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# Tunable High Acoustic Impedance Alumina Epoxy Composite Matching for High Frequency Ultrasound Transducer

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## Abstract

Matching layer is a critical component that determines the performance of piezoelectric ultrasound transducer. For most piezoelectric materials, their acoustic impedances are significantly higher than human tissues and organs, so a tunable matching layer with a high acoustic impedance is required for optimizing the acoustic wave transmission. In this article, a high compression fabrication method is presented, with which the acoustic impedance of alumina-epoxy composite matching layer can be tuned from 6.50 to 9.47 MRayl by controlling the applied compression pressure and ratio of the components. The maximum acoustic impedance 9.47 MRayl can be achieved by compressing a mixture of 80% alumina weight ratio under a 62.4MPa pressure. This enhancement mainly relies on the increased acoustic longitudinal velocity which enlarged the tolerance of high to ultra-high frequency transducer fabrication using quarter wavelength matching design. Furthermore, the attenuation of the matching layer developed by this method is only -10 dB/mm at 40 MHz. The very high acoustic impedance value and very low attenuation make this matching material superior than all reported matching materials, and therefore, can enhance the performance of the ultrasound transducers, especially for medical imaging applications.

## Introduction

Ultrasound medical imaging is one of the most important tools in clinical and biomedical research for diagnostic, surgery assisting, observation and investigation etc.[1-5]. Ultrasound biomedical imaging contains three components including an ultrasound transducer, a computation system and a transmission/receiving electronic circuit. In recent decades, the ultrasound transducers have been mainly investigated for accomplishing higher performance including high sensitivity and image resolution, and among them, to increase the operation frequency of the ultrasound transducer to the regime of 20 to 200 MHz[6-15] is a general trend in either clinical application and biomedical research. Other than enhancing center frequency, increasing bandwidth of the transducers is essential for achieving higher resolution. Among many factors affecting ultrasound transducer's performance, matching layer is one of the most important part needs to be optimized in acoustic impedance and attenuation. The acoustic reflective ($R_i$) and transmission ($T_i$) coefficients depends on the acoustic impedance mismatch between two medium and can be calculated by equations [16]:

$$R_i = \frac{Z_l - Z_p}{Z_l + Z_p} \tag{1}$$

$$T_i = \frac{2Z_p}{Z_l + Z_p} \tag{2}$$

Where $Z_l$ and $Z_p$ are the acoustic impedance of the loading medium and the piezoelectric material. For clinical applications, the human tissues are around 1.5 MRayl, leading to over 80% reflection of the acoustic wave energy if the ceramic based piezoelectric material (usually with acoustic impedance of 32 MRayl) is directly contacted to the loading medium. Therefore, for optimizing the propagation intensity, a medium with acoustic impedance value in between the piezoelectric layer and the loading is required. Previous research has shown that the required value of matching follows the equations listed in Table 1 depending the number of matching [17].

*Table 1 The required acostic impedance of different matching combination.*

| | $Z_1$ | $Z_2$ | $Z_3$ |
|---|---|---|---|
| Single matching layer | $Z_p^{\frac{1}{3}} Z_r^{\frac{2}{3}}$ | | |
| Double matching layer | $Z_p^{\frac{4}{7}} Z_r^{\frac{3}{7}}$ | $Z_p^{\frac{1}{7}} Z_r^{\frac{6}{7}}$ | |
| Triple matching layer | $Z_p^{\frac{11}{15}} Z_r^{\frac{4}{15}}$ | $Z_p^{\frac{1}{3}} Z_r^{\frac{2}{3}}$ | $Z_p^{\frac{1}{15}} Z_r^{\frac{14}{15}}$ |

In this table, the values of acoustic impedance of the first matching layer in single, double and triple matching schemes are 4.2 MRaly, 8.4 MRayl and 14.15 MRayl, respectively. The value of single matching can be easily achieved, however, the single matching layer has a slightly lower sensitivity and bandwidth comparing with double and triple matching schemes [18,19]. Even the double and triple matching schemes are much better than single layer matching for transducer's performance, they are more difficult to be optimized since the first layer of them needs much higher acoustic impedance, especially the first layer of triple matching. Traditionally, matching layer is made using centrifugal force to concentrate the 0-3 composite like mixture of epoxy with other high acoustic impedance materials. However, the force supplied by centrifugal is far less than enough to enhance either the density or velocity, resulting in low acoustic impedance and cavity on the surface. Previous investigations have reported that matching layers composed of high-density metal and epoxy using traditional fabrication method can barely achieve a comparable value listed in the above table. However, metal involved matching layers have a relatively higher attenuation thus reducing the sensitivity and possibly the frequency bandwidth of the transducers [20,21]. Moreover, the developed matching by centrifugal has a low uniformity along thickness direction due to the force gradient along radial axial. Recently, some reported findings have been shown that matching layer containing oxide powders has an impedance ranging from 2.8 to 10 MRayl by using new structural material or development methods but are too complex for manufacturing or unsuitable for wide frequency range transducers [19,22-25].

Therefore, to develop a suitable matching to further enhance the performance of transducers is still a critical problem bothering the transducers research filed. A matching layer developed method that can accomplish a high acoustic impedance, and simultaneously, can manipulate the value for multiple matching layer structure along with varying piezoelectric material is highly desired. In this article, a method using a high pressure compressed preparation method has been employed for enhancing and manipulating the density and acoustic longitudinal velocity is demonstrated. This method possesses the advantages of low cost and is easy for manufacturing. More importantly, the acoustic impedance of the alumina-epoxy matching is enhanced to maximum 9.50 MRayl. Thus, the developed matching is suitable for transducers with high acoustic impedance piezoelectric active layer.

# Fabrication and characterization

In the preparation of the compressed matching layer, alumina powder with 1-2 μm particle size (Buehler, U.S.A.) was heated up to 1200 °C for 2 hours in a furnace with a 5 °C/mins heating rate. This process changed the alumina power from γ phase to α phase which possesses relatively higher longitudinal acoustic velocity. The mixture of different weight ratios of the powders with epoxy (Insulcast 502, ITW Insulcast, U.S.A). were agitated for 30 minutes in an agate mortars to accomplish a more uniform distribution of alumina. This agitate time was set as close as the epoxy's pot life which obtained a double epoxy viscosity before compressing.

Then the mixture was placed into a 4 cm diameters circular compartment of a customized stainless-steel mold. Two stainless steel circular rods with same diameter where located on the top and the bottom of the compartment was compressed by a hydraulic press shown in Figure 2. A 4-hr prepress of 7.8 MPa pressure was applied for squeezing the exceeded epoxy to further increase the concentration of the alumina powder. A high compressing pressure was continuously added to the mold maintained for 12 hours at room temperature preventing a relaxation of the epoxy during curing process. The pressure would drop after 12 hours compression, and therefore, a recompression process was employed to rise the pressure back to the original compression pressure for another 3 hours. Afterward, a final curing process was done by placing the mixture released from pressure in an oven for 12 hours at 65 °C. The setup during compression and the profile of the compressed matching layer are shown in Figures 1(a) and (b), where one can see that the cured composite is very dense without observable voids.

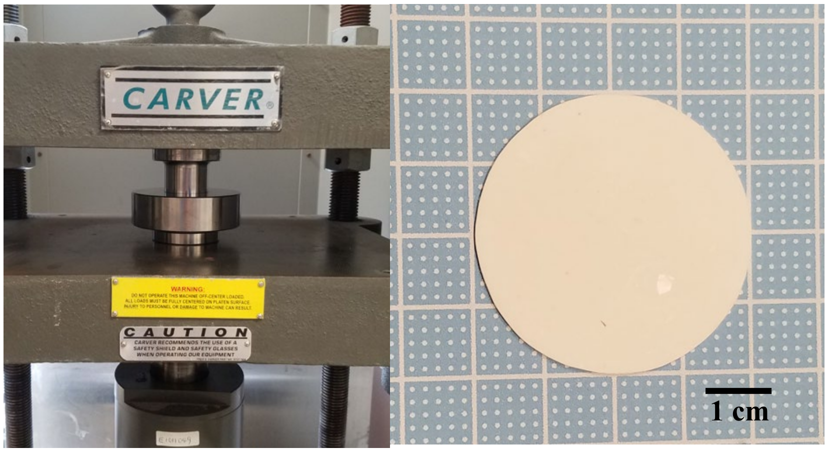

*Figure 1. Custom designed mold (Left) and the cured matching layer after the compression (Right).*

This matching material was then subject to acoustic property characterization, and effects of two main factors, i.e., compression pressure and alumina concentration, to its acoustic properties, are studied. The compression pressure was controlled by an applied weight with a range from 39 MPa to 85.8 MPa, and the ratio of alumina power to epoxy from 1:1 to 4:1. In the longitudinal velocity measurement, those samples were clamped by two 4-MHz ultrasounds transducers with identical acoustic performance. A pulser/receiver (Panametrics 5900PR, Olympus) in through transmission mode was connected to one of the transducers for emitting an acoustic pulse. The execution electrical signal energy was 1uJ within a frequency range from 1kHz to 20MHz. The emitted acoustic pulse passing through with and without the sample are received by another transducer which surface is aligned perfectly to the emitted transducer. An acoustic jell with water like acoustic attenuation was filled in all interfaces along the acoustic propagation path to prevent the energy loss caused by the air gap. The received signal was returned back to pulser/receiver through the receiver port. A digital oscilloscope (HP Infinium DSO-S 204A, Keysight Technologies, U.S.A.) with 50 Ohms electrical coupling mode was connected to the pulser/receiver for monitoring both emission and transmission pulses. The photos of this setup are shown in Figure 2 .

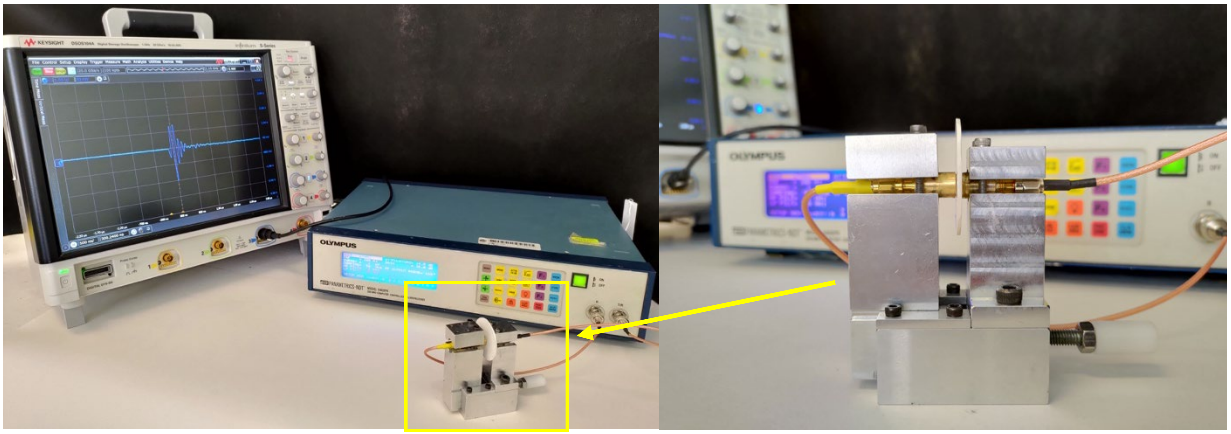

*Figure 2 The setup (Left) and the fixture (Right)of the measuerment of acoustic velocity and attenuation*

Time delay of acoustic wave passing through the matching was measured and the longitudinal velocity $\nu$ can be calculated by the following equation

$$\nu = \frac{d}{\Delta t} \tag{1}$$

where $d$ is the thickness of the tested matching layer and $\Delta t$ is the time delay. The density of the matching layer was measured by using the Archimedes' principle. The acoustic impedance $Z$ of the matching layer was calculated by multiple the longitudinal velocity and density as the following equation

$$Z = \nu\rho \tag{2}$$

The attenuation characterization was also carried out with both surface of the matching layer polished by 1200 grid sandpaper for standardizing the surface roughness; this can eliminate acoustic power variant caused by an uneven reflection. A flat surface is important since the attenuation is not only affected by the absorption and scattering inside the matching but also the reflection at the two surfaces along the acoustic propagation. The transmission amplitude $V_0$ of the matching layer at a thickness $d_0$ was measured using the same setup for acoustic velocity measurement. The thickness of the matching layer was lapped to half of the original thickness and the surface was polished. The transmission amplitude $V_l$ after lapping was measured again and the attenuation can be calculated by the equation shown as follows

$$\text{Attenuation (dB/mm)} = 20log(V_l/V_0)/(d_l - d_0) \tag{3}$$

where $V_0$ and $V_l$ are the transmission acoustic amplitude before and after lapping, respectively. The $d_0$ and $d_l$ are the thicknesses of the matching layer before and after the lapping.

# Result

In the first part, the weight ratio of alumina power to epoxy is fixed at 2:1 and the applied weight varies in an range from 39.0 MPa to 85.8 MPa with a 7.8 MPa step. All the developed specimens before characterization have been lapped to a 2mm thickness. Besides, each condition in the result has sampled multiple specimens developed individually for achieving a repeatable and precise result. The measured longitudinal velocity of each step is shown in Figure 3 (a), where a velocity enhancement from 3376 $ms^{-1}$ to maximum value 3652 $ms^{-1}$ can be seen when the applied pressures increases from 39.0 MPa and 62.4 MPa. When the applied pressure is beyond 62.4 MPa, the acoustic velocity suddenly drops and maintains at around 3380 $ms^{-1}$ within the applied pressure up to 85.8 MP. The increase of sound speed in the matching material with the increased pressure is due to the correlation effect of alumina particles inside the composite when the density is beyond a threshold value above which the sound speed of alumina will dominate. The decrease of sound speed after a critical pressure of 62.4 MPa is believed to be due to the fact that beyond this pressure, the over-pressed the composite rebounds and causes the decrease of density of alumina in the composite; this can be seen in the trend of density as a function of pressure as shown in Fig. 3(a) which has a similar trend to sound speed change. One may notice that the density has a little incoherent to the longitudinal velocity as shown in Fig. 3 (a), where the applied weight for obtaining maximum value in density shifts to 54.6 MPa instead of 62.4 MPa in the velocity. This suggests a non-linear relationship of the sound velocity and the density of alumina, and it could be process history dependent.

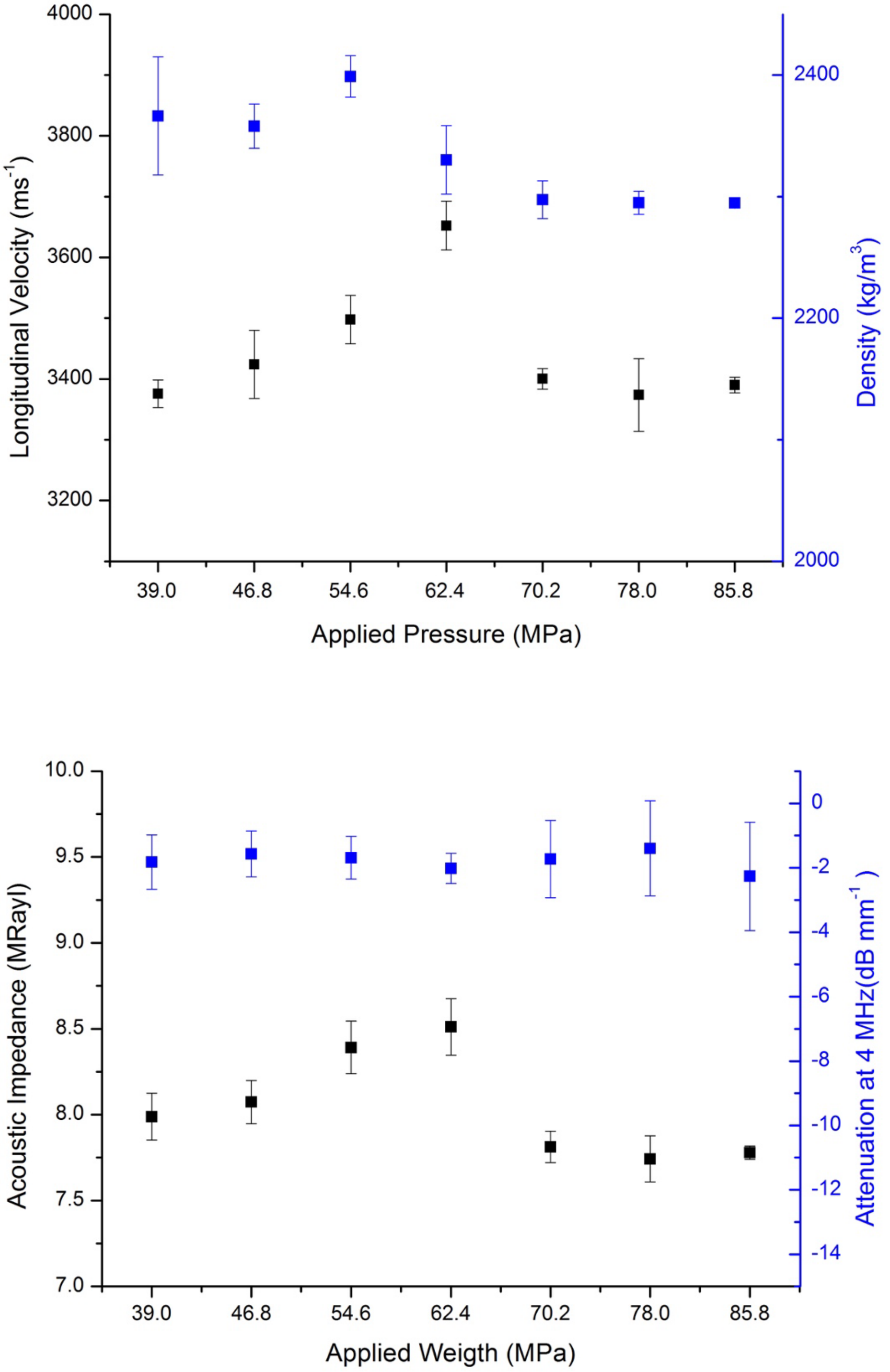

*Figure 3. a) The graph of acoustic longitudinal velocity (Black) and density (Blue)versus applied pressure and b) the relationship between acoustic impedance (Black) or attenuation at 4 MHz (Blue) at a fixed 2:1 aluminum oxide powder to epoxy ratio and applied weight.*

Figure 3 (b) shows the dependence of the acoustic impedance and loss to the applied pressure. The relationship of acoustic impedance an applied pressure shows the same trend as the velocity, i.e. the value increases from 7.99 MRayl to maximum 8.51 MRayl when the applied weight increases from 39.0 MPa to 62.4 MPa, beyond which, the impedance drops. It is apparent that the attenuation values have only a little variation from -1.40 dB/mm to -2.27 dB/mm in all applied weights at 4 MHz. The calculated attenuation at 40 MHz is between -11.12 dB/mm and -18.03 dB/mm according to the 0.9 average frequency dependent exponent. At the pressure point that obtains the maximum acoustic impedance, the attenuation is -2.08 dB/mm at 4 MHz and -16.5 dB/mm at 40 MHz respectively. This value is compatible to previous research finding from other investigators using the same ceramic material which has shown a minimum -15 dB/mm attenuation at 40 MHz.

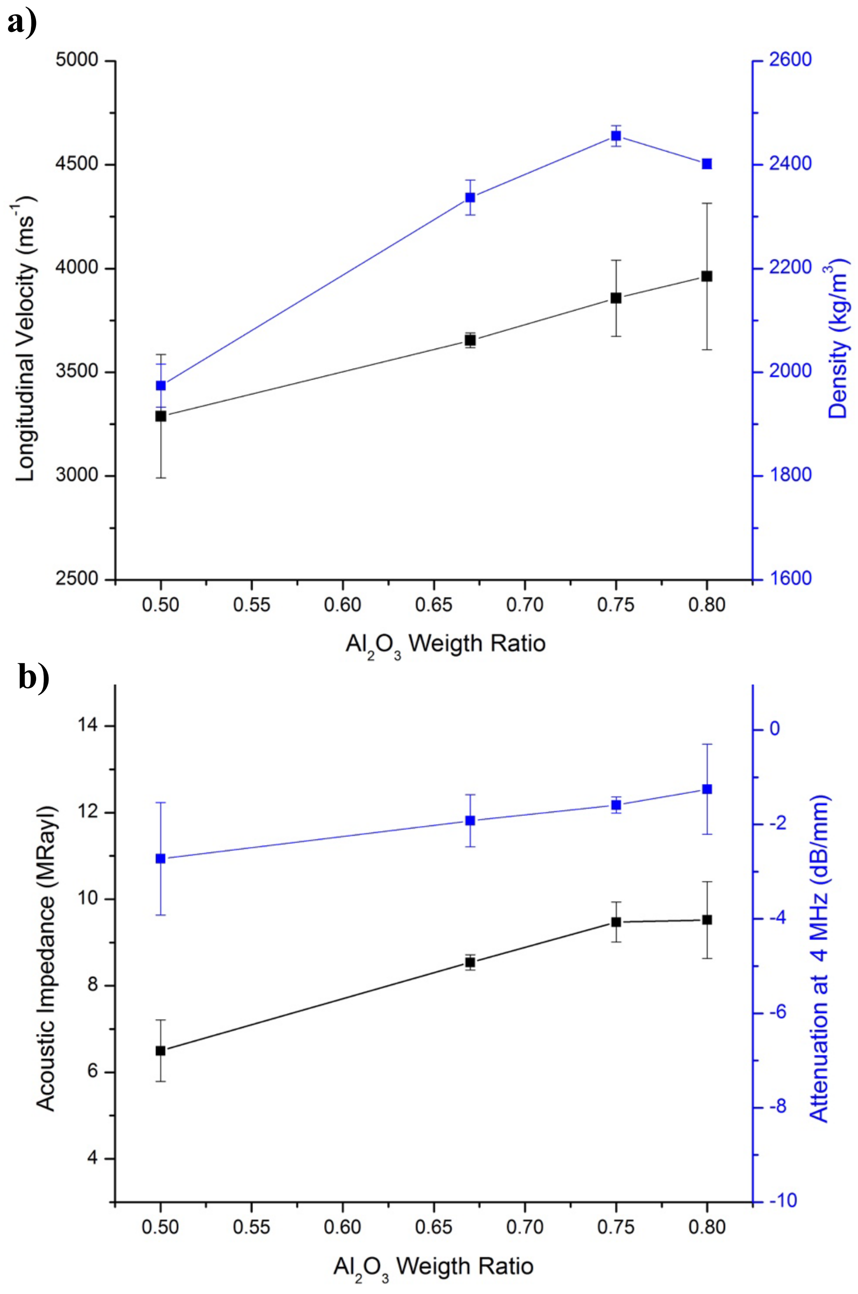

*Figure 4 a) The longitudinal velocity (Black) and density (Blue) versus the weigth ratio of aluminum oxide and b) the acoustic impedacne calculated by the measured results (Black) and the attenuation versus the weigth ratio of aluminum oxide.*

Figure 4 shows acoustic properties of the matching material as a function of alumina weight ratio in the mixture. In Figure 4 (a), the longitudinal velocity shows nearly linear increase from 3288 $ms^{-1}$ to 3961 $ms^{-1}$ at aluminum oxide to epoxy ratio from 1:1 to 4:1. The measured density illustrates an increment from 1974 kg/m$^3$ to a maximum 2456 kg/m$^3$ in a weight ratio from 1:1 to 3:1. The density slightly drops down to 2402 kg/m$^3$ while the weight ratio raises up to 4:1. As shown in Figure 4 (b), the acoustic impedance of the matching shown linearly increases from 6.50 to 9.47 MRayl when alumina to epoxy weight ratio increases from ratio 1:1 to 3:1, and then it saturates. One can also see that the attenuation saturates at 1.26 dB/mm when the alumina to epoxy weight ratio reaches 3:1. We can conclude that the 3:1 aluminum oxide powder to epoxy weight ratio and 62.4 MPa applied compression pressure are the best parameters in this new matching layer fabrication method which results in the highest acoustic impedance and lowest attenuation simultaneously. One can see from the listed date shown in Table 2, that the matching fabricated by our developed high compression pressure method shows excellent acoustic properties compared to other fabrication methods in previous reported articles. The only reported matching layer with comparable acoustic impedance to our method is by extremely high-density metal tungsten[26], however, its attenuation is -25 dB/mm at 30 MHz which is remarkable higher than the matching layer develop by our method. The matching reported in this article even has a higher acoustic impedance than matching reported by Manh *et al.* using a ceramic material, silicon, which has higher acoustic impedance than alumina in bulk format [19,24] [22].

*Table 2 The acoustic properties of matching layer developed by mutilpute method from pervious reported acticles.*

| | Longitudinal velocity(ms$^{-1}$) | Density(kg/m$^3$) | Acoustic Impedance (MRayl) | Attenuation (dB/mm) |
|---|---|---|---|---|
| $Al_2O_3$ + Insulcast 502 (0.75 Weight ration compressed under 62.4 MPa) | 3857 | 2456 | 9.47 | -10.0 (at 40 MHz) |
| $Al_2O_3$ + EPO-TEK 301[25] | 3200 | 1630 | 5.22 | -15.0 (at 40 MHz) |
| $Al_2O_3$ + Insulcast 502 (Centrifuge at 62.8 MPa/kg) | 2803 | 1812 | 5.19 | -16.6 (at 40 MHz) |
| Tungsten + EPO-TEK 301 [26] | ~1680 | ~5654 | ~9.50 | ~ -25.0 (at 30 MHz) |
| Silver + Insulcast 502 (Centrifuge at 62.8 MPa/kg)) | 1936 | 3192 | 6.18 | - 38.4 (at 40 MHz) |
| $Al_2O_3$ + EPO-TEK 301[26] | ~2868 | ~1980 | ~5.68 | -12.6 (at 30 MHz) |
| Silicon polymer 2-2 composite (Chemical Etched) [19,24] | 5818 | 1349 | 7.85 | Not addressed |
| Silicon polymer 1-3 composite(Chemical Etched) [22] | 4730 | 1335 | 6.31 | -1.72 (only in Silicon at 40 MHz) |

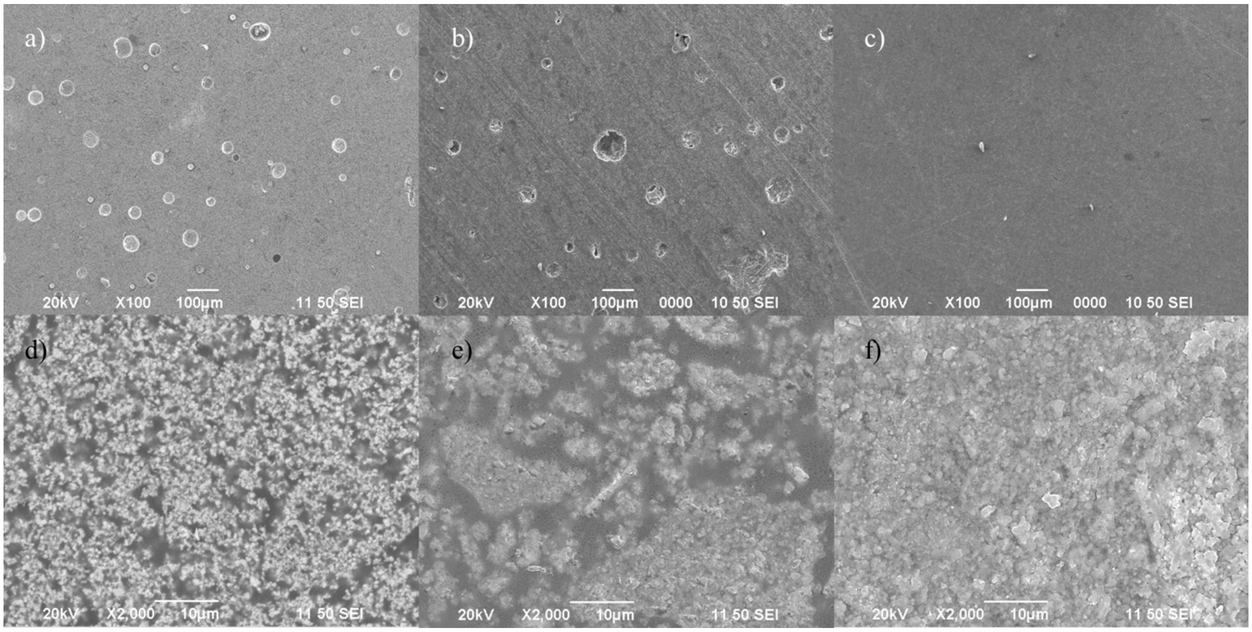

*Figure 5 a), b) and c) The scanning electron microscopy image of matching layers developed by centrifuge method with silver powder, centrifuge method with aluminum oxide and high pressure compression method with aluminum oxide, respectively, at 100X magnification. d), e) and f) at 2000X magnification.*

Our developed matching layer possesses not only excellent acoustic properties but also high uniformity microscopically. Figure 5 show the macro and microscopy structures of the matching layers developed by the high compression pressure method and metal-epoxy composite by centrifuge method. Figures 5 a), b) and c) show SEM images of the surface structure of matching layers developed by centrifuge method with silver, centrifuge method with alumina, and high compression method with alumina, respectively; while Figures 5 (d), (e) and (f) are magnified images. It is apparent that the matching layers made by centrifuge method possess much larger cavities than the compressed matching layer. The generation of cavities is possibly due to the air bubble generated by the stirring while mixing the epoxy and the powder, and these cavities have extremely low acoustic impedance and high attenuation. This may reduce the sensitivity and frequency bandwidth of the developed transducer, since the acoustic wave may be reflected or attenuated while penetrating these bubbles. On the other hand, The compression method applied a remarkable higher force than the centrifuge method, more importantly, higher than the viscosity although the aluminum oxide to epoxy weight ratio reached 4:1. Therefore, the matching layer developed using the high pressure compression method does not present any cavity on the polished surface. This high microscopically homogeneity of matching confirmed the equality of acoustic pulse transmission with its aperture to reduce the aberration of acoustic pulse which is more effective in high frequency array transducer.

To demonstrate the merit of our developed matching material, a high-frequency transducer with a double-layered matching scheme utilizing the 62.4 MPa compressed alumina-epoxy composite with 3:1 weight ratio as the first matching layer and parylene-C as the second matching layer, is fabricated. The double matching layer is casted on a single element transducer using PZT (PIC151, PI Ceramic, Germany) as the piezoelectric layer. The acoustic impedance of the PZT, designed first matching layer and second matching layer are 38.89 MRayl, 9.49 MRayl and 2.59 MRayl, respectively. Those factors were imported to a simulation programme PiezoCAD based on KLM model, so the optimized thickness of each layer can be determined. Considering the clamping effect of ultrasound transducer at high frequency, the simulated center frequency was set as 60 MHz in the programme to implement a 55 MHz transducer realistically. The optimized thickness of all layers including the piezoelectric layer are showing the in Table 3.

*Table 3 The optimized specification of each layer of the developed transducer*

| | **Piezoelectric Layer** | **First matching** | **Second Matching** | **Backing layer** |
|---|---|---|---|---|
| **Material** | PZT | High pressure compressed $Al_2O_3$ powder + Epoxy 502 | Parylene C | EPO-TEK 301-1 |
| **Weight ratio** | N/A | 3:1 at 62.4 MPa | N/A | N/A |
| **Acoustic impedance ($MRayl$)** | 38.82 | 9.47 | 2.59 | 3.00 |
| **Velocity ($ms^{-1}$)** | 4967 | 3857 | 2350 | 2650 |
| **Density ($kgm^{-3}$)** | 7816 | 2456 | 1100 | 1132 |
| **Thickness (mm)** | 0.033 | 0.018 | 0.009 | 5 |

According to Table 3, the thicknesses of both first and second matching layers may not be the exactly quarter wavelength but really close to that value. The simulated thicknesses of the PZT, the first matching layer and the second matching layer are 33, 18 and 9 µm, respectively. In the fabrication process, the PZT was lapped to the required thickness, and a Cr/Au electrode with 95 nm total thickness was deposited on the PZT's surface by magnetron sputtering. Subsequently, an aluminium housing was bounded around the PZT and a EPO-TEK 301-1 was filled in the housing as a backing layer and a mounting medium. A SMA connector was installed on the transducer and a line electrode was deposited on the front surface of the transducer to produce an electrical connection between the PZT and housing. Finally, a lapped 15 µm-thick compressed alumina/epoxy composite matching layer was attached on the front surface of the transducer using epoxy M-Bond 610 (Micro-Measurements, Raleigh, U.S.A). A fixture was employed for clamping the matching layer attached to the transducer during epoxy curing. This made the epoxy layer as thin as possible. The epoxy was cured in an oven at 65 ºC under atmospheric pressure for 24 hours. Finally, a thin layer of parylene C was deposited on the transducer using a parylene deposition system (SCS PDS2010E LABCOTER, Specialty Coating System, Inc., USA). A representative acoustic response in water of the developed transducer is showing in Figure 6, where the center frequency of the reflected acoustic pulse is 53.03 MHz. The -6 dB bandwidth shown in the frequency spectrum is around 48.37 MHz which is 91.21%. Besides the insertion loss is -36.66 dB. The measured -12 dB pulse length is 20 ns. The emission pulse of pulser/receiver (Panametrics 5900PR) in this measurement is 1μJ energy. The peak-to-peak amplitude of the received pulse with a 26 dB gain is 2.72 V. In this article, 5 transducers using the same specification have been developed. All the measured results are showing in the following Table 3.

*Table 4. Measured acoustic responses of transducers attached with alumina epoxy composite matching layer under high compression pressure at 62.4 MPa and 3:1 weight ratio.*

| | Center Frequency (MHz) | Bandwidth (MHz) | Bandwidth (%) | Insertion Loss (dB) |
|---|---|---|---|---|
| Representative Transducer | 53.03 | 48.37 | 91.21 | -36.66 |
| Transducer-2 | 52.90 | 45.08 | 85.22 | -36.27 |
| Transducer-3 | 52.67 | 46.45 | 88.19 | -34.11 |
| Transducer-4 | 49.70 | 44.13 | 88.79 | -33.25 |
| Transducer-5 | 51.29 | 44.00 | 85.79 | -33.55 |

The transducer with the matching layer developed by the high-pressure compression method shows an ultra-wide bandwidth and high consistency. However, for achieving a massive wide bandwidth, the signal amplitude has to be sacrificed due to the large back reflected wave absorption. Fortunately, the signal-to-noise ratio of this developed transducer is high, so the signal can be amplified massively to produce a high amplitude signal.

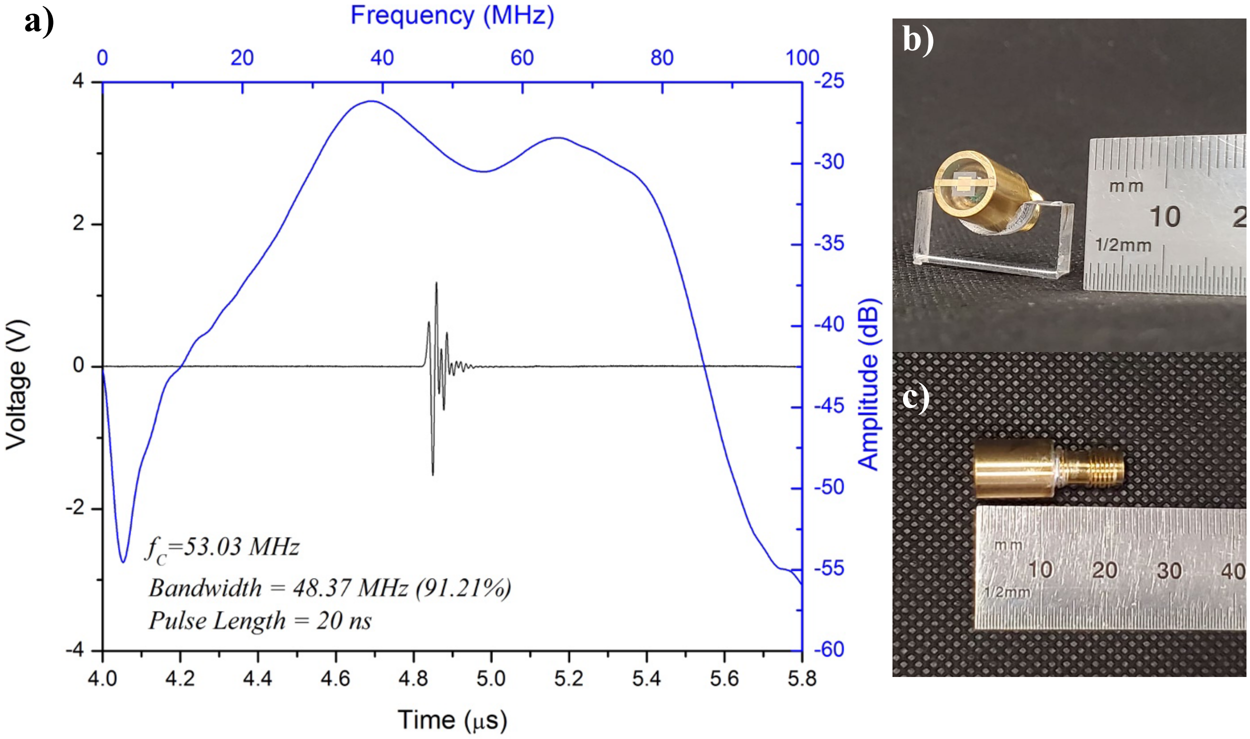

*Figure 6 The obtained acoustic response of the transducer casted the matching layer fabricated by high pressure compression method (Black) and its frequency spectrum (Blue).*

# Conclusion

In this article, a new matching layer development method using high pressure compression has been presented. The longitudinal velocity and acoustic impedance of the developed matching can be manipulated by the applied pressure and the component weight ratio. From the aluminum oxide and epoxy mixture demonstration, the maximum longitudinal velocity and acoustic impedance can be accomplished as 3857 $ms^{-1}$ and 9.47 MRayl, respectively, with a 3:1 aluminum oxide to epoxy ratio and prepared under 62.4 MPa pressure. The acoustic properties are relatively higher than others reported matching with different material and method. The great uniformity and homogeneity of the developed matching by this high-pressure compassion method also has been shown in macro and microscopic scale. This may reduce the distortion or the aberration of the matching to produce a more coherence acoustic signal in array transducer especially the one using electrical steering method for biomedical imaging. A transducer has demonstrated an excellent performance by using the matching fabricated in this investigation. The ultrawide 91% -6 dB bandwidth of a 52 MHz transducer is comparably higher than those formerly reported results.

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