the X-ray diffraction analysis, the electro-magnetic measurement, ultrasonic measurement, and so on. For example, the creep damage was evaluated with the half-value width of the X-ray diffraction pattern [1], the velocity [2, 3] and the attenuation [4) – 10] of the ultrasonic wave, and the leakage surface acoustic wave [11]. The fatigue damage was also evaluated with the half-value width of the X-ray diffraction pattern [12, 13], Barkhausen noise [14) – 16] and the electric potential difference [17], and the velocity and attenuation of the ultrasonic wave [18) – 21].

In the ultrasonic damage evaluation, Fukuhara et al. [3] measured the Fourier spectrum of the ultrasonic wave to deduce the energy decay, and obtained a relation between the energy decay and the creep damage rate. Authors [22] also carried out the ultrasonic measurement during tensile testing of the aluminum alloy A2024-T3 and showed that the peak intensity of the Fourier spectrum (PI) and the average gradient of the transfer function (AGTF) decreased with increasing plastic strain. Also, the authors carried out the ultrasonic measurement during the fatigue testing [23) – 25], and showed that the ultrasonic parameters, such as PI and AGTF, monotonically increased in the fatigue process. In these studies [22) – 25], the ultrasonic measurement was carried out by using a water bag made of a Teflon membrane with a thickness of about 70 μm, in which case the Teflon membrane may influence the propagation of the ultrasonic wave. Hence the authors [26] examined the influence of the water bag made of different materials on the waveform of the echo reflected from the specimen surface, and found that the Teflon membrane did not affect the waveform and gave almost the same waveform as that obtained by the immersion method. However, the ultrasonic measurement was not conducted with the immersion method during mechanical testing to compare the waveform with those measured with the water bag. Therefore, in the present work, the ultrasonic measurement was carried out during tensile testing of aluminum alloy A2024-T3 with a water container to obtain the ultrasonic parameters to compare with the previous results [22] measured with the water bag.

In the previous works [22)-25], the authors carried out the ultrasonic measurement with the aluminum alloy plate A2024-T3 in plastic deformation and fatigue process, but it is interesting to clarify the change in ultrasonic parameters during mechanical testing of other alloys. Therefore, in the present work, the ultrasonic measurement was also carried out with the copper alloy C2200P-O composed of the α phase of the FCC crystal structure, which is the same crystal structure as the aluminum alloy, and the ultrasonic parameters were compared with those of the aluminum alloy.

2. Experimental Procedure

2.1 Preparation of specimen

In the present work, tensile specimens, as shown in Fig. 1, were prepared from aluminum alloy plates (A2024-T3, the average composition of Al-4 mass% Cu – 1.5 mass% Mg – 0.6 mass% Mn) of 4 mm in thickness and copper alloy plates (C2200P-O, the average composition of Cu – 10 mass% Zn) of 4 mm in thickness. The specimen was made so that the tensile direction was parallel to the rolling direction of the plate. Average tensile properties of these alloys are tabulated in Table 1. The T3 treatment of the aluminum alloy plate consisted of solution-treatment, cold rolling and aging at room temperature, and the O treatment of copper plate consisted of cold rolling and annealing for recrystalization.

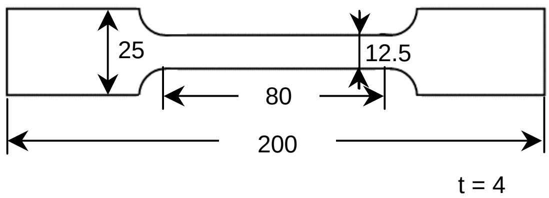

Fig. 1 Shape and dimensions of tensile specimen.

Table 1 Mechanical properties of aluminum alloy and copper alloy.

	Yield strength (MPa)	Tensile strength (MPa)	Elongation to fracture (%)
A2024	328	465	21
C2200	325	328	55

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* Department of Mechanical Engineering, Saitama University (255 Sakura, Saitama 338-8570, Japan)

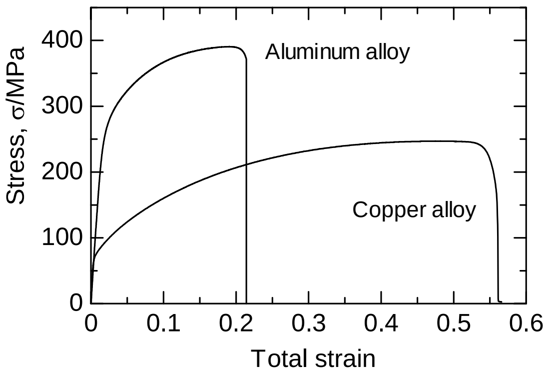

Fig. 2 Comparison of stress-strain curves for aluminum alloy and copper alloy.

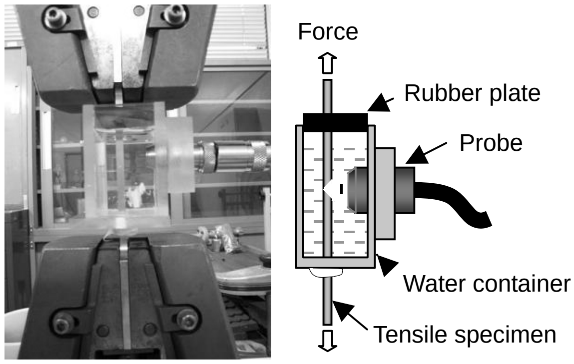

Fig. 3 Setup for in-process measurement with water container.

2.2 Tensile testing

The tensile testing was carried out with a crosshead speed of 0.5 mm/min to fracture to obtain the load-time diagram. Then the nominal stress was calculated as the load divided by the initial cross section, and the nominal strain (the total strain) was evaluated from the elapsed time and the crosshead speed to obtain the stress-strain diagram, as shown in Fig. 2.

In the tensile testing, at a required interval of time, the tensile tester was stopped and then the specimen was taken out from the tester for off-line ultrasonic measurement. Finally eight and ten specimens deformed with different amounts of plastic strains were obtained for aluminum alloy and copper alloy specimens, respectively.

Also, during tensile testing, the in-process ultrasonic measurement was carried out.

2.3 Ultrasonic measurement

In the tensile testing, two types of ultrasonic measurements, such as the off-line and in-process ultrasonic measurements, were carried out.

(1) Off-line ultrasonic measurement:

At a required time, the specimen was taken out from the tensile tester, and then subjected to the ultrasonic measurement. Hereafter, this ultrasonic measurement will be referred to as the off-line ultrasonic measurement. In the measurement, by using a focal-type probe generating a longitudinal wave of 20 MHz in frequency with a focal distance of 25.4 mm in water, the ultrasonic wave was irradiated normal to the specimen surface to obtain an echo reflected from the specimen bottom (the bottom echo). The measurement was carried out at 21 positions along the specimen axis with an interval of 3 mm. To maximize the intensity of the bottom echo, the ultrasonic wave was focused on the specimen bottom (the over side) with a water path (a distance between the probe and the specimen surface) of about 8.0 mm and 13.4 mm for aluminum alloy and copper alloy specimens, respectively.

(2) In-process ultrasonic measurement:

During tensile testing, the ultrasonic measurement was carried out repeatedly without stopping the tensile tester. As shown in Fig. 3, a small water container was fixed to the specimen, and the probe was set normal to the specimen surface. In the measurement, the focal-type probe generating a longitudinal wave of 20 MHz in frequency was used, and the ultrasonic wave was focused on the opposite side. The ultrasonic measurement was repeated every few minutes until the specimen was broken. Hereafter referred to as the in-process measurement.

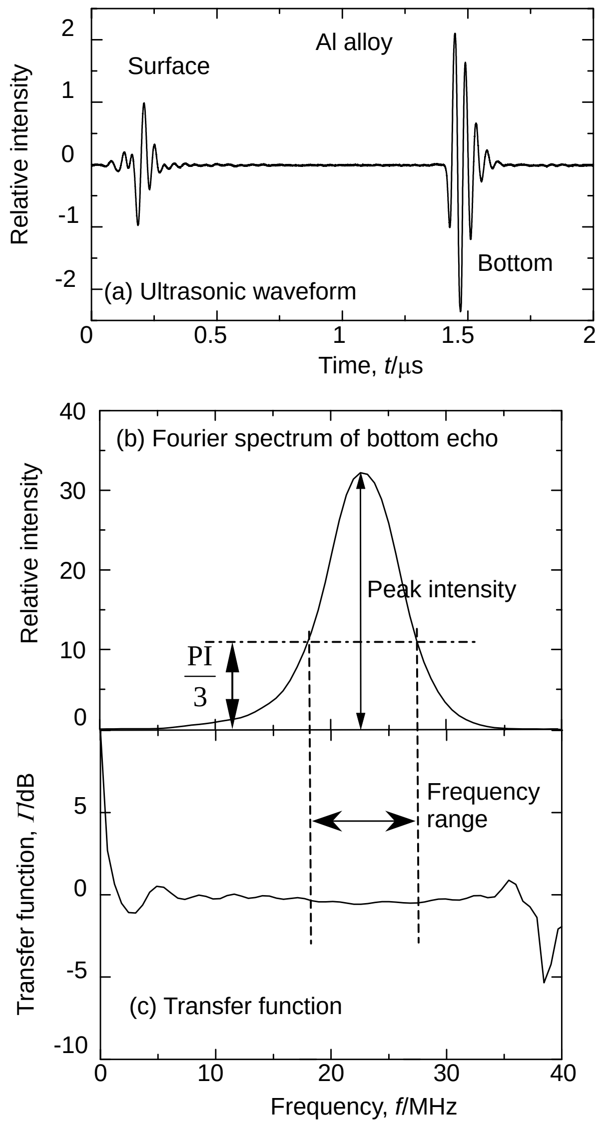

Fig. 4 Typical waveforms and spectrum analysis of aluminum alloy.

After ultrasonic measurements, the waveform analysis was carried out as follows to obtain ultrasonic parameters. The bottom echo obtained was subjected to the FFT analysis to obtain the Fourier spectrum. As examples, typical surface and

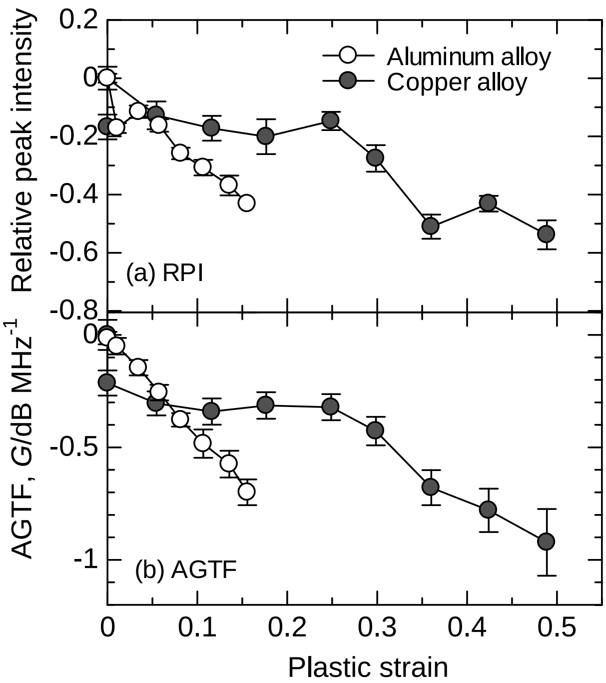

Fig. 5 Change in ultrasonic parameters with the plastic strain obtained by off-line measurement.

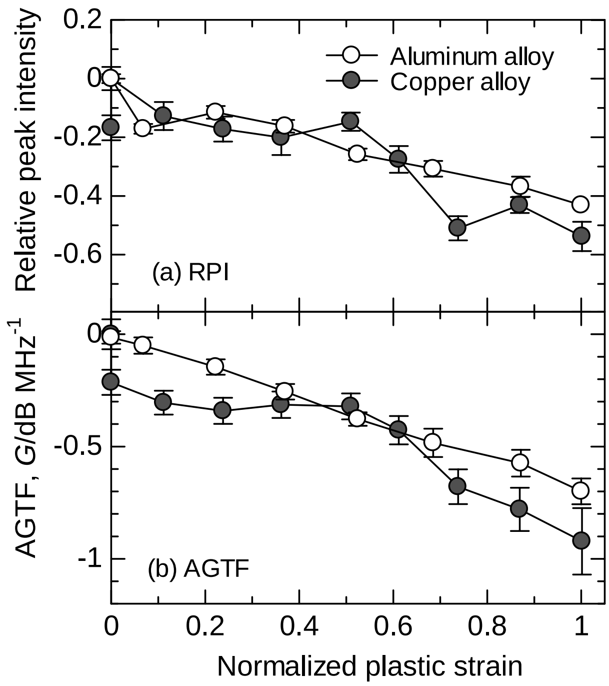

Fig. 6 Change in ultrasonic parameters with normalized plastic strain obtained by off-line measurement.

bottom echoes of the aluminum alloy and Fourier spectrum of the bottom echo are shown in Figs. 4 (a) and (b), respectively. From the Fourier spectrum of the bottom echo, the maximum value was obtained and normalized by the initial value. Hereafter referred to as the normalized peak intensity (RPI). Then the following transfer function $H(\omega)$ was obtained to examine the change in the waveform of the bottom echo due to plastic deformation.

$$H(\omega) = 20\log_{10}\left(\frac{F_{\mathrm{i}}(\omega)}{F_{\mathrm{o}}(\omega)}\right), \quad (1)$$

where $F_{\mathrm{o}}(\omega)$ and $F_{\mathrm{i}}(\omega)$ are Fourier spectra of the bottom echo measured before and during tensile testing, respectively. The typical transfer function of the aluminum alloy is shown in Fig. 4 (c). In the previous work [22], the gradient of the transfer function decreased with increasing plastic strain in a frequency range including the generating frequency. Therefore, as a measure of the degradation of the material, an average gradient of the transfer function (AGTF) was obtained in a frequency range including 20 MHz. As shown in the figure, a frequency range to obtain the average gradient was 18 MHz ~ 27 MHz for aluminum alloy (the range with the echo intensity of 1/4 of the peak intensity or higher) and 13 MHz ~ 23 MHz for copper alloy (the range with the echo intensity of 1/3 of the peak intensity or higher).

3. Results and Discussion

3.1 Change in ultrasonic parameters obtained by off-line measurement

In the tensile testing, the off-line measurement was carried out to obtain the ultrasonic parameters, as shown in Fig. 5. In the figures, error bars show the standard deviation of data measured at 21 points. RPI and AGTF decreased with increasing plastic strain for both alloys, but the ultrasonic parameters of the aluminum alloy decreased more rapidly than those of the copper alloy. Then the plastic strain of each specimen was normalized by the maximum strain of each specimen in the measurement. As shown in Fig. 6, the ultrasonic parameters of the aluminum alloy showed the same tendency as those of the copper alloy.

3.2 Change in ultrasonic parameters obtained by in-process ultrasonic measurement

The in-process ultrasonic measurement was carried out during tensile testing, and RPI and AGTF were obtained from the Fourier spectrum of the bottom echo, as shown in Fig. 7. In the figure, results of three specimens are included. And, for comparison, the parameters measured with the water bag [22] are also shown as solid circles. RPI measured with the water container decreased with the same rate as that measured with the water bag, but the fluctuation was smaller than that measured with the water bag. This is due to the following reason. In the measurement with the water container, the specimen directly contacted with water and the contact condition did not change during testing to result in small fluctuation of the measured waveform. To the contrary, in the measurement with the water bag, the water bag did not follow the deformation of the specimen during tensile testing to cause irregular slip. Also AGTF measured with the water bag largely decreased compared to that measured with the water container, and especially at larger plastic strains more than 0.1, the decrease in AGTF measured with the water bag is prominent. From these results, it was concluded that in the measurement with the water bag, the stick-slip occurred between the water bag and the specimen at a plastic strain of about 0.08 and the contact condition between the water bag and the specimen was largely fluctuated to result in large decrease of AGTF.

RPI and AGTF obtained with the in-process ultrasonic measurement of copper alloy are compared with those of aluminum alloy, as shown in Fig. 8. In the figure, the results of aluminum alloy showing the intermediate change are represented as solid rectangles. When the plastic strain was normalized by the maximum strain of each specimen, the results of both alloys showed a good agreement, as shown in Fig. 9. This agreement of the ultrasonic parameters measured with the

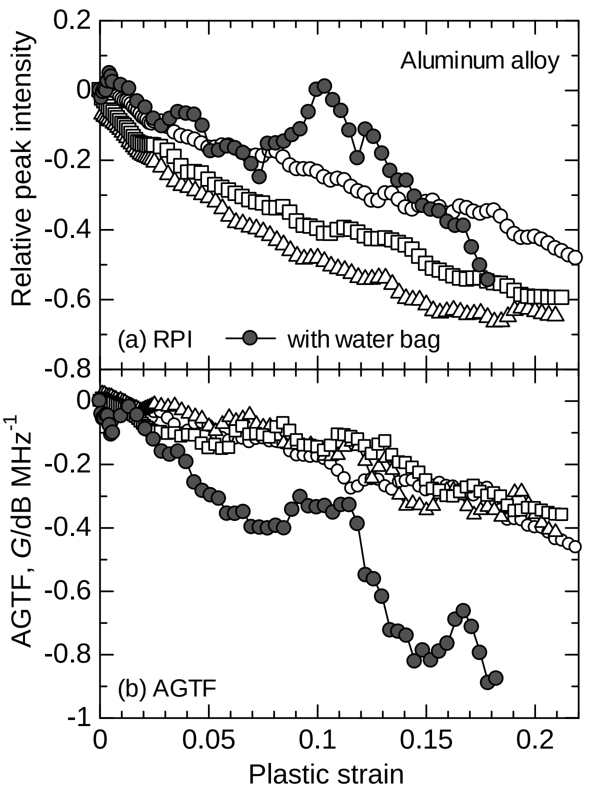

Fig. 7 Typical change in ultrasonic parameters in aluminum alloy with plastic strain.

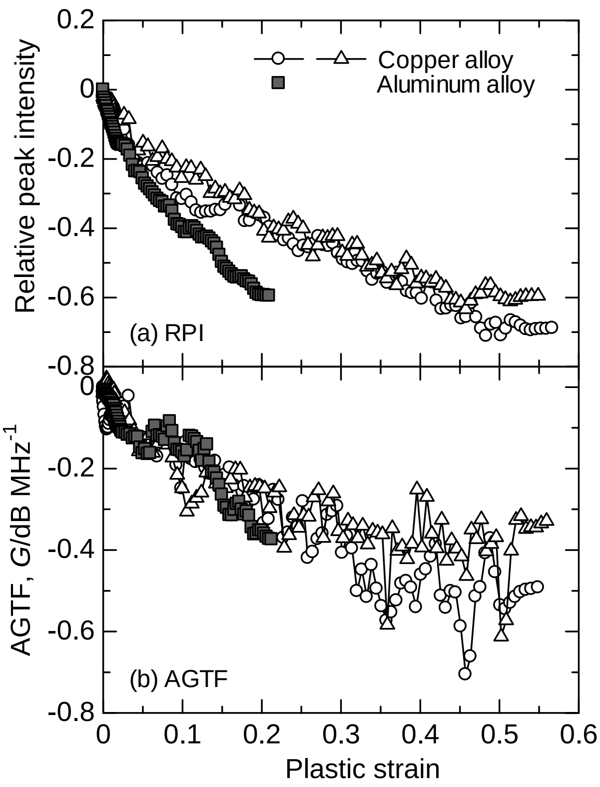

Fig. 8 Typical change in ultrasonic parameters in copper alloy with plastic strain.

water container and the water bag was coincident with results of the off-line measurement.

4. Conclusions

The aluminum alloy A2024-T3 and the copper alloy C2200-P plates were subjected to the tensile testing and the off-line and in-process ultrasonic measurements to obtain the change in the ultrasonic parameters with plastic strain, and the following results were obtained.

(1) The relative peak intensity (RPI) and the average gradient of the transfer function (AGTF) obtained by the off-line ultrasonic measurement decreased with increasing plastic strain. And, by normalizing the plastic strain by the maximum strain, RPI and AGTF decreased with the same rate for both alloys.

(2) RPI and AGTF obtained by the in-process ultrasonic measurement decreased with increasing normalized plastic strain with the same rate for both alloys. And the results of RPI and AGTF measured with the water container showed the same tendency as the results measured with the water bag. At larger deformation, however, the parameters measured with the water container showed smaller fluctuation than those measured with the water bag, which showed stick-slip between the water bag and the specimen.

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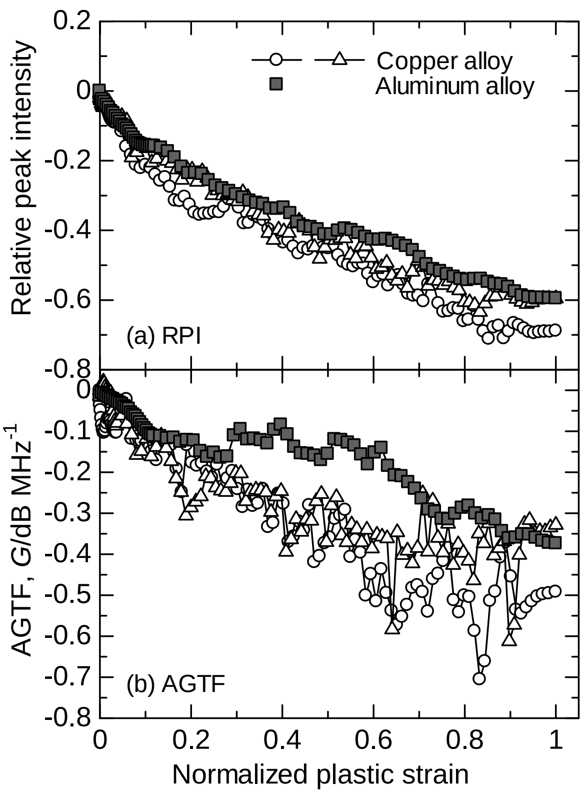

Fig. 9 Comparison of change in ultrasonic parameters with normalized plastic strain in copper alloy and aluminum alloy.

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