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Plastic Strain Determination with Nonlinear Ultrasonic Waves using In-situ Integrated Piezoelectric Ultrasonic Transducers

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***Abstract*—The detection of plastic deformation of metallic alloy materials with second harmonic Rayleigh ultrasonic wave is firstly investigated using direct-write piezoelectric ultrasonic transducers, in which piezoelectric poly(vinylidenefluoride/trifluoroethylene) (P(VDF/TrFE)) polymer coatings and electrodes are directly deposited, processed and patterned on the alloy to be evaluated. Rayleigh ultrasonic signals, generated by the direct-write transducers on titanium alloy specimens, are characterized by a laser scanning vibrometer. The results show that acoustic nonlinearity increases with plastic strain, and an increase of ~40% in the acoustic nonlinearity corresponding to a plastic strain of 5.1%. The measurement data and technical features with use of the direct-write transducers are compared with the conventional discrete angle beam piezoelectric transducer. The results and analyses show that compared with the conventional discrete angle beam piezoelectric transducer, implementation of the direct-write piezoelectric transducers has significant technical advantages and is promising for applications in determining nonlinear ultrasonic waves and plastic strain of structural materials.**

***Index Terms*—Acoustic nonlinearity, Plastic strain, Piezoelectric, Ultrasonic transducers, Second harmonic signals**

I. INTRODUCTION

Overloading that exceeds yield strength of structural materials permanently damages the structural integrity and may ultimately cause a catastrophic failure. Therefore, a reliable non-destructive strain deformation testing method is crucial for assuring safety and reliability of structural materials. Although plastic deformation can be determined by measuring dimensional change of structures, it is not an effective way in many practical applications in consideration of production tolerance, localization of plastic strain, and complex shape of the mechanical parts to be monitored.

The second harmonic-based nonlinear ultrasonic method has been investigated to assess micro-damages of metallic materials with plastic deformation, including fatigue, thermal aging, creep damaging and overloading [1]. In general, the accumulation of dislocations associated with plastic strain will cause a nonlinear distortion in a traveling ultrasonic wave, and thus generate higher harmonic ultrasonic signals [2, 3].. The second order acoustic nonlinearity, which relates to the amplitude of fundamental and second harmonic waves, provides information of the micro-structural changes of materials at much smaller dimensions than the wavelength [4, 5]. This nonlinear ultrasonic method for determining plastic deformation has been attempted on a variety of metallic materials, including aluminum alloys [4, 6], titanium alloy [7], and stainless steel [8]. It is observed that in general acoustic nonlinearity increases with plastic deformation.

To date, the reported nonlinear ultrasonic techniques for determining plastic deformation utilize discrete piezoelectric transducers to generate acoustic wave and detect the nonlinearity, including longitudinal, Rayleigh or Lamb waves [2, 9, 10], with the frequency in the range between 2.25 MHz to 10 MHz The discrete ultrasonic transducers are typically assembled with precise alignment on the structural material to be evaluated, and the transducer misalignment and variation in acoustic coupling may significantly affect the reliability and consistency of the testing results. For the most common Rayleigh wave or Lamb wave based methods, additional coupling wedges are required, which could introduce extra assembling complexity. In addition, the amount and homogeneity of the applied acoustic coupling agent could affect the testing results. It is also challenging to implement discrete transducers in structural material with curved shape or in limited space. All of the aforementioned limitations often make it difficult to obtain reproducible testing results of the second order harmonic acoustic signals, which are typically two orders of magnitude smaller than the fundamental signals. Therefore, it is challenging to determine plastic deformation with the desired reliability using the discrete acoustic transducers in practical applications.

The limitations arising from discrete piezoelectric transducers in acoustic nonlinearity testing may be solved by using direct-write piezoelectric acoustic transducers in which the piezoelectric and electrode layers are in-situ deposited and patterned on the structural materials to be measured. In contrast to manually assembling the discrete transducers, integrating the piezoelectric film transducers by direct-write process with production quality control on the structural materials promises improving consistency, conformability, and alignment,

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and thus improving testing repeatability and reliability. In addition, the minimized weight and lowered profile are important advantages for real-time in-situ monitoring. In the literature, conventionally direct-write process involved in ultrasonic transducer fabrication only refers to patterning electrodes, while the piezoelectric materials are attached as separated parts [11-14], which are surface mounted on or embedded in the structure materials using adhesives, which will greatly affect the consistency and reproducibility and may not be suitable for acoustic nonlinearity testing considering the extremely low second harmonic signal. Recently, our group reported the whole piezoelectric ultrasonic transducers including piezoelectric films directly fabricated on a structure to be monitored, and demonstrated their ability for generating and detecting ultrasonic wave for structural health monitoring purpose [15]. However, so far the direct-write transducers are only designed to generate and detect fundamental acoustic signals, not for detecting any higher order harmonic acoustic signals or for evaluating any plastic deformation.

Rayleigh waves are widely selected for acoustic nonlinearity testing as the waves are generated and detected on the same side of the structure, which is particularly important for filed applications as in most cases it is not feasible to access both sides of structures to install acoustic transducers. Also, the Rayleigh waves propagate far distances over surface, making them an ideal means to examine structure and components with large size or complex shape. Here we first report a unique method of determining plastic deformation, with Ti alloy as an example, by using direct-write ultrasonic transducers. Rayleigh wave ultrasonic signals, generated by the direct-write transducers and propagated along the structures, were measured to obtain acoustic nonlinearity parameter, and to determine the relation between the acoustic nonlinearity and plastic deformation. The outcomes on the measurement of acoustic nonlinearity and determination of plastic strain with use of the direct-write transducers were analyzed, in contrast with the discrete piezoelectric transducers.

II. METHOD AND EXPERIMENTAL DETAILS

A. Ti Alloy Specimen Preparation

The dog-bone Ti alloy specimens were produced according to the standard of ASTM E8-04 for tensile strength testing. The gauge length, width and thickness of the Ti alloy specimens were 50.8 mm, 13 mm, and 32 mm, respectively. Specimens with residual plastic strains of 0, 0.9% and 5.1% were produced by using a tensile testing machine (Instron 8801, USA). The direct-write piezoelectric transducers were designed and thereafter directly fabricated onto the Ti alloy specimens to be evaluated.

B. Design and Fabrication of Direct-write Piezoelectric Ultrasonic Transducers

The Ti alloy specimens with different plastic strains were cleaned by ethanol and deionized water. Poly(vinylidenefluoride-co-trifluoroethylene) (P(VDF/TrFE)) (72/28, Solvay, Belgium) were dissolved in a mixed solvent of dimethylformamide (DMF, Sigma-Aldrich) and acetone (Sigma-Aldrich) (1:1 in volume) at a concentration of 5 wt%. The solution was then sprayed on the Ti alloy specimens using an airbrush (Badger NH200, Badger Air-Brush Co., US). After spraying and drying, the P(VDF/TrFE) films were annealed at 135 ^{o}C. The thickness of the films was controlled to be approximate 25 µm. To fabricate the comb-shaped top electrode patterns, gold films with thickness of 200 nm were deposited on the P(VDF/TrFE) films by E-beam evaporation, and patterned with the aid of photoresist mask fabricated by photolithography process. The fabrication process is schematically shown in Fig. 1a.

The direct-write piezoelectric transducers were designed and fabricated to generate Rayleigh ultrasonic waves with central frequency of 4.5 MHz for acoustic nonlinearity testing, corresponding to gaps of 656 µm between the central lines of two adjacent electrode comb fingers (i.e. periodicity of electrode). Figure 1b presents images of the transducer produced on the Ti alloy plate after deposition of P(VDF/TrFE) film and gold electrode. The transducer was connected to external electrical driving source to excite the ultrasonic Rayleigh surface wave propagating along the Ti alloy specimens with different plastic strains, which was detected by an ultra-high-frequency LSV (UHF-120 Polytec GmbH) (Fig. 1c).

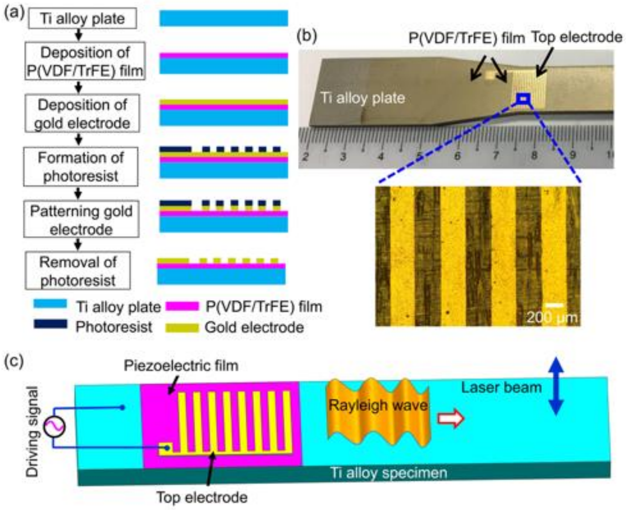

Fig. 1. A direct-write piezoelectric transducer fabricated on the Ti alloy plate for plastic deformation monitoring. (a) The fabrication process of direct-write transducer; (b) the microscopic image of the comb transducer patterned on the Ti alloy specimen; (c) the schematic of the direct-write transducer to generate Rayleigh ultrasonic surface wave propagating along the Ti-alloy specimen and detected by a LSV.

C. Acoustic Nonlinearity with Surface Normal Displacement of Rayleigh Waves

The selection of parameter used for characterizing acoustic nonlinearity is essential for evaluating ultrasonic acoustic nonlinearity with plastic deformation. The acoustic nonlinearity parameter β can be expressed as [2, 16]:

$$\beta = \frac{8u_2}{\omega^2 u_1^2 x} \frac{C_L\sqrt{C_L^2 - C_R^2}}{2\left(C_S/C_R\right)^2 - 1}$$

where u_1 and u_2 are the measured amplitude of fundamental and second harmonic signals, respectively, x is the wave propagation distance, C_L, C_R, and C_s are longitudinal, Rayleigh and shear wave velocity in the Ti alloy specimen, respectively, and ω is the angular frequency. The parameter of u_2/u_1^2 is used to quantify the relative acoustic nonlinearity of the Ti alloy specimens under different plastic strain.

D. Nonlinear Ultrasound Measurement System

The schematic of experimental setup of using piezoelectric transducers to generate Rayleigh ultrasonic waves on the Ti alloy specimen is shown in Fig. 2. A tone burst sinusoidal signal of 100 cycles at 4.5 MHz from the function generator (Agilent 3210A, USA) was amplified by the linear power amplifier (EI2100L, USA), and was applied onto the top and bottom electrode (Ti alloy plate) to drive the direct-write transducer (Fig. 2a, 2b). The Rayleigh ultrasonic surface waves propagating along the Ti alloy specimens were detected by an ultra-high-frequency LSV, and the data were analyzed to evaluate the effect of plastic deformation on acoustic nonlinearity.

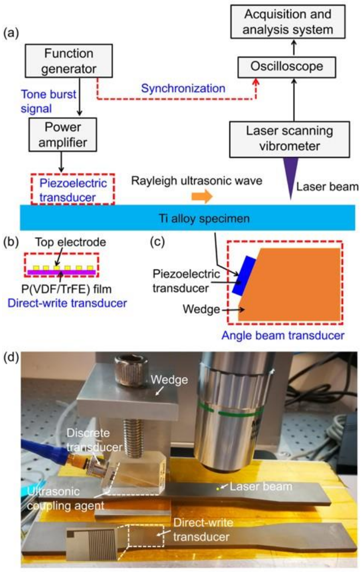

Fig. 2. (a) Schematic of experimental setup for evaluating plastic deformation with the Rayleigh ultrasonic wave excited by piezoelectric transducers and detected by LSV; (b) direct-write piezoelectric ultrasonic transducer; (c) discrete angle beam piezoelectric ultrasonic transducer; and (d) typical setup of nonlinear Rayleigh ultrasonic testing using angle beam and direct-write transducer. The Rayleigh waves generated by the transducers are detected by the LSV.

In addition, experiments of using the bulky conventional discrete angle beam transducer were conducted for comparison (Fig. 2c). Likewise, a tone burst signal of 100 cycles at 4.5 MHz from the function generator was input into the power amplifier to drive the angle beam piezoelectric transducer (A543S, Olympus) assembled with the Ti alloy specimens with different plastic deformation. The configuration of angle beam and direct write transducers assembled on the Ti alloy for acoustic nonlinearity test is compared and shown in Fig 3d.

III. RESULTS AND DISCUSSION

A. Transducer Characterization

The effective piezoelectric constant *(d_{33})* of the P(VDF/TrFE) film after electrical poling was determined using a well-established laser scanning vibrometer method (OFV-3001-SF6, PolyTech GmbH) [17]. In the measurement, a unipolar 1.1 kHz AC voltage of 20 Volts was applied onto the direct-write transducer and an area covering the regions with and without electrode were scanned (Fig. 3a) and the vibration pattern was obtained (Fig. 3b). The effective piezoelectric coefficient d_{33} value of the P(VDF/TrFE) thin film was determined at around −21 pm/V, under the clamping effect of the substrate (Fig. 3c). The measured piezoelectric coefficient is consistent with the value of spin-coated P(VDF/TrFE) films [18].

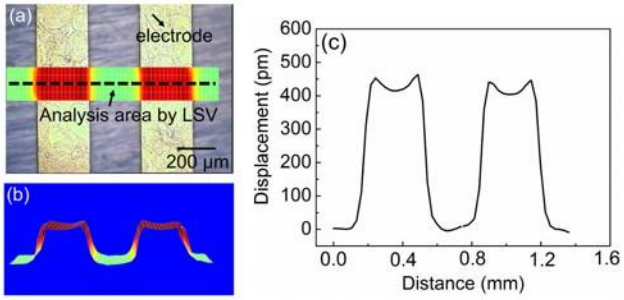

Fig. 3. (a) Piezoelectric response of the P(VDF-TrFE) film deposited on the Ti alloy specimen measured by a laser scanning vibrometer and the scanned area; (b) The vibration profile during the electric driving, and (c) the displacement magnitude from which d_{33} was obtained.

B. Acoustic Nonlinearity Measurement Using Direct-write Piezoelectric Transducers

The representative time domain ultrasonic signal, generated by the direct-write piezoelectric transducer and detected by the LSV at a propagation distance of 40 mm on the Ti alloy specimen with plastic strain level of 5.1%, is presented in Fig. 4(a). A Hanning window was applied on the steady-state portion of the signal, and the fast Fourier transform (FFT) was performed to analyze the windowed signal. The amplitudes of the fundamental (u_1) and the second harmonic (u_2) signal were obtained, as shown in Fig. 4 (b). The ratio of u_2/u_1^2 is used as the parameter to relatively quantify the material's relative acoustic nonlinearity.

The relative acoustic nonlinearity (u_2/u_1^2) versus propagation distance for the Ti alloy specimen with 5.1% plastic strain is shown in Fig. 4(c), and it is found that the relative acoustic nonlinearity increased approximately in a linear trend with increased propagation distance (Fig. 4c). It therefore indicates that the measured acoustic nonlinearity is mainly attributed from the material's nonlinearity as the nonlinear effect of instrumentation is always constant with respect to propagation distance [19].

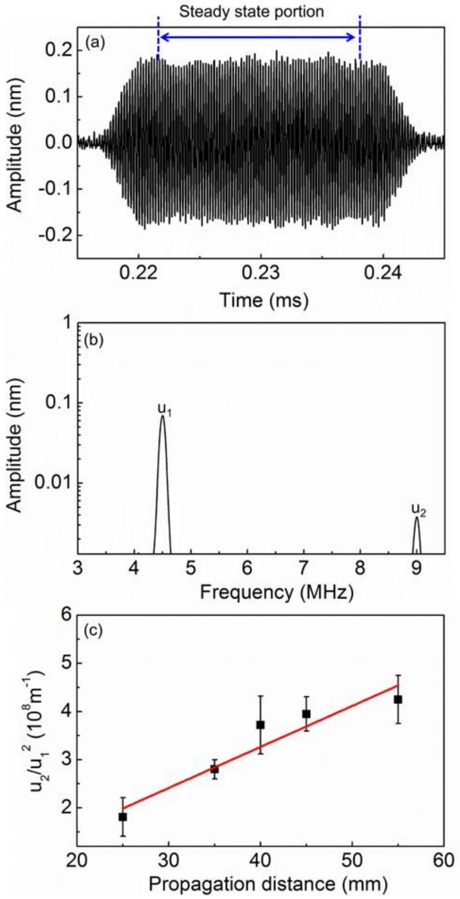

Fig. 4. Data analysis of Rayleigh wave signal generated by the direct-write ultrasonic transducer and detected by the LSV on a Ti alloy specimen with 5.1% plastic strain. (a) Representative time-domain signal detected with LSV; (b) FFT analysis showing the amplitude of fundamental (u_1) and second harmonic (u_2) signal; and (c) the relation between acoustic nonlinearity and propagation distance.

The representative Rayleigh ultrasonic waves propagating along the Ti alloy specimen with plastic deformation of 5.1%, were detected by LSV. The fundamental wave of the Rayleigh ultrasonic signal was obtained and verified by the Rayleigh wavelength at 4.5 MHz on the Ti alloy (Fig. 5(a)-(b)). Simultaneously, the generation of second harmonic Rayleigh ultrasonic wave on the Ti alloy specimen was detected, which was verified by the Rayleigh wavelength of 9 MHz (Fig. 5(c)-(d)). The detection of second harmonic wave using LSV is firstly reported here.

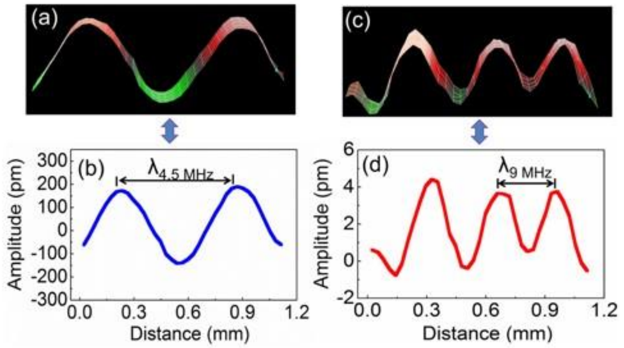

Fig 5. The observation of ultrasonic waves using LSV on the Ti alloy specimen with 5.1% plastic strain. (a) The fundamental wave of 4.5 MHz; (b) the wavelength measured corresponding to the fundamental Rayleigh wavelength of 4.5 MHz on the Ti alloy specimen; (c) the second harmonic wave of 9 MHz; and (d) the wavelength measured corresponding to the second harmonic Rayleigh wavelength of 9 MHz on the Ti alloy specimen.

C. Acoustic Nonlinearity Measurement by Conventional Angle Beam Piezoelectric Transducers

The representative time domain ultrasonic signal, generated by the conventional discrete angle beam piezoelectric transducer and detected under the same condition as above on the Ti alloy specimen with the same plastic strain of 5.1%, is presented in Fig. 6(a). The amplitudes of the fundamental (u_1) and the second harmonic (u_2) signal were obtained, as shown in Fig. 6(b).

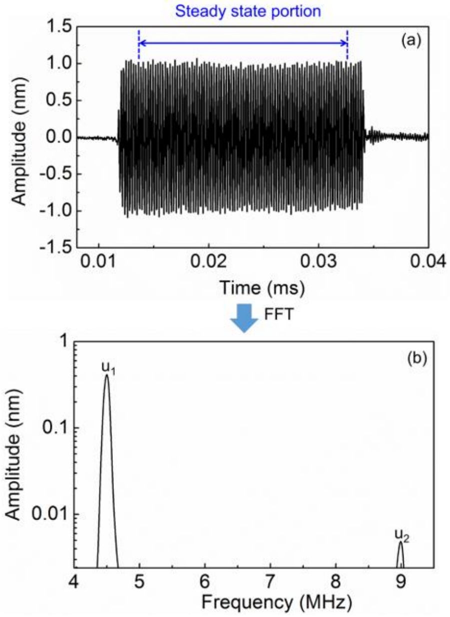

Fig. 6. (a) Representative time-domain signal generated by angle beam transducer and detected by LSV; and (b) FFT analysis showing the amplitude of fundamental (u_1) and second harmonic signal (u_2).

D. Acoustic Nonlinearity with Plastic Strain

The relation between relative acoustic nonlinearity and material's plastic deformation is explored on Ti alloy with plastic strains of 0, 0.9% and 5.1% (Fig. 7). The ultrasonic waves generated by the direct-write piezoelectric transducers were measured by the LSV and analyzed. The relative acoustic nonlinearity (u_2/u_1^2) is found increasing with plastic deformation (Fig. 7a). The result was compared with that obtained using angle beam transducers, which demonstrated similar trend of measured acoustic nonlinearity with plastic strainThe normalized relative acoustic nonlinearity, which is quantified by dividing the measured parameters (u_2/u_1^2) over that obtained from the initial, without plastic deformed Ti alloy specimen, is presented in Fig. 7b. The result showed that there is no difference between the nominalized data, *ie.* with a 40% increase at the plastic strain of 5.1% compared with the unstrained specimen.

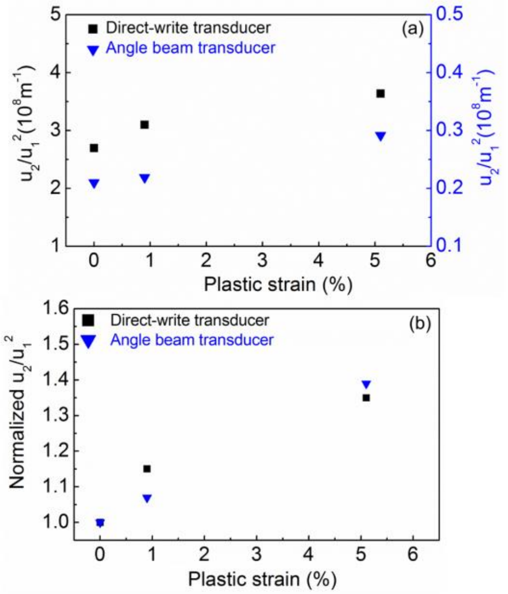

Fig. 7. (a) The comparison of relative acoustic nonlinearity (u_2/u_1^2) with plastic strain, obtained from direct-write transducers and angle beam transducers; and (b) the comparison of normalized acoustic nonlinearity obtained from direct-write piezoelectric transducer and angle beam transducer.

In practical applications, the direct-write transducers can be fabricated closed to interested locations and obtain the initial acoustic nonlinearity data. The increased acoustic nonlinearity thereafter detected can be used to monitor the plastic strain of the structures. For the discrete transducers, although they can be used in different locations and samples, the limitations as we discussed above make it extremely difficult to obtain reproducibility and consistency in practical applications. For structures with curved shape and limited space, the bulky discrete piezoelectric transducers can't even be accessed. Another important factor to consider is the cost, the price of the angle beam transducer is estimated one magnitude higher than the direct-write transducer.

Furthermore, the ultrasonic signals (obtained from front side and back side of the Ti alloy specimen) generated by the direct-write transducer and angle beam transducer, with the same propagation distance of 40 mm, were measured using LSV (Fig. 8a). For the ultrasonic time-domain signals generated by the direct-write transducer, the amplitude from the front point (same side as the transducer) is about 6-7 times larger than that measured from the bottom side (Fig. 8b). In contrast, the amplitude of the ultrasonic signals measured with angle beam transducer from the front side is only approximately 3 times larger than signals measured from the back side of the specimen (Fig. 8c).). The results show that the direct-write piezoelectric thin film transducer can generate more dominant Rayleigh surface ultrasonic wave relative to bulk wave or vibration. For the angle beam transducer, the discrete piezoelectric transducer was coupled with a wedge and assembled to the Ti alloy specimen using fixture and ultrasonic coupling agent to generate Rayleigh wave. Such a bulky configuration therefore induced leakage of ultrasonic energy to possibly form dispersive waves, such as Lamb waves. As specific conditions must be met for the fundamental and the second harmonic signal to be coupled constructively for dispersive waves [20], these parts of leaked ultrasonic energy may not contribute to the generation of second harmonic in materials. For the direct-write transducers, with precisely controlled interdigital finger sizes and selected frequency, more dominant Rayleigh wave which is non-dispersive can be generated. The advantages of using Rayleigh wave in nonlinear acoustics include stronger nonlinear effects, ease of field applications due to its single sided configuration [2]. Therefore the direct-write transducers show great potential on the measurement of acoustic nonlinearity.

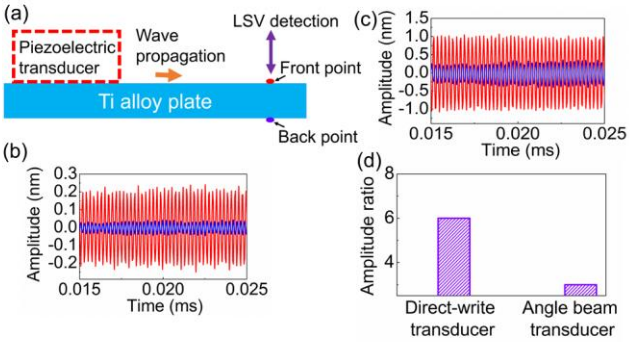

Fig. 8. (a) The comparison of ultrasonic signals generated by the direct-write transducer and discrete angle beam transducer obtained from the front side and back side of Ti alloy specimen with plastic deformation of 5.1% at the same propagation distance of 40 mm. The red color indicates ultrasonic signal measured from the front-side of the specimen (same side as the transducer) and the blue color indicates ultrasonic signal from back side (opposite side of the transducer) of the specimen; (b) comparison of ultrasonic signals (front and back side) generated by the direct-write transducer; (c) comparison of ultrasonic signals generated by the discrete angle beam transducer; and (d) comparison of amplitude ratio of the ultrasonic signals obtained from front and back side of the specimen.

E. Effect of parameter variables on ultrasonic testing

Variables such as coupling conditions, clamping forces for affixing transducers, transducers position and alignment were reported substantially affecting the acoustic nonlinearity measurement using longitudinal ultrasonic waves [21]. In Rayleigh/lamb wave based acoustic nonlinearity testing, the discrete angle beam transducers are generally used for generation or detection of ultrasonic waves, which may induce more complexity due to transducer alignment, fixing force, acoustic coupling.

For the angle beam transducer assembled setup as shown in Fig 2d, the generated ultrasonic signals generated were significantly affected by the transducer misalignment angle (Fig. 9a), and the amplitude of the output ultrasonic signal was reduced to half when the transducer misalignment angle reached 4 degrees. Also, the generated ultrasonic signal magnitude varied with the clamping force for affixing the wedge transducer to be specimen (Fig. 9b). Another factor, the ultrasonic coupling agent, which was used to couple the piezoelectric transducer and wedge (Fig 9c), was found affecting the generation of ultrasonic signal significantly. The amplitude of ultrasonic signals dropped significantly with the increased air gap among the coupling agent (Fig. 9d). Therefore, to use the conventional piezoelectric transducers for acoustic nonlinearity testing, extreme careful control of the transducer assembly conditions should be taken, which is time consuming and costly. With use of the direct-write transducers, the variations in transducer alignment, fixing force, and acoustic coupling are eliminated, which can therefore improve the reliability and consistence substantially.

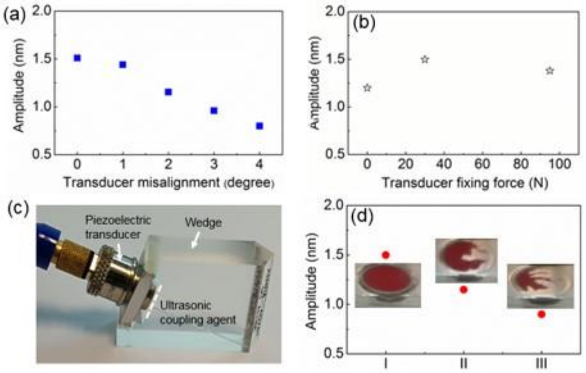

Fig. 9. (a) The effect of transducer misalignment angle on the generated ultrasonic signal; (b) the effect of transducer fixing force on the generated ultrasonic signal; and (c) Piezoelectric transducer assemblied with wedge using ultrasonic coupling agent; (d) the effect of air gap present in acoustic coupling agent on the generated ultrasonic signal.

IV. CONCLUSION

Direct-write ultrasonic transducers, for the first time, were implemented to evaluate plastic deformation of metallic alloy materials by using second harmonic based nonlinear ultrasonic method. The direct-write ultrasonic transducers, comprising of the piezoelectric films and comb-shaped electrodes, were directly deposited, processed and patterned on Ti alloy specimens with different plastic strains. The Rayleigh ultrasonic signals, generated by the direct-write transducers on the specimens, were characterized by a laser scanning vibrometer. The results showed that acoustic nonlinearity increased with plastic strain, and an increase of ~40% in the second harmonic signal was measured when the plastic strain was increased to 5.1%, which is quantitatively consistent with the results as obtained using conventional discrete angle beam transducer. However, compared with angle beam transducer, it was noted that the direct-write transducer can generate more dominant Rayleigh wave and potentially improve reliability and consistency, which is valuable for determining plastic deformation based on nonlinear testing. In addition, the use of direct-write piezoelectric transducers eliminates the procedure of fixing and aligning of transducers on the structure, requires no additional wedges and coupling agents, thus can secure the reproducibility and consistency in practical applications. Direct-write transducers are also much smaller, more flexible and conformable, thus can be integrated on curved structures and used in limited spaces when the bulky discrete angle beam transducer cannot be applied. All of these merits suggest that direct-write transducers are promising for determining nonlinear ultrasonic waves and plastic strain of structural materials.

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