Article

Detectable Depth of Copper, Steel, and Aluminum Alloy Plates with Pulse-Echo Laser Ultrasonic Propagation Imaging System

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Abstract: Pulse-echo laser ultrasonic propagation imaging is a nondestructive testing technique developed for composite materials and aluminum alloys used in aerospace. Although this method has been in usage for a considerable time, information of the detectable depth and the relationship between ultrasonic frequencies and the acoustic properties of metals is not readily available. Therefore, we investigate the A-scan and C-scan ultrasonic testing data of aluminum alloy, hot rolled steel, stainless steel, and copper alloy, which are used in aircraft bodies, frameworks, and gas pipelines. Experiments are performed with the pulse-width and excitation laser power fixed at 32 ns and approximately 4 W, respectively. The metal specimens include 24 artificial cylindrical defects with a diameter of 5 mm, located at depths of 1–12 mm on the front surface. The A-scan and C-scan data obtained at room temperature indicate the detectable depth for metals via the pulse-echo laser ultrasonic propagation imaging technique.

Keywords: laser ultrasonics; laser FF PE UPI; non-contact ultrasonic testing; copper alloy; hot rolled steel; stainless steel; aluminum alloy

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1. Introduction

Composite materials, such as glass fiber reinforced plastics (GFRPs), carbon fiber reinforced plastics (CFRPs), and honeycomb composite sandwich structures, are extensively used in aerospace and other industries. Thus, suitable ultrasonic testing techniques have been investigated for detecting the defects in composite materials [1–3]. If delamination or other defects are present in GFRP, CFRP, or honeycomb composite sandwich structures, the strength of the material can be critically degraded. Therefore, inspection is crucial for composite materials and aluminum alloys, for which ultrasonic testing is an effective method. When an ultrasonic wave impinges on the interface of a medium, it is immediately reflected. The greater the difference in the speed of sound between the media across the interface, the greater the reflection. Compared to solid bodies, gases and vacuum have significantly smaller sound speeds. Since delaminated spaces can be regarded as air or vacuum, the intensity of the reflected ultrasound wave is strong, and the delaminated area can be detected.

To improve the precision and convenience of ultrasonic testing, various techniques have been proposed for ultrasound generation and detection, including laser ultrasonics [4–6]. In laser ultrasonics, high accuracy can easily be achieved owing to the small spot size of the laser beam [7]. Moreover, it is more convenient compared to conventional ultrasonic testing methods, in which couplants such as gel and water are used, because it enables non-contact inspection in air. Ultrasonic laser generation can be categorized into two regimes: ablation and thermoelastic [8,9]. In the ablation regime, the repulsive force of the evaporated particles through the absorption of a high-power pulse laser beam contributes to

ultrasound generation. Generally, the intensity of the generated ultrasound increases with the pulse laser power; however, there may be exceptions [9]. In the thermoelastic regime, thermoelastic expansion through the absorption of a pulse laser beam generates ultrasound without evaporation. In this regime, the intensity of the generated ultrasound is weaker than that in the ablation regime [8]. One of the methods for detecting ultrasound involves the usage of a continuous laser and an interferometer [10,11]. When the reflected continuous laser beam from the surface of the target arrives at the interferometer, the brightness of the interferometer changes with the surface vibrations; thus, the ultrasound reaching the surface can be detected and analyzed using the interferometer signals.

In this study, we use a laser full-field pulse-echo ultrasonic propagation imaging (FF PE UPI) system [12] for defect detection. In a laser FF PE UPI, ultrasound is generated by an Nd:YAG pulse laser in the thermoelastic regime, the echo-wave is detected by a laser Doppler vibrometer (LDV), and the LDV signals are processed and visualized on a computer as C-scan images, which depict the defect distribution in the target. Using the laser FF PE UPI technique, the successful nondestructive tests of CFRP, GFRP, and 6061-T6 aluminum as well as graphite-to-aluminum, graphite-to-graphite, and steel-to-graphite substrate composite specimens have been reported [12–14].

Although the laser FF PE UPI technique has already been used in aerospace industries, its effectiveness in applications, such as the inspection of steel structures, pipelines, and vessels, is unclear, and further investigation for other materials is required. This study examines the results of the laser FF PE UPI inspection of copper alloy, hot rolled steel, stainless steel, and aluminum alloy specimens. Hot rolled steel is used in steel structures and vessels, whereas copper alloy and stainless steel are mainly used in pipelines. The acoustic properties of steel and copper differ from those of composite materials and aluminum alloy, which are used in aerospace industries. In this study, all the metals are cut into plates, and artificial defects are created on the back of the plates. The results are visualized as A-scan graphs and C-scan images. An A-scan graph shows the LDV signals of a single point as time domain, and a C-scan image shows the distributions of the LDV signals on the cross section of a specimen [2,12]. Based on this information, the effectiveness of the laser FF PE UPI technique for metals is assessed.

2. Experimental

2.1. Laser FF PE UPI System

The laser FF PE UPI system (XNDT Mobile Pulse-Echo UPI System) includes an Nd:YAG laser, LDV, and other components. The LDV uses a 633-nm continuous wave (CW) laser beam with a laser-cavity length of 204 mm to detect vibration. The area step size of the laser FF PE UPI system is typically equal to the area line spacing. The sampling rate of the LDV signal is fixed for each ultrasound frequency band; for example, the sampling rates of the 50–250 kHz and other bands were 20 MHz and 60 MHz, respectively.

Figure 1 shows the A-scan process using the laser FF PE UPI system. When a 1064-nm pulse laser beam is incident on the surface of the specimen, ultrasound is generated and dispersed from the surface to the inner space of the specimen, as shown in Figure 1a. If the ultrasound wave traveling perpendicularly to the surface collides with a defect or the medium interface, it is reflected and returns to the spot shown in Figure 1b. Within several microseconds, the LDV collects the reflected 633-nm CW laser beam as vibration signals on the same point, and a band splitter extracts the specific frequency band from the LDV vibration signals. The A-scan data represent a time-domain graph.

Figure 2 displays the C-scan process using the laser FF PE UPI system. A temperature sensor was attached to a test sample to monitor its temperature and was covered with cork for thermal insulation. After arranging the test samples, two-dimensional scanning, as shown in Figure 1, was performed spot-by-spot. The two-dimensional scan collects the A-scan data of the spot on the scan area and converts them to C-scan images, as shown in Figure 2.

Figure 1. Ultrasound generation and detection with the laser FF PE UPI system: (a) ultrasound generation using a pulse laser beam and (b) detection of the vibrations by a continuous laser beam.

Figure 2. Scanning and generating C-scan images with the laser FF PE UPI system.

The pulse laser beam of the laser FF PE UPI system can drive various ultrasound frequencies, and the LDV can divide the ultrasonic waves into several ultrasound bands. In this study, eight narrow bands were used. The 50–250, 250–500, 500–750, 750–1000, 1000–1160, 1160–1320, 1320–1500, and 1500–2500 kHz bands were called Band1, Band2, Band3, ..., and Band8, respectively, as shown in Figure 3.

Figure 3. Illustration of the selected ultrasonic narrow bands and the nomenclature.

2.2. Metal Plate Specimens

To investigate the effect of the density and ultrasonic speed of the medium on the LDV signal, copper, hot rolled steel, stainless steel, and aluminum specimens were employed. The copper alloy used was phosphor deoxidized copper C1220. In phosphor deoxidized copper, phosphor is added to copper to improve corrosion resistance. C1220 copper is used in gas lines, heater lines, steam and water lines, and tanks. Based on the Korean Industrial Standards (KS), the percentage composition of Cu must be more than 99.90 wt% and that of P must be within the range of 0.015–0.040 wt% [15]. Hence, C1220 is equivalent to C12200. Based on C12200, the density and Young's modulus are $8.94 \text{ g}\cdot\text{cm}^{-3}$ and 117 GPa, respectively, [16]. As per pure-copper data, the longitudinal velocity of sound is

4.66 mm·μs⁻¹ [17]. The hot rolled steel used was SS400 steel, which is extensively used in the construction and automotive industries. Since the tensile strength must be within the range of 400–510 MPa, the properties and usage of SS400 are similar to those in ASTM A 36. Based on the Japanese Industrial Standards (JIS), the quantity of P and S in the SS400 steel must be less than 0.0050 wt% [18]. The density, Young's modulus, and longitudinal sound velocity are 7.870 g·cm⁻³, 214 GPa, and 5.920 mm·μs⁻¹, respectively [19]. The stainless steel used was STS304 steel, which is used in chemical and food processing equipment and cryogenic vessels. The Fe quantity must be more than 66.4 wt%, and C, Cr, Ni, and Mn must be 0.08, 19.0, 9.25, and 2.0 wt%, respectively [20]. The density, Young's modulus, and longitudinal velocity of sound are 8.00 g·cm⁻³, 193 GPa, and 5.800 mm·μs⁻¹, respectively [21]. The aluminum alloy is the AL6061 aluminum, which is a structural material for aircraft. In the AL6061 alloy, Al must be more than 95.85 wt%, and Mg, Si, Cu, and Cr must be 1.0, 0.6, 0.30, and 0.20 wt%, respectively [20]. The density, Young's modulus, and longitudinal sound velocity are 2.80 g·cm⁻³, 69 GPa, and 6.300 mm·μs⁻¹, respectively [12,20].

Figure 4 shows the design of the specimens and the nomenclature. To compare the specimen measurements, all the samples were cut and milled with uniform shapes. The height, width, and depth of the metal plates were 80, 80, and 13 mm, respectively. To simulate the defects, holes with a diameter of 5 mm were drilled on the back of the metal plates, and the vertical and horizontal spacings between the center points were 15 mm. The hole depth varied from 1 to 12 mm. Since the plate's thickness was 13 mm, the thickness of the wall, which is the depth of the artificial defect, varied from 12 to 1 mm. This is referred to as the defect depth.

Figure 4. Design and distribution of artificial defects and nomenclature of the parts. (a) Cross-section of a defect, (b) structure of the backside, and (c) front side of a specimen and defect distribution.

Table 1 lists the measured data of the defect depth, shown in Figure 4, for each metal plate using a digital micrometer (Nikon Digimicro MF-501). The observed values are the average of five points on each hole. Defect depths greater than 4.5 mm were omitted because they were not detected in this study. Artificial defects with designed defect depths of 1.0, 1.5, 2.0, ..., and 4.5 mm were denoted as Defect-1.0, Defect-1.5, Defect-2.0, ..., and Defect-4.5, respectively. Two artificial defects were designed with a defect depth of 4.0 mm to investigate the effect of the defect positions; a defect was located at (10,40) mm and denoted as Defect-4.0-a and the other was located at (10,70) mm and denoted as Defect-4.0-b.

Table 1. Measured values of the defect depth.

Designed Depth Position [†]	1.0 (55, 10)	1.5 (40, 10)	2.0 (25, 10)	2.5 (10, 10)	3.0 (10, 25)	4.0 (10, 40)	3.5 (10, 55)	4.0 (10, 70)	4.5 (25, 70)
Copper alloy	0.94	1.45	1.96	2.46	2.96	3.97	3.46	3.95	4.45
Stainless steel	1.04	1.54	2.03	2.52	3.01	4.00	3.49	3.99	4.48
Hot rolled steel	0.97	1.47	1.98	2.49	2.98	3.99	3.50	4.03	4.50
Aluminum alloy	0.92	1.41	1.91	2.40	2.90	3.89	3.38	3.88	4.39

Designed Position [†] denotes the center of the defect position based on Figure 4c. The unit is mm.

3. Results and Analysis

The temperature of each metal plate was recorded every second using a digital thermometer (Maxim Integrated DS18B20). During the measurements, the average temperature of the metal plates was 21.2 ± 0.1 °C. The copper alloy, hot rolled steel, stainless steel, and aluminum alloy plates were measured in a single scan. The height and width of the scan area were 220 and 180 mm, respectively, and the spacing of each beam spot on the metal surface was 0.10 mm. Since the scan step was 0.10 mm, the real size of the C-scan image pixel was 0.10 by 0.10 mm for each metal plate. The distance from the 633-nm CW laser head to the metal plate was 846 mm. The pulse repetition rate (PRR) and pulse width of the 1064-nm pulsed laser were 1 kHz and 32 ns, respectively. The power of the pulse laser was approximately 4 W. The data for a single band were collected in a single scan.

3.1. Characteristics of the Pulse-Echo Laser Ultrasonic Technique

The LDV signals of the defect surroundings are unequal, and those of the defect areas are inhomogeneous, respectively, as shown in Figure 5. Figure 5a shows the C-scan image of the AL6061 specimen at 6.00 μ s in Band1, and the point at (0,0) mm in Figure 5 is the same as that at (55,10) mm in Figure 4c. In Figure 5a, a gradated ring with an outer radius of approximately 2.5 mm can be observed. The radius of Defect-1.0 is 2.5 mm, and the minimum value of the color scale bar in Figure 5a is -1×10^4 . The nonuniformity of the LDV signals at 6.00 μ s is clearly observed in Figure 5d, which depicts the LDV signals on the *x*-axis of Figure 5a. In Figure 5d, the LDV signal on the center of Defect-1.0 is the least, and the signal is saturated at the ± 2.5 mm position, beyond which the signal fluctuates.

The difference between the LDV signals of a defect and its surroundings vary over time. Figure 5b,c show the changes in the signals of Figure 5a over time. When the measuring time is changed from 6.00 μ s to 7.50 μ s, it is difficult to identify the disc originating from Defect-1.0, as shown in Figure 5b. After 1.5 μ s later from the measuring time shown in Figure 5b, Defect-1.0 is detected again, as shown in Figure 5c. Figure 5d–f show this tendency clearly. The LDV signals of the surroundings are approximately -3.9×10^3 , and those of the Defect-1.0 area are lower as depicted in Figure 5d. Then, 1.5 μ s later, the LDV signals of the Defect-1.0 area are approximately -1.5×10^3 , and those of the surroundings are approximately -6.3×10^2 , as shown in Figure 5e. In Figure 5f, the LDV signals of the surroundings are approximately 1.7×10^3 , and those of the Defect-1.0 area are higher.

Figure 6 displays an extreme case of the LDV signal nonuniformity in the same defect area and the disappearance of the detected defects. Figure 6a is the C-scan image of Defect-1.0 of the AL6061 specimen at 2.60 μ s in Band4, and Figure 6b depicts the LDV signals along the *x*-axis of Figure 6a. Figure 6a indicates that a single color and its gradation cannot represent the defect areas, and more than two peaks are observed in Figure 6b. Figure 6c is the C-scan image of the AL6061 specimen at 3.35 μ s in Band4. Defects-1.0, 1.5, and 3.0 (blue-disk) and Defects-4.5, 4.0-a, and 4.0-b (red-disk) can be observed. However, Defects-2.0, 2.5, and 3.5 cannot be identified in Figure 6c. Thus, all the detected artificial defects cannot be observed in a single C-scan image (frame). It should be noted that defects can be identified based on the signal difference between the defect area and the surroundings, and the LDV signals of the defects and their surroundings vary constantly during ultrasonic testing with a pulse-echo laser ultrasonic propagation imaging system.

Figure 5. LDV signal distribution for Defect-1.0 of the AL6061 specimen in Band1 and its variation over time: (a–c) C-scan images at 6.00, 7.50, and 9.00 μs , respectively, and (d–f) LDV signals as a function of the x -position at the same measuring time as in (a–c), respectively. The zero positions in (d–f) are the same as the origins in (a–c).

Figure 6. LDV signals of the AL6061 specimen in Band4: (a,b) LDV signals of Defect-1.0 of the AL6061 specimen at 2.60 μs , and (c) disappearance of artificial defects such as Defect-2.0, -2.5, and -3.5 of the AL6061 specimen in Band4 when the measuring time is 3.35 μs .

3.2. Criterion for the Detected Defects

Before deriving the maximum detected defect depth, the criterion for the detected defects needs to be discussed. In this study, the mean value of a defect was calculated using a disk that was (orange disk in Figure 7a) concentric with the defect and had a radius of 2 mm. The mean value of the defect surroundings was calculated using a ring that was concentric with the defect and had a radius of 5 mm (black solid ring in Figure 7a). The measured value was defined as the mean value $\pm$ standard deviation. The standard deviation was also used for the error bars. The number of selected pixels for the mean values of a defect and its surroundings were 1313 and 284, respectively.

In this study, for a detected defect, the measured values of the defect and its surroundings do not overlap. Simultaneously, the isolated area, originating from the defect, is observed in the C-scan image. For example, Figure 7b shows the variation of the LDV signals of Defect-1.0 in Band1; the C-scan images corresponding to 6.00 and 7.50 μs in Figure 7b are shown in Figure 5a,b, respectively. At 6.00 μs in Figure 7b, the measured values of Defect-1.0 and its surrounding are $-10,006 \pm 3581$ and -3939 ± 132 , respectively. Moreover, their error bars do not overlap. In the C-scan image at a measuring time of 6.00 μs , Defect-1.0 can be clearly distinguished from its surrounding as shown in Figure 5a. However, at 7.50 μs in Figure 7b, the measured values of Defect-1.0 and its surrounding (-1514 ± 844 and -638 ± 90 , respectively) overlap. In the C-scan image at 7.50 μs , Defect-1.0 cannot be distinguished from its surrounding as shown in Figure 5b.

Figure 7. Schematic of the collected pixels for an artificial defect and its surrounding, and A-scan graph of Defect-1.0 and its surrounding in Band1: (a) Description of the range of a defect and its surrounding for the measured values, and (b) LDV signals of Defect-1.0 in the AL6061 specimen as a function of the measured time in Band1.

3.3. Detected Artificial Defects

Table 2 presents the detected defects in each band. In the case of the copper alloy C1220 specimen, the deepest detected artificial defect is Defect-3.0 in Band1. Moreover, an increase in the band frequency leads to a decrease in the depth of the detected defect; Defect-1.0 alone can be detected in Band8. In the case of the stainless-steel STS304 specimen, the deepest detected defect is Defect-4.0-a, and the number of the detected defects is the least in Band8. In the case of the hot rolled steel SS400 specimen, the deepest detected defect is Defect-2.0. In the aluminum alloy AL6061 specimen, the deepest detected defect is Defect-4.5 in Band3 and Band4, and, the number of detected defects is the least when Band8 is applied. There is no artificial defect deeper than Defect-4.5, and the number of the detected defects is the least when Band8 is used in all the trials.

All the defects listed in Table 2 cannot be visualized as disks in the corresponding C-scan image. Although Defect-4.0-a in the stainless-steel STS304 specimen is detected at 7.20 μs in Band1, its shape is not depicted as a disk in the C-scan image at 7.20 μs , as shown in Figure 8a. With the increase in the defect depth, the attenuation and dispersion of the reflected wave increase; hence, the LDV-signal difference due to the defect decreases, and the shape of the defect on the C-scan image can be distorted. Defects that are not mentioned in Table 2 are often identified in the C-scan images. Defect-4.0-a of the aluminum alloy AL6061 specimen is not detected at 3.10 μs in Band5 because the measured values of Defect-4.0-a and its surrounding overlap, as shown in Table 2. However, in the C-scan image at 3.10 μs , a red spot originating from Defect-4.0-a can be distinguished, as shown in Figure 8b.

Table 2. Detected artificial defects.

		Defect-1.0	Defect-1.5	Defect-2.0	Defect-2.5	Defect-3.0	Defect-4.0-a	Defect-3.5	Defect-4.0-b	Defect-4.5
Copper alloy (C1220)	Band1	○	○	○	○	○				
	Band2	○	○	○	○					
	Band3	○	○	○	○					
	Band4	○	○	○	○					
	Band5	○	○	○						
	Band6	○	○	○						
	Band7	○	○	○						
	Band8	○								
Stainless steel (STS304)	Band1	○	○	○	○	○	○			
	Band2	○	○	○	○	○	○	○		
	Band3	○	○	○	○	○	○	○		
	Band4	○	○	○	○	○	○	○		
	Band5	○	○	○	○	○		○		
	Band6	○	○	○	○	○				
	Band7	○	○	○	○	○				
	Band8	○	○	○	○					
Hot rolled steel (SS400)	Band1	○	○	○						
	Band2	○	○	○						
	Band3	○	○	○						
	Band4	○	○	○						
	Band5	○	○	○						
	Band6	○	○	○						
	Band7	○	○	○						
	Band8	○	○							
Aluminum alloy (AL6061)	Band1	○	○	○	○	○	○			
	Band2	○	○	○	○	○	○	○		
	Band3	○	○	○	○	○	○	○	○	
	Band4	○	○	○	○	○	○	○	○	○
	Band5	○	○	○	○	○		○	○	
	Band6	○	○	○	○	○	○			
	Band7	○	○	○	○	○				
	Band8	○	○	○						

Symbol ○ indicates that the defect is detected in the band.

Figure 8. C-scan images of stainless steel STS304 and aluminum alloy AL6061 plates: (a) Stainless steel STS304 plate at 7.20 μ s in Band1 and (b) aluminum alloy AL6061 plate at 3.10 μ s in Band5.

The A-scan data were affected not only by the defect depth and material, but also by the band. Figure 9a,b show the effect of the defect depth and material, respectively. The arrival time of a longitudinal reflective wave depends on the longitudinal velocity and

distance, which are determined by the material and the defect depth, respectively. The selected band also affects the A-scan data, as shown in Figure 9c.

Figure 9. A-scan graphs showing the effect of the defect depth, band, and material: (a) A-scan data of the center of Defects-1.0, -2.0, and -3.0 in aluminum alloy AL6061 in Band3, (b) A-scan data of the center of Defect-1.0 in the AL6061, STS304, SS400, and C1220 specimens in Band1, and (c) A-scan data of the center of Defect-1.0 in aluminum alloy AL6061 in Band1, Band2, Band5, and Band8.

4. Discussion

The density and the modulus of the metals were not dominant factors to the maximum detected depth in this study. Usually, the density and the modulus of a metal are major factors of acoustic properties. For example, the shear and the longitudinal velocity can be derived from the Young's modulus, the Poisson's ratio and the density of the metal [5,7,8,20]. In Figure 9b, the LDV signals of the STS304 (yellow solid line) and the SS400 (green dotted line) are alike, while their amplitude and phase were quite different from the copper alloy C1220 (red dotted line) and the aluminum alloy AL6061 (blue dash line), until 13 μs . As mentioned in Section 2.2, the Young's modulus, the Poisson's ratio and the density of the SS400 steel and the STS304 stainless steel are similar to each other. However, the maximum detected depth of the SS400 steel was shallower than C1220 copper alloy, as shown in Table 2. The maximum detected depth was determined by the attenuation of ultrasound, which is affected by absorption and scattering of waves. The microscopic properties, such as grain size and residual strain, are one of the major factors in the absorption and the scattering of ultrasound [1,6].

Averaging data, signal processing, and adjustment of band range can help to detect defects. First, averaging data reduces noise originating from random errors. Second, signal processing can control the effect of anomalous waves. For instance, the laser FF PE UPI system used in this paper can apply the variable time window amplitude mapping (VTWAM) method to scanned data additionally. VTWAM method removes noise originating from the residual incident wave [22]. Last, the suitable ultrasound band range can improve

the results because the frequency of ultrasound affects diffraction and energy of the wave. To focus on raw data, these methods did not need be applied in this study, but to improve accuracy and detectable depth, these methods have to be considered.

5. Conclusions

Non-contact and nondestructive inspections of metal specimens were performed with a pulse-echo laser ultrasonic propagation imaging system using an FF PE UPI technique. In these experiments, the power and pulse-width of the 1064-nm pulsed laser were fixed at 4 W and 32 ns, respectively. The detectable depth values of the artificial cylindrical defects (5 mm diameter) in C1220 copper, STS304 stainless steel, SS400 hot rolled steel, and AL6061 aluminum specimens were 2.96, 3.49, 1.98, and 4.39 mm, respectively; in addition, defects with a depth of 1 mm were distinguished in all the specimens and bands. The LDV signals were affected not only by the defect depth and material, but also by the utilized band. Consequently, our results showed that the pulse-echo laser ultrasonic propagation imaging system could detect the defects of C1220, STS304, SS400, and AL6061 metal plates up to a depth of 1 mm, regardless of the used band, when a relatively strong laser of 4 W is used. The diameter of the defects is larger than 5 mm, and the defects within a depth range of 1–5 mm could be detected using a suitable band.

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