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Comparison of Linear and Nonlinear Ultrasonic Parameters in Characterizing Grain Size and Mechanical Properties of 304L Stainless Steel

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Abstract: Ultrasonic nondestructive techniques can be used to characterize grain size and to evaluate mechanical properties of metals more practically than conventional destructive optical metallography and tensile tests. Typical ultrasonic parameters that can be correlated with material properties include ultrasonic velocity, ultrasonic attenuation coefficient, and nonlinear ultrasonic parameters. In this work, the abilities of these ultrasonic parameters to characterize the grain size and the mechanical properties of 304L stainless steel were evaluated and compared. Heat-treated specimens with different grain sizes were prepared and tested, where grain size ranged from approximately 40 to 300 μm. The measurements of ultrasonic velocity and ultrasonic attenuation coefficient were based on a pulse-echo mode, and the nonlinear ultrasonic parameter was measured based on a through-transmission mode. Grain size, elastic modulus, yield strength, and hardness were measured using conventional destructive methods, and their results were correlated with the results of ultrasonic measurements. The experimental results showed that all the measured ultrasonic parameters correlated well with the average grain size and the mechanical properties of the specimens. The nonlinear ultrasonic parameter provided better sensitivity than the ultrasonic velocity and the ultrasonic attenuation coefficient, which suggests that the nonlinear ultrasonic measurement would be more effective in characterizing grain size and mechanical properties than linear ultrasonic measurements.

Keywords: grain size; ultrasonic velocity; ultrasonic attenuation coefficient; nonlinear ultrasonic parameter; 304L stainless steel

1. Introduction

There have been increasing demands for quantitative characterization of material microstructures that correlate with mechanical properties of metals in many industrial fields, such as power plant, manufacturing, infrastructure, and so on [1–3]. Grain size is one of the fundamental microstructural quantities of interest, and it correlates with mechanical properties such as elasticity, plasticity, creep, fatigue, and yield strength [4–6]. Characterizing the grain size can be used to monitor the changes in mechanical properties during the service of structures. Furthermore, the characterization also has potential for evaluating material degradation due to thermal aging or damage and for predicting the remaining service life of structures [7–9].

Ultrasonic nondestructive techniques have the ability to characterize grain size and evaluate mechanical properties [2,10], which is emerging as an alternative to conventional destructive

optical metallography and tensile tests that are time consuming and require cutting specimens from structures [5,6]. Ultrasonic parameters that can be effectively used to characterize material microstructures include ultrasonic velocity, ultrasonic attenuation coefficient, and nonlinear ultrasonic parameters [11–38]. The ultrasonic velocity is directly related to mechanical properties, including the elastic modulus and the material density, which are influenced by microstructures such as grains, precipitates, and phase transformations [11–15]. The attenuation of ultrasonic waves depends on microstructural features such as grains, dislocations, inclusions, and pores based on absorption, diffraction, and scattering of ultrasonic waves by the microstructures [16–21]. In most cases, scattering by grains is the dominant attenuation mechanism. The nonlinear ultrasonic parameter is related to the amplitude of a monochromatic fundamental wave propagating through a medium and the amplitude of higher harmonics due to waveform distortion caused by interaction between the fundamental wave and the microstructures. This nonlinear parameter is also known to be sensitive to microstructural features. The use of nonlinear ultrasonics was recently intensively studied for characterizing the microstructure and the material degradation [22–38].

Correlations between grain size and linear ultrasonic parameters, including ultrasonic velocity and attenuation coefficient, have been actively studied [12–15,17–21]. Ultrasonic velocities and scattering coefficients of plane longitudinal and shear waves in polycrystals as a function of grain size and wavenumber were theoretically explained by Hirsekorn [12]. Attenuation coefficients and scattering regimes, including Rayleigh, stochastic, and diffusion scattering, according to the ratio of ultrasonic wavelength and grain size are well described in the literature [17,18]. Experimental studies on ultrasonic velocity and attenuation coefficient in various steel grades showed that these linear ultrasonic parameters were highly correlated with the average grain size [6,13,14]. The increase in average grain size caused a decrease in ultrasonic velocity and an increase in attenuation coefficient. Botvina et al. [18] reanalyzed the published data on the correlation between the ultrasonic attenuation coefficient and the grain size in a number of metals and alloys involving a range of average grain sizes from 12.5 to 300 μm and derived one master curve graph showing the correlation. Non-contact techniques such as electromagnetic acoustic transducers [19] and laser ultrasonics [20] were also studied to evaluate grain size. It has been reported that the ultrasonic velocity and the attenuation coefficient are also related to the mechanical properties affected by grain size, including hardness [5,10,21], yield strength [5,15], and tensile strength [10]. The increase in average grain size resulted in a decrease in mechanical properties (hardness and strength), which caused a decrease in ultrasonic velocity and an increase in attenuation coefficient.

Reports on the correlation between grain size and nonlinear ultrasonic parameter are rare in the literature [7,22]. This is because most previous nonlinear ultrasound studies have focused mainly on evaluating material degradation, such as fatigue damage [23–25], creep damage [26,27], thermal aging [28–30], and plastic deformation [31,32], in which dominant microstructural characteristics that affect the nonlinear ultrasonic parameter are dislocation densities [33,34], precipitates [35–37], and phase transformations [38]. Several previous studies showed that there was a good correlation between the grain size and the nonlinear ultrasonic parameter [7,22]. The increase in average grain size caused a decrease in the nonlinear ultrasonic parameter and the hardness.

The previously mentioned studies demonstrated that both linear and nonlinear ultrasonic parameters have a good correlation with grain size and can be effectively used to evaluate grain size and mechanical properties. After this fundamental verification, the question arises as to which ultrasonic parameter is most sensitive to changes in grain size and mechanical properties. However, it is still difficult to determine the most sensitive parameter simply by comparing the results of previous studies because experimental conditions and materials are different in each previous study. Ultrasonic parameters measured under the same experimental conditions must be compared, and it is also necessary to analyze and compare the sensitivity to both grain size and mechanical properties, including hardness and strength. A comparison of the measurement deviations in each ultrasonic parameter should also be conducted.

This work evaluated and compared the capabilities of linear and nonlinear ultrasonic parameters in characterizing the grain size and the mechanical properties of 304L stainless steel. The next section describes the experimental procedures, including the preparation of specimens with different grain sizes, linear and nonlinear ultrasonic measurements, and hardness and tensile tests to measure mechanical properties. The experimental results for the sensitivity of each ultrasonic parameter to grain size and mechanical properties and the measurement deviations in each parameter are presented and summarized in Section 3, and these are followed by the conclusions in Section 4.

2. Experimental Procedures

2.1. Specimen Preparation

The material used in this work was 304L stainless steel, which is widely used in various industrial applications. Six specimens with dimensions of 150 mm × 150 mm × 20 mm were cut from a stainless steel plate. All the specimens were given common heat-treatment at 1040 °C for 50 min with a holding time of 2 min/mm followed by water quenching to obtain a uniform structure with the same substructural features. Then, the grain size of metals could generally be increased by increasing the heat-treatment temperature or by increasing the heat treatment holding time. In this work, the holding time was controlled to obtain different grain sizes, and the heat-treatment temperature was fixed. One of the specimens was used as an intact specimen, and the other five specimens were heat-treated at a constant temperature of 1250 °C for different heat-treatment holding times of 1, 5, 10, 25, and 34 h followed by water quenching.

Three different shapes of specimens were cut from each heat-treated specimen for different measurements. For metallographic examination, small specimens were cut, mounted, and polished according to the standard procedure. Subsequently, they were etched with aqua regia for a few minutes. The average grain sizes of specimens were determined using the intercept procedure on the basis of the American Society for Testing and Materials (ASTM) E112-13 [39]. Specimens for ultrasonic measurements were cut and carefully polished on the top and the bottom surfaces with emery papers. Their final dimensions were 135 mm × 30 mm × 17.5 mm. Tensile test specimens with a 36 mm gauge length, 6 mm wide, and 3 mm thick (in accordance with ASTM E8M standard [40]) were taken by using electric discharge wire cutting. Five samples were taken from each heat-treated specimen for repeated tensile tests.

2.2. Ultrasonic Velocity and Attenuation Measurements

Typical linear ultrasonic parameters that are widely used for ultrasonic nondestructive evaluation include ultrasonic velocity and attenuation coefficient. The ultrasonic velocity is directly related to mechanical properties, including elastic modulus and material density [11]. Ultrasonic attenuation refers to the energy loss of ultrasonic waves as they propagate through the material. Attenuation is attributed to various mechanisms, including diffraction, absorption, and scattering of ultrasonic waves [2,8]. For polycrystalline materials, the scattering by grains is known to be dominant in ultrasonic attenuation compared to other mechanisms [8,18].

The ultrasonic pulse-echo method is a popular nondestructive technique for measuring ultrasonic velocity and attenuation coefficient [11,16]. In this method, two consecutive back-wall echoes measured on a specimen of known thickness are used to determine both linear ultrasonic parameters. The ultrasonic velocity can be determined by measuring the time-of-flight (TOF) between two consecutive back-wall echoes from the following relationship:

$$v = \frac{2d}{t},$$
(1)

where v, d, and t are the ultrasonic velocity, the specimen thickness, and the TOF between two consecutive back-wall echoes, respectively. The attenuation coefficient can be calculated from the amplitude ratio of two consecutive back-wall echoes as follows [2,16]:

$$\alpha = \frac{20 \log(S_1/S_2)}{2d}, \tag{2}$$

where α is the attenuation coefficient, and S_1 and S_2 are the amplitudes of the two-consecutive back-wall echoes, respectively.

A schematic of the experimental setup for linear ultrasonic measurements based on a pulse-echo mode is shown in Figure 1. A 2.25 MHz piezoelectric longitudinal transducer (V106-RM, Panametrics-NDT, Waltham, MA, USA) was used with a pulser/receiver (5072PR, Panametrics-NDT, Waltham, MA, USA) that sends a negative electric pulse to the transducer and receives ultrasonic echo signals detected by the transducer. The contact pressure between the transducer and the test specimen was kept constant at 300 kPa using a pneumatic control system to minimize variations in the contact conditions during the repeated measurements. The electric signal acquired from the pulser/receiver was averaged 300 times with an oscilloscope (HDO4034A, Teledyne LeCroy, Chestnut Ridge, NY, USA) that digitizes the analog signal with a time resolution of 0.1 ns. Then, the averaged digital signal was transferred to a computer. The first and the second back-wall echoes were analyzed to measure the ultrasonic velocity and the attenuation coefficient. An auto-correlation function was used for precise measurements of TOF between the two back-wall echoes. Then, the ultrasonic velocity was calculated using Equation (1). From the amplitude ratio of the two back-wall echoes, the attenuation coefficient was calculated using Equation (2). Repeated measurements were conducted ten times for each specimen.
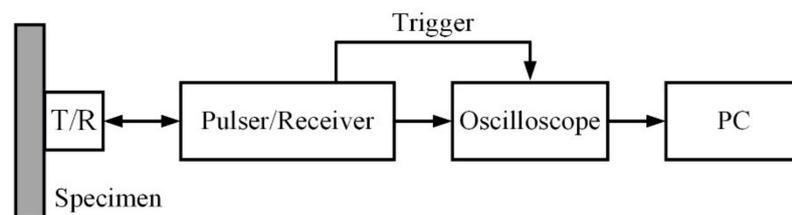
Figure 1. Schematic of the experimental setup for linear ultrasonic measurements based on a pulse-echo mode.

2.3. Nonlinear Ultrasonic Measurements

The nonlinear ultrasonic technique using second-order harmonic generation based on the nonlinear elastic response of a material to an ultrasonic wave propagating through the material can effectively evaluate microstructural features of metals. The theory and the principles of this technique are well described in the literature [9]. In this technique, the nonlinear ultrasonic parameter is used as a quantitative indicator corresponding to microstructural features, and it is defined as follows:

$$\beta = \frac{8A_2}{k^2 x A_1^2}, \tag{3}$$

where β is the absolute nonlinear ultrasonic parameter, A_1 and A_2 are the displacement amplitudes of the fundamental and the second-order harmonic waves after they have propagated through the material, respectively, k is the wavenumber, and x is the wave propagation distance.

The measurement of the absolute nonlinear ultrasonic parameter requires not only the information on wavenumber and wave propagation distance but also the measurement of absolute displacement. Therefore, many researchers have alternatively used the relative nonlinear ultrasonic parameter, which is relatively simple to measure. When the wavenumber and the propagation distance are kept constant

in a series of measurements, the relative nonlinear ultrasonic parameter β' is defined by the measured electric signal amplitudes as follows:

$$\beta' = \frac{A_2'}{(A_1')^2},\tag{4}$$

where A_1' and A_2' are the electric signal amplitudes of the fundamental and the second-order harmonic waves measured by an ultrasonic sensor, respectively.

In general, the measurement of the relative nonlinear ultrasonic parameter is conducted on a series of specimens of the same thickness with varying levels of material degradation or microstructures while maintaining the same experimental conditions. Then, the variation in the relative nonlinear parameter is correlated with the microstructural features.

A schematic of the experimental setup for nonlinear ultrasonic measurements is shown in Figure 2, which is based on a through-transmission mode. A high-power electric signal generator (RAM-5000-SNAP, Ritec, Warwick, MA, USA) was used to provide the high power electric sinusoidal signal of 11 cycles with a 2.5 MHz center frequency. The output electric signal from the generator passed through a high power 50 Ω termination and a 3 MHz low pass filter to suppress the initial harmonics generated in the electric signal generator and then went to the transmitter. Narrowband piezoelectric transducers with center frequencies of 2.25 and 5 MHz (V106-RM and V109-RM, Panametrics-NDT, Waltham, MA, USA) were used as a transmitter and a receiver, respectively. A specially designed fixture was used to maintain the transmitter and the receiver alignment on the same centerline axis. The contact pressure between the transducers and the test specimen was kept constant at 300 kPa using a pneumatic control system. The signal acquired from the receiver was averaged 300 times with an oscilloscope and then transferred to a computer. A fast Fourier transform (FFT) was then performed to analyze the amplitudes of the fundamental wave (A_1') and the second-order harmonic wave (A_2') in the received signal after applying a Hanning window. Then, $(A_1')^2$ and A_2' obtained at different input power levels were plotted and fitted linearly. Thereafter, the relative nonlinear ultrasonic parameter β' was calculated as the slope of the fitted line, as in Equation (4). Repeated measurements were conducted six times for each specimen.
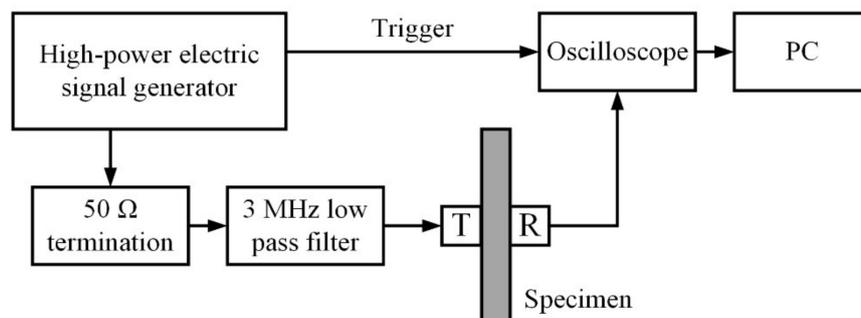
Figure 2. Schematic of the experimental setup for nonlinear ultrasonic measurements based on a through-transmission mode.

2.4. Mechanical Property Measurements

The mechanical properties analyzed in this work included hardness, elastic modulus, and yield strength. The hardness measurements were conducted on the specimens used for ultrasonic measurements. The hardness was measured using a Vickers hardness tester (HMV-2T, Shimadzu, Kyoto, Japan), in accordance with the ASTM E384 standard [41], at a test load of 9.8 N and a dwell time of 10 s at room temperature. For each specimen, the measurement was repeated over ten different locations. The elastic modulus and the yield strength were obtained from tensile tests. The tensile tests were performed using a universal testing machine (MTS793, MTS, Eden Prairie, MN, USA) at a crosshead speed of 2 mm/min at room temperature. For each heat-treated type, the tensile test was repeated five times.

3. Experimental Results and Discussion

3.1. Grain Size

The standard intercept count method of ASTM E112 was applied to the photographs, as shown in Figure 3, which were obtained with an optical microscope to measure average grain size of heat-treated specimens. The measured values for ASTM grain size number, *G*, and average grain size are given in Table 1. The average grain size of the intact specimen was 41 µm. The heat-treatment at 1250 °C caused grain coarsening, and the average grain size increased to 294 µm when the heat-treatment holding time increased to 34 h. There was no meaningful relationship between holding time and grain size, but such a relationship is beyond the scope of this study. In this study, the average grain size measured on each heat-treated specimen, given in Table 1, was correlated with ultrasonic parameters.
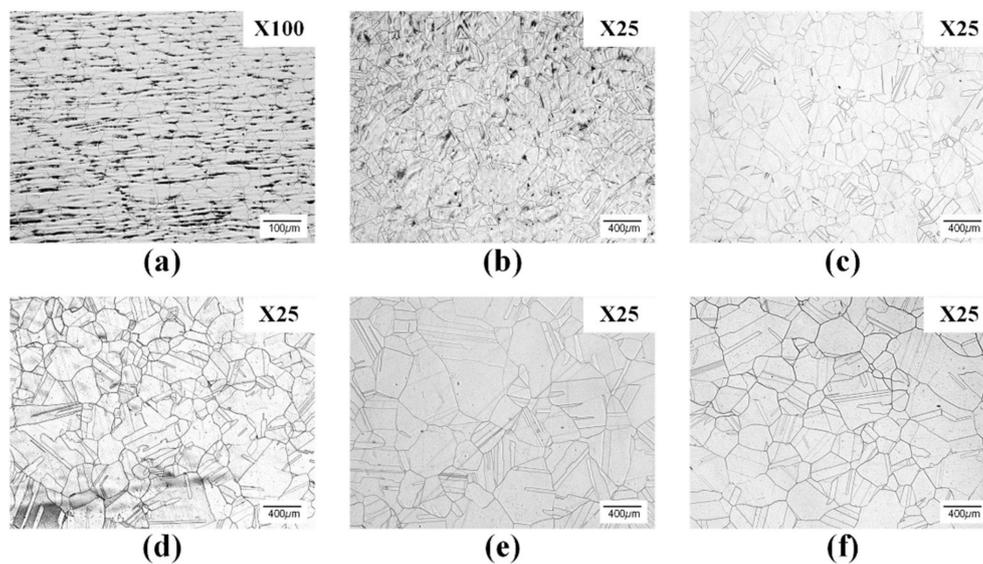

Figure 3. Optical photographs of specimens heat-treated at a constant temperature of 1250 °C for different holding times: (**a**) no heat treatment; (**b**) 1 h; (**c**) 5 h; (**d**) 10 h; (**e**) 25 h; and (**f**) 34 h.

Table 1. The American Society for Testing and Materials (ASTM) grain size number *G* and average grain size of specimens heat-treated with different holding times.

| Holding Time (h)	ASTM Grain Size No. G	Average Grain Size (µm)
0	6.3	41
1	1.8	192
5	1.7	202
10	1.3	232
25	0.7	286
34	0.6	294

3.2. Ultrasonic Velocity vs. Grain Size

A typical ultrasonic echo signal is shown in Figure 4a. The first and the second back-wall echoes are clearly observed and separated in the time domain. The auto-correlation function was used to accurately calculate the TOF between the two echoes. Figure 4b shows the auto-correlation results of the echo signal shown in Figure 4a. The TOF was determined as the time lag when the magnitude reached a maximum, as shown in the figure.
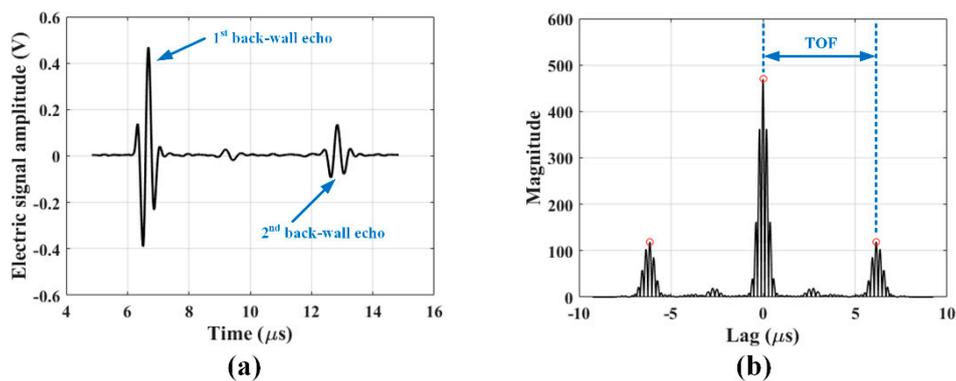
Figure 4. (**a**) Typical ultrasonic echo signal; and (**b**) auto-correlation results of the signal shown in (**a**).

The measured ultrasonic velocity as a function of grain size is shown in Figure 5, where each symbol is the average of ten measurements, and error bars represent the data range. The average ultrasonic velocity was 5682.5 m/s for the intact specimen, and it decreased by approximately 0.25% to 5668.2 m/s as the grain size increased to 294 µm. As indicated by the dashed line in the figure, a linear relationship existed with a good correlation coefficient of 0.9906. The reduction of the ultrasonic velocity would be mainly attributed to the increase in grain size. Though microstructural features, including dislocations and precipitates, can also affect the ultrasonic velocity, their effects would be small enough to be neglected because the microstructural features are much smaller than the ultrasonic wavelength. The present experimental results also matched well with those of the theoretical model based on mode conversion and multiple scattering theories proposed by Hirsekorn [12]. The theoretical model calculated the ultrasonic velocity in polycrystalline material as a function of the wavenumber, k, and the grain diameter, D, and showed that the ultrasonic velocity decreased almost linearly with increasing grain size when the value of kD ranged from 0 to 1. In this study, the kD values ranged from 0.1 to 0.7, and the ultrasonic velocity decreased almost linearly by approximately 0.25%, which is reasonable and can be explained by ultrasonic scattering by grains.
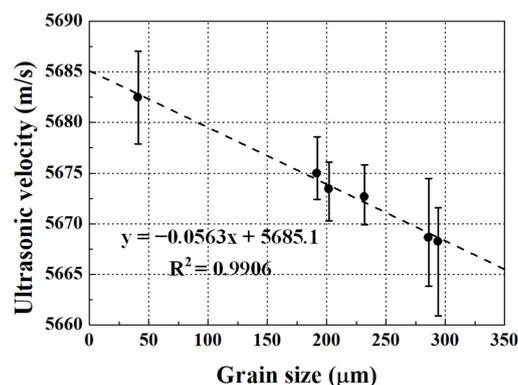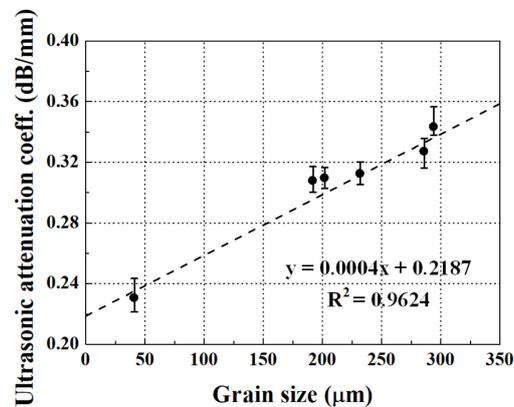

Figure 5. Ultrasonic velocity as a function of grain size.

3.3. Ultrasonic Attenuation Coefficient vs. Gain Size

The ultrasonic attenuation coefficient as a function of grain size is shown in Figure 6, where both the average value and the data range for ten repeated measurements are shown. All measurements were made in the Rayleigh scattering region. The average attenuation coefficient was 0.2305 dB/mm for the intact specimen with a grain size of 41 µm, and it approximately doubled to 0.3433 dB/mm as the grain size increased to 294 µm. There was also a linear relationship between the attenuation coefficient and the grain size, but the correlation coefficient was 0.9624, which was lower than that between the ultrasonic velocity and the grain size. However, the sensitivity of the ultrasonic attenuation coefficient

to the change in grain size and the stability of ultrasonic attenuation measurements were better than those in the ultrasonic velocity measurements.


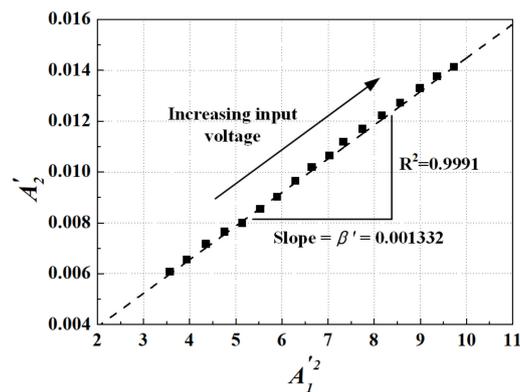**Figure 6.** Ultrasonic attenuation coefficient as a function of grain size.

In the present experimental results, the increase in ultrasonic attenuation coefficient with increasing grain size resulted from the increase in the ultrasonic energy loss due to the ultrasonic scattering by grains. Although the ultrasonic attenuation coefficient includes both absorption and scattering terms, the ultrasonic absorption term is very small and can be ignored in the case of polycrystalline materials, and ultrasonic scattering by grains and interfaces dominates the change in the ultrasonic attenuation coefficient [5,8].

3.4. Nonlinear Ultrasonic Parameter vs. Grain Size

A typical tone-burst ultrasonic signal and its frequency spectrum used for the nonlinear ultrasonic measurement are shown in Figure 7. Both the 2.5 MHz fundamental component and the 5 MHz second-order harmonic component are present, and they are separated clearly in the frequency domain. Figure 8 illustrates the relationship between the second-order harmonic amplitude A_2' and the square of the fundamental amplitude $(A_1')^2$ as a function of increasing input voltage level in the intact specimen. A good-fit linear relationship was observed between A_2' and $(A_1')^2$ with a high correlation coefficient of 0.9991. The slope of the linearly fitted line corresponds to the relative nonlinear ultrasonic parameter β', as in Equation (4).
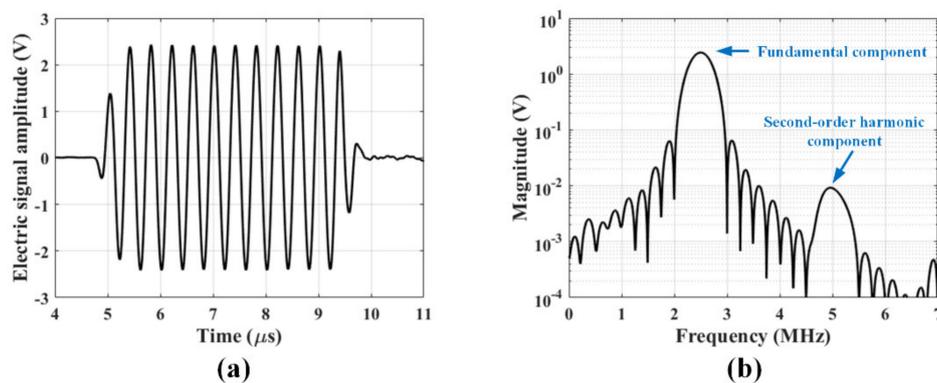

Figure 7. (**a**) Typical tone-burst ultrasonic signal; and (**b**) its frequency spectrum used for the nonlinear ultrasonic measurement.

Figure 8. Linear relationship between A_2' and $(A_1')^2$ as a function of increasing input voltage level in the intact specimen.

The average values and the data ranges of the measured nonlinear ultrasonic parameters as a function of grain size are shown in Figure 9. The average nonlinear ultrasonic parameter was 0.001356 for the intact specimen, and it was reduced by about half as the grain size increased to 294 µm. The tendency of the nonlinear ultrasonic parameter to decrease with increasing grain size was the same as that of the ultrasonic velocity, while it was the opposite that of the ultrasonic attenuation coefficient. A linear relationship between the nonlinear ultrasonic parameter and the grain size was also observed with a correlation coefficient of 0.9761. The sensitivity of the nonlinear ultrasonic parameter to the change in grain size and the stability of nonlinear ultrasonic measurements were at levels similar to those in the ultrasonic attenuation measurements.
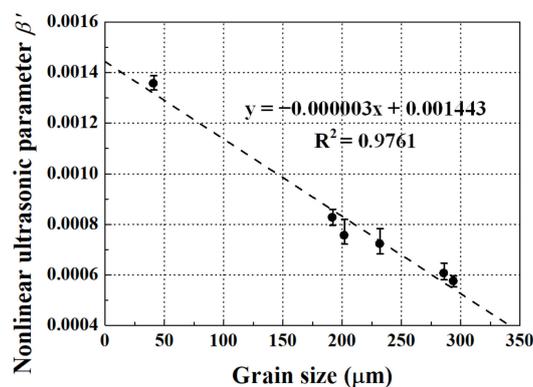
Figure 9. Nonlinear ultrasonic parameter as a function of grain size.
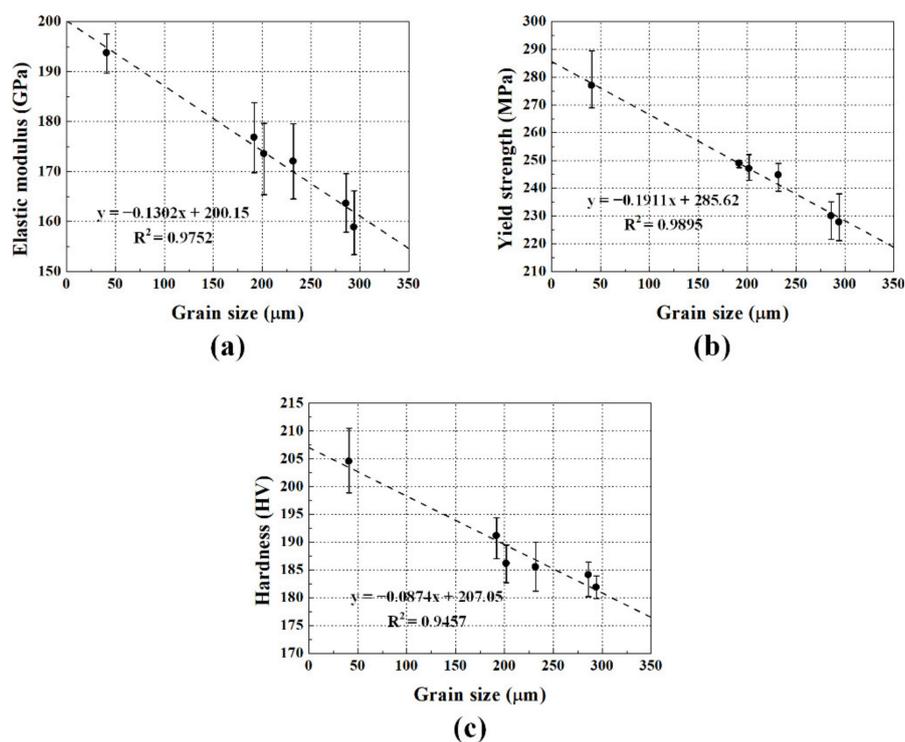
The decrease in nonlinear ultrasonic parameter with increasing grain size was due to the decrease in the number of grain boundaries in a unit volume. Grain boundaries, which separate grains with different crystallographic orientations, can be regarded as interfacial defects that result in ultrasonic nonlinearity [7,22]. While ultrasonic waves pass through the interfacial discontinuities with high localized strains, the ultrasonic waveform is distorted, and such distortion leads to the generation of higher harmonics. A larger number of grain boundaries in the wave propagation path results in higher ultrasonic nonlinearity. For the specimens used in this study, larger grain size means a smaller number of grain boundaries in the wave propagation path and lower ultrasonic nonlinearity. Note that ultrasonic velocity and attenuation coefficient are directly sensitive to grain size based on ultrasonic scattering by grains. In contrast, the nonlinear ultrasonic parameter is dependent on the number of grain boundaries rather than grain size.

Note that the values of the measured nonlinear ultrasonic parameters might include not only the ultrasonic nonlinearity caused by nonlinear elastic response of a material to an ultrasonic wave but also the system nonlinearity that could occur in various measurement system elements such as an electric

signal generator, transducers, couplant layers, and so on. In this work, the system nonlinearity was minimized as much as possible and was also kept constant in a series of ultrasonic measurements by using a low pass filter, surface polishing of specimens, and a pneumatic system. Assuming the system nonlinearities measured on each specimen were constant, the relative values of nonlinear ultrasonic parameters were compared and correlated with grain size.

3.5. Mechanical Properties vs. Grain Size

Mechanical properties, including elastic modulus, yield strength, and hardness, were analyzed according to grain size. The elastic modulus and the yield strength were measured using tensile tests, and their average values and data ranges are shown in Figure 10a,b, respectively. Both mechanical properties decreased with increasing grain size. This material weakening was attributed to the smaller number of grain boundaries that act as barriers to dislocation movement [4,5,22]. The change in elastic modulus with grain size, shown in Figure 10a, could also be correlated with the change in ultrasonic velocity, shown in Figure 5. It is well known that ultrasonic velocity is a function of elastic modulus and material density. The decrease in the elastic modulus corresponds to a decrease in the ultrasonic velocity, assuming there is almost no change in material density, even if grain size changes. The increase in grain size also caused a decrease in hardness, as shown in Figure 10c. The reduction in hardness was also due to a decrease in the number of grain boundaries that prevent plastic deformation [22]. Overall, the increase in grain size caused a decrease in the number of grain boundaries, which weakened the mechanical properties.
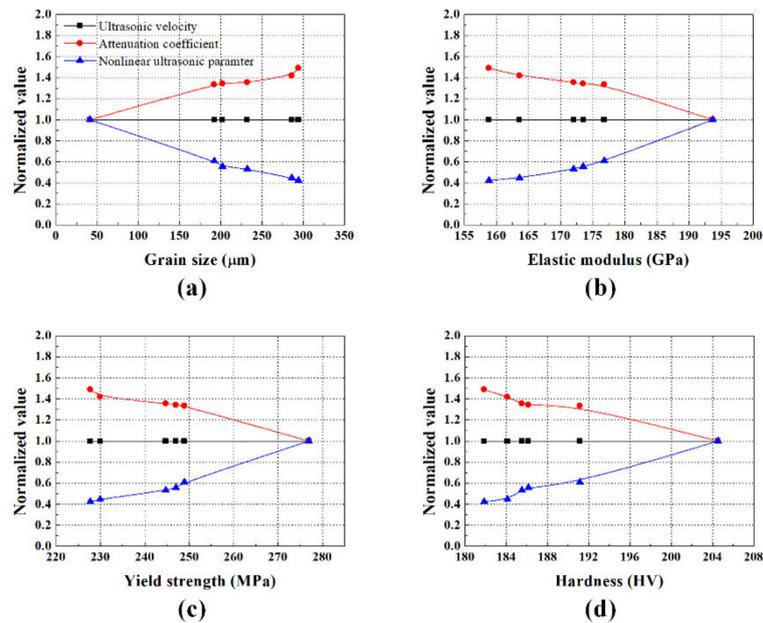

Figure 10. (**a**) Elastic modulus; (**b**) yield strength; and (**c**) hardness as a function of grain size.

3.6. Summary

Linear and nonlinear ultrasonic parameters were correlated with grain size and mechanical properties, and the normalized values of ultrasonic parameters as a function of the material properties were compared, as shown in Figure 11. These values were normalized with respect to the values of each ultrasonic parameter in the intact specimen. The sensitivity of ultrasonic parameters to material properties was determined by the slope of the fitted line when the correlation was linearly fitted. The sensitivity of each ultrasonic parameter is summarized in Table 2. The sensitivity of the ultrasonic

attenuation coefficient and the nonlinear ultrasonic parameter to changes in grain size and mechanical properties was much better than that of the ultrasonic velocity. In particular, the sensitivity of the nonlinear ultrasonic parameter was the best, and it was about 25% higher than that of the ultrasonic attenuation coefficient. The experimental results summarized here suggest that the use of the nonlinear ultrasonic parameter would be more effective in characterizing the material properties than the linear ultrasonic parameters.

Figure 11. Normalized linear and nonlinear ultrasonic parameters with respect to the values of each ultrasonic parameter in the intact specimen as a function of (**a**) grain size; (**b**) elastic modulus; (**c**) yield strength; and (**d**) hardness.

Table 2. The sensitivity of linear and nonlinear ultrasonic parameters to grain size and mechanical properties.

Item	v (m/s)	α (dB/mm)	β'
Sensitivity to grain size (1/um)	−0.00001	0.0018	−0.0023
Sensitivity to elastic modulus (1/GPa)	0.00008	−0.0135	0.0168
Sensitivity to yield strength (1/MPa)	0.00005	−0.0093	0.0116
Sensitivity to hardness (1/HV)	0.0001	−0.02	0.0252

Note that, if microstructural features of specimens intended to characterize grain size involve not only changes in grain size but also other microstructural changes, the use of the nonlinear ultrasonic parameter could be difficult because the nonlinear ultrasonic parameter is sensitive not only to grain size but also to various microstructural features, including dislocations, precipitates, and phase transformations. For example, the nonlinear ultrasonic parameter increases with increasing dislocation density, while it decreases with increasing grain size. When various microstructural features are present, the use of the ultrasonic attenuation coefficient would be better in characterizing grain size, since ultrasonic attenuation is primarily sensitive to changes in grain size among various microstructural features.

It should also be noted that nonlinear ultrasonic measurements require more sophisticated experimental setup and more careful attention than linear ultrasonic measurements for reliable ultrasonic measurements. It would be essential to minimize the system nonlinearity mentioned in Section 3.4. as much as possible and to keep it constant in a series of ultrasonic measurements, which would require careful surface preparation of specimens and the use of additional auxiliary devices,

such as a pneumatic system and a specially designed fixture. If practical applications do not allow these requirements, ultrasonic attenuation coefficient measurements would be an effective alternative.

4. Conclusions

The abilities of ultrasonic velocity, ultrasonic attenuation coefficient, and nonlinear ultrasonic parameter to characterize the grain size and the mechanical properties of 304L stainless steel were evaluated and compared. The increase in grain size caused a decrease in ultrasonic velocity and an increase in ultrasonic attenuation coefficient, which was due to ultrasonic scattering by grains. The nonlinear ultrasonic parameter decreased with increasing grain size. This was because the number of grain boundaries that were the sources of ultrasonic nonlinearity decreased as the grain size increased. In terms of mechanical properties, the increase in grain size resulted in a decrease in elastic modulus, yield strength, and hardness. The nonlinear ultrasonic parameter provided better sensitivity than the ultrasonic velocity and the ultrasonic attenuation coefficient, which suggests that the nonlinear ultrasonic measurement would be more effective in characterizing grain size and mechanical properties than the linear ultrasonic measurements. Future work will analyze the effects of surface roughness and measurement system on linear and nonlinear ultrasonic measurements.

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