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Research Article

Elastic Properties Measurement of the Multi-layered Materials using the Pulse-Echo Immersion Technique

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ABSTRACT

Elastic properties measurement is a crucial aspect in understanding and estimating the quality of materials. Even though the multi-layered materials are widely used in various industries, there is still a lack of research has been conducted to measure the elastic properties of each layer within multi-layered materials to monitor the quality of each layer. Hence, this research is performed to determine the elastic properties for each layer within multi-layered materials using the pulse echo immersion technique (PEIT). Five elastic properties are determined in this study: longitudinal modulus, Young's modulus, shear modulus, bulk modulus, and lame constant. The measurement accuracy was validated using four different thicknesses of three-layered poly(methyl methacrylate) samples and a transducer of 10 MHz center frequency. The findings indicate that the measured values of the elastic properties are consistent within 9.91% compared to the reference values. In conclusion, the elastic properties of each layer within multi-layered materials can be determined using the PEIT.

Keywords: Elastic properties, pulse echo immersion technique, multi-layered material

1. INTRODUCTION

The elastic properties are important characteristics of a material that determine its potential application in various industries such as automotive (Fentahun and Savas, 2018; Khatkar et al., 2020; Merneedi et al., 2021; Salihu et al., 2019; Zhang and Xu, 2022), aerospace (Salihu et al., 2019; Zhu et al., 2018), aviation (Kesarwani, 2017), biomedical (Salihu et al., 2019) and marine industry (Salihu et al., 2019). Previous researches employed various methods such as indentation testing to determine the elastic properties of a material (Puchi-Cabrera et al., 2015; Rao et al., 2019). However, those methods destruct sample. Hence, previous researches took the initiative to utilise the non-destructive method, such as an ultrasonic method, for the elastic characterisation of materials to avoid the destruction of sample during the test (Chen et al., 2020; Judawisastra et al., 2019; Messineo et al., 2016).

There are two common techniques of ultrasonic method for the elastic characterisation of materials; through transmission technique (TT) (Mailyan et al., 2021; Takahashi and Lematre, 2021; Xu et al., 2014) and pulse-echo technique (PET) (Erol et al., 2022; Huang et al., 2022;

Yang et al., 2021). However, the TT requires the alignment of two identical transducers in a line facing each other (Umiatin et al., 2021) and the accessibility of two sides of the materials. On the other hand, the PET only requires the accessibility of one side of the material (Liu et al., 2017) and a single transducer to measure its material properties. In 2022, Erol et al. (2022) employed the PET to measure the elastic properties of nickel-cobalt-tungsten carbide composite. However, they could only determine the Young's modulus of the material. In addition, it requires the separate measurement of longitudinal and shear wave velocities to calculate the value of Young's modulus. Other previous researches also determined the elastic properties of monolayer materials by measuring the longitudinal and shear wave velocities (Afifi, 2003; Chen et al., 2020; Donahue et al., 2019; Evans et al., 2021; Li et al., 2019; Wu et al., 2019).

Hence, this study is carried out to determine the elastic properties of each layer within multi-layered materials from the single measurement of longitudinal wave velocity using the pulse-echo immersion technique (PEIT) which utilise water as the propagation medium. This study is the extended study of Huang et al. (2022) which employed the PEIT to estimate the bulk properties of multi-layered lithium-ion batteries. However, this study offers the determination of five elastic properties of each layer within multi-layered materials; longitudinal modulus, L, Young's modulus, E, bulk modulus, G, shear modulus, K, and lame constant, λ, compared to Huang et al. (2022). The proposed technique is validated by comparing the experimental values and reference values of L, E, G, K and λ of each layer within three-layered poly(methyl methacrylate) (PMMA) samples.

2. MATERIALS AND METHODS

The material characterisation system for this study employs the PEIT. It consists of an ultrasonic pulser/receiver (Olympus Panametric NDT model 5072PR) to generate the ultrasonic pulse, a transducer (Olympus Panametric NDT) acts as transmitter and receiver, a digital oscilloscope (LeCroy Wave Surfer 42 MX-s 400 MHz 5 GS/s) to display the received ultrasonic signal and a personal computer preinstalled with the custom-developed program to determine the elastic properties of the tested multi-layered material. The tested material will be positioned on a platform so that most ultrasonic pulse will be reflected back at its last layer interface due to the large acoustic impedance difference between the material and water. The schematic diagram for the material characterisation system is shown in Figure 1.

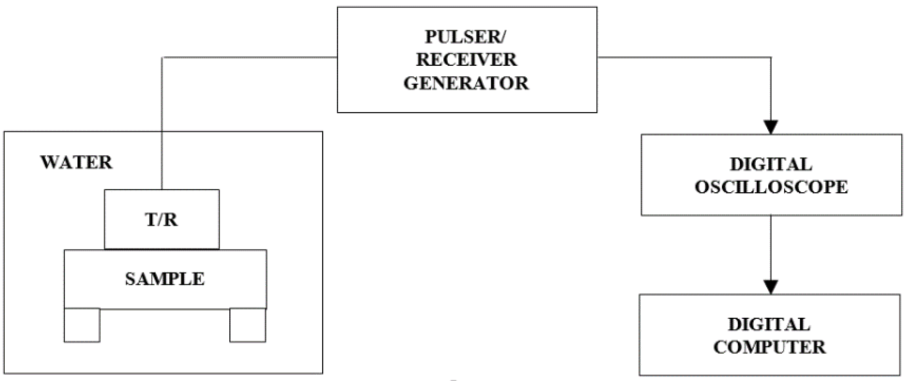

Figure 1. Material characterisation system

This study focuses on the multi-layered materials with three layers as shown in Figure 2 (a). Meanwhile, the example of the displayed signal when the ultrasonic signal propagates through Layer 1, Layer 2 and Layer 3 of the multi-layered material as shown in Figure 2 (b).

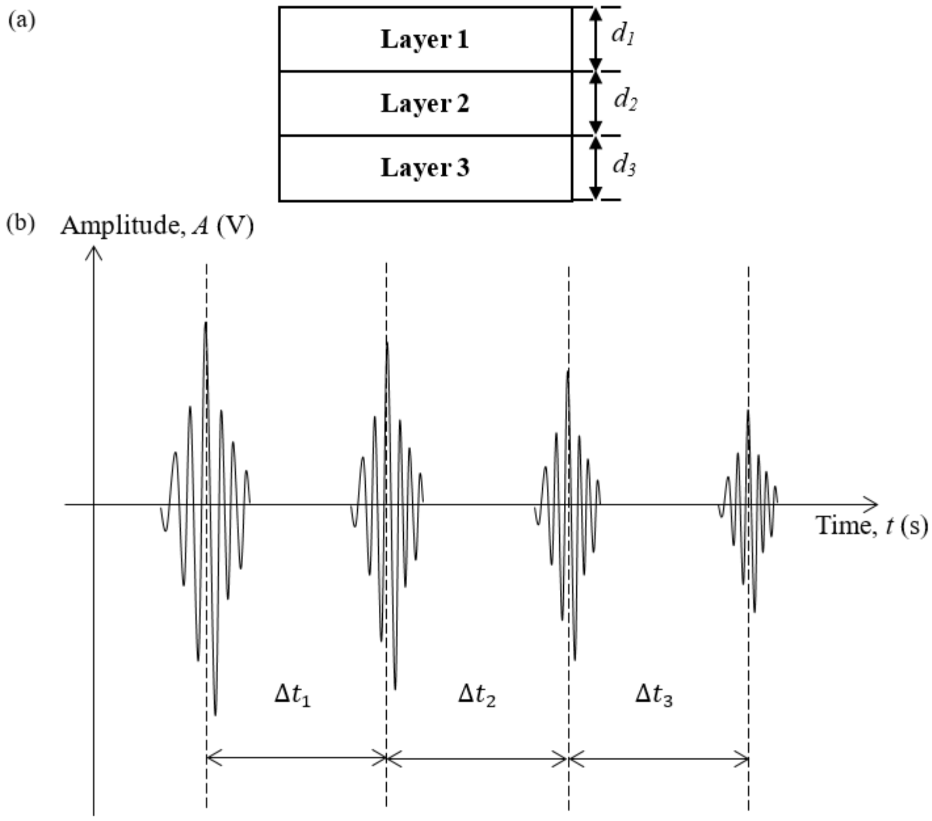

Figure 2. (a) Multi-layered materials with three layers, and (b) example of the displayed signal when the ultrasonic signal propagates through Layer 1, Layer 2 and Layer 3 of the multi-layered material

The signal is analysed to calculate the longitudinal velocity for Layer 1, v_{L1} , Layer 2, v_{L2}, and Layer 3, v_{L3}, from its respective thickness, d, and the transit time of the ultrasonic pulse in each layer, Δt, as shown in Eq. 1.

$$v_{L1} = \frac{2d_1}{\Delta t_1}, v_{L2} = \frac{2d_2}{\Delta t_2}, v_{L3} = \frac{2d_3}{\Delta t_3} \quad \text{Eq.1}$$

Five elastic properties are determined in this study; L, E, G, K and λ. The elastic properties for each layer are determined from its density, ρ, longitudinal velocity, v_L, and Poisson ratio, υ, using Eq. 2 (Afifi, 2003), Eq. 3 (Afifi, 2003), Eq. 4 (Afifi, 2003), Eq. 5 (Afifi, 2003) and Eq. 6 (Workman & Kishoni, 2007). G, K and λ are derived from L which are v_L dependent.

$$L = \rho v_L^2 \quad \text{Eq. 2}$$

$$E = \frac{v_L^2 \rho(1+\upsilon)(1-2\upsilon)}{1-\upsilon} \quad \text{Eq. 3}$$

$$G = \frac{E}{2(1+\nu)} \quad \text{Eq. 4}$$

$$K = \frac{E}{3(1-2\nu)} \quad \text{Eq. 5}$$

$$\lambda = L - 2G \quad \text{Eq. 6}$$

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3. RESULTS AND DISCUSSION

The proposed technique was validated using four different thicknesses of three-layered PMMA samples probed by a transducer of 10 MHz center frequency. The PMMA is selected as a validation sample because its acoustic properties are consistent within a small range of surrounding temperatures (Carlson et al., 2003; Mat Daud et al., 2018, 2013) and its mechanical properties are independent to the heat change (Lochab and Singh, 2004). The three-layered samples are constructed by clamping three PMMA sheets together without using the chemical couplant to avoid any change in the properties of the sample. The dimensions for each layer of PMMA samples are $(10.00 \times 5.00 \times d)$ cm^3 where d is the thickness of layer. Table 1 summarises the thicknesses of each layer for four different thicknesses of three-layered PMMA samples. The densities of all samples are 1180 kg m^{-3} and their Poisson ratio values are 0.339 (Afifi, 2003).

Table 1. The thicknesses of each layer of Sample A, Sample B, Sample C and Sample D.

Sample	**Thickness, d (cm)**		
	d_1	d_2	d_3
A	0.30	0.30	0.30
B	0.30	0.30	0.50
C	0.15	0.30	0.15
D	0.15	0.30	0.50

Figure 3 shows an example of the real displayed signal when the ultrasonic signal propagates through Layer 1, Layer 2 and Layer 3 of the three-layered PMMA sample. The measurement is validated by comparing the experimental values and reference values of L, E, G, K and λ for each layer. The experimental values of L, E, G, K and λ for each layer are in the range of 8.25 GPa to 9.30 GPa, 5.38 GPa to 6.07 GPa, 2.01 GPa to 2.27 GPa, 5.57 GPa to 6.28 GPa and 4.23 GPa to 4.77 GPa, respectively. Table 2 shows the comparisons between experimental values and reference values of L, E, G, K and λ for each layer of Sample A, Sample B, Sample C and Sample D.

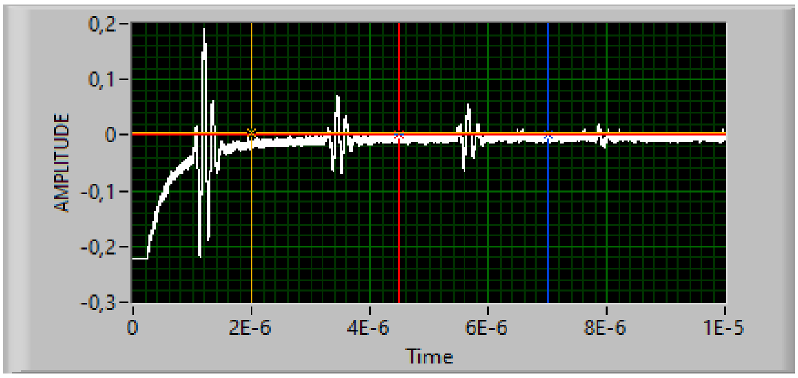

Figure 3. Example of the real displayed signal when the ultrasonic signal propagates through Layer 1, Layer 2 and Layer 3 of the three-layered PMMA sample

Refering to Table 2, the experimental values of L, E, G, K and λ for each layer of Sample A are within the range of 8.39 GPa to 9.02 GPa, 5.60 GPa to 5.89 GPa, 2.04 GPa to 2.20 GPa, 5.66 GPa to 6.09 GPa and 4.30 GPa to 4.63 GPa, respectively. However, each layer of Sample B, Sample C and Sample D have consistent values of L, E, G, K and λ although they have different thicknesses. It indicates that L, E, G, K and λ for each layer of multi-layered materials is independent to its thickness (Afifi, 2003; Jordan et al., 2021). The experimental values of L, E, G, K and λ for each layer of Sample A, Sample B, Sample C and Sample D are within 9.91% compared to the reference values. The error could be caused by the inhomogeneity of materials, which could occur during the manufacturing process (Lane et al., 2012; Mat Daud et al., 2018). Furthermore, the error may also be caused by signals that overlap as they reflect at each layer's boundaries (Raišutis et al., 2008). However, the small percentage difference indicates that the PEIT can be utilised to determine L, E, G, K and λ for each layer within multi-layered materials.

Table 2. Comparisons between experimental values and reference values of L, E, G, K and λ for each layer of Sample A, Sample B, Sample C and Sample D

Sample		**A**			**B**			**C**			**D**		
d **(cm)**		**Layer 1**	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**
		0.30	0.30	0.30	0.30	0.30	0.50	0.15	0.30	0.15	0.15	0.30	0.50
L **(GPa)**	L_e	8.58	8.39	9.02	8.25	8.95	9.12	8.44	8.69	8.65	8.43	8.52	9.30
	L_r	9.10*											
	%	5.71	7.80	0.88	**9.34**	1.65	0.22	7.25	4.84	4.95	7.36	6.37	2.20
E **(GPa)**	E_e	5.60	5.87	5.89	5.38	5.84	5.95	5.61	5.67	5.64	5.50	5.56	6.07
	E_r	5.91*											
	%	5.25	0.68	0.34	**8.96**	1.18	0.68	5.08	4.06	4.57	6.94	5.92	2.71
G **(GPa)**	G_e	2.09	2.04	2.20	2.01	2.18	2.22	2.06	2.12	2.11	2.05	2.08	2.27
	G_r	2.21*											
	%	5.43	7.69	0.45	**9.05**	1.36	0.45	6.79	4.07	4.52	7.24	5.88	2.71
K **(GPa)**	K_e	5.79	5.66	6.09	5.57	6.04	6.16	5.70	5.87	5.84	5.69	5.75	6.28
	K_r	5.99*											
	%	3.34	5.51	1.67	**7.01**	0.83	2.83	4.84	2.00	2.50	5.01	4.01	4.84
λ **(GPa)**	λ_e	4.40	4.30	4.63	4.23	4.59	4.68	4.33	4.46	4.43	4.32	4.37	4.77
	λ_r	4.34**											
	%	1.38	0.92	6.68	2.53	5.76	7.83	0.23	2.76	2.07	0.46	0.69	**9.91**

Note: Subscript e refers to the experimental value and r refers to the reference value; * Afifi, 2003; ** Cristman, 1972

4. CONCLUSION

The elastic properties of each layer within multi-layered material are successfully determined using the PEIT in this study. The finding indicated that the experimental values of elastic properties (L, E, G, K and λ) of each layer are comparable to reference value within the range of 10.0%. However, this study only validates the utilisation of the proposed technique for non-porous multi-layered materials. Hence, further research should be carried out to determine the elastic properties of each layer within porous multi-layered material.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contribution Statement

Sri Maiyena: Investigation, Methodology, Formal analysis, Writing - Original Draft. Anis Nazihah Mat Daud: Conceptualization, Validation, Project administration, Writing - Review & Editing. Shahrul Kadri Ayop: Resources, Supervision, Writing - Review & Editing

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

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