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Experimental Investigation of a Functionally Graded Composite Layer for Sound Absorption in Ultrasonic Transducers with an Approach to Fabrication and Characterization

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Abstract: Conventional single-layer backing materials in ultrasonic transducers often show limited sound absorption and suffer from particle agglomeration, bubble formation, and uneven impedance distribution, reducing transducer efficiency. This study focuses on developing and characterizing epoxy-Al_2O_3 functionally graded composites (FGMs) to overcome these limitations. FGMs were fabricated with alumina particle sizes of 50, 100, and 200 µm and varying volume percentages to optimize acoustic and mechanical properties. Mechanical testing showed that hardness and elastic modulus increased up to 19% and 15% alumina content, respectively, while higher contents caused bubbles and cavities that reduced performance. Acoustic analysis demonstrated that FGMs achieved up to 98% sound absorption, representing a 30% improvement in attenuation compared to single-layer composites, due to impedance gradients and enhanced wave energy dissipation. Scanning electron microscope confirmed uniform particle dispersion at optimal alumina concentrations, mitigating agglomeration and structural defects. These results highlight the potential of epoxy-Al_2O_3 FGMs as high-performance backing layers for ultrasonic transducers, with further studies recommended on frequency-dependent behavior and long-term stability.

Keywords: ultrasonic transducer, backing layer, FGMs, polymer composite, sound absorber composite

1. Introduction

Ultrasonic transducers, with their remarkable versatility and effectiveness, have evolved into indispensable tools across a broad spectrum of applications. Initially recognized for their pivotal role in medical imaging, where they enable precise visualization of internal body structures with minimal invasiveness, these transducers have transcended their original domain to permeate numerous other fields [1]. In the realm of energy harvesting, ultrasonic transducers emerge as catalysts for transforming ambient vibrations into usable electrical energy, offering sustainable solutions for powering various devices and systems [2]. Moreover, in the realm of nondestructive testing, ultrasonic transducers serve as invaluable assets, facilitating thorough inspection and evaluation of materials and structures without causing any damage [3]. By emitting high-frequency sound waves and analyzing their reflections, these transducers enable precise detection of defects, cracks, or irregularities in diverse materials, thereby ensuring safety and reliability across industries ranging from aerospace to automotive [4].

Ultrasonic transducers used in nondestructive testing have a complex design comprising key elements for generating and propagating ultrasonic waves [5]. The piezoelectric element is at the core, converting electrical energy to mechanical vibrations and emitting sound waves [6]. This pivotal element serves as the primary source of ultrasonic waves responding to electrical signals by oscillating at high frequencies, thereby emitting sound waves into the surrounding medium [7]. An additional layer is a matching layer, strategically positioned between the piezoelectric element and the medium of interest [8]. The matching layer acts as an impedance-matching interface, ensuring efficient transmission of ultrasonic waves from the piezoelectric element into the target medium while minimizing reflections and maximizing energy transfer [9]. Furthermore, to optimize the acoustic properties and stability of the transducer system, a backing layer is often incorporated [10]. This layer serves as a sound absorption medium that attenuates unwanted acoustic reflections and reverberations within the transducer assembly [11]. By dampening undesirable acoustic phenomena such as ringing or reverberation, the backing layer contributes to the production of clear and accurate ultrasonic signals, which is essential for precise imaging and reliable nondestructive testing [12]. Figure 1 illustrates all components of a nondestructive ultrasonic transducer.

The backing layer in ultrasonic transducers plays a crucial and important key role in their performance. It serves as a dampener for vibrations generated by piezoelectric materials and facilitates efficient energy transfer throughout the transducer

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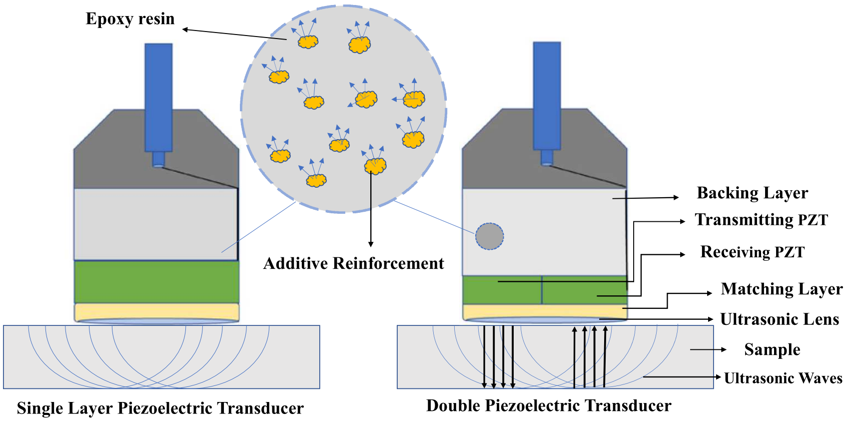
Figure 1
A schematic of the components of single and double piezoelectric ultrasonic transducers



assembly [13]. In other words, a material with strong sound absorption properties is placed behind the active component to control how long the sound lingers. This material serves two main purposes: first, it dampens the sound waves, cutting down on echoes at the back of the active part, and second, it has a similar acoustic impedance to the active element, ensuring they connect well acoustically [14]. Metal particle–polymer composites are commonly used for this purpose, but their fabrication process is complex [15]. Several factors, such as the difficulty of precisely controlling the backing layer's thickness using traditional grinding methods and the uneven distribution of acoustic impedance due to sedimentation layering of heavy metal powder within the composite, contribute to potential deviations in the composite material's properties. The intricacies of designing and manufacturing the backing layer are emphasized by the precise requirements imposed by the transducer's operation. Not only does the backing layer need to absorb a significant portion of the backward wave to minimize unwanted reflections, but it also must reflect a portion of the wave to maintain sensitivity. This delicate balance is crucial for optimal transducer performance. Meeting these precise acoustic impedance requirements is a fundamental challenge in transducer design and manufacturing, requiring meticulous attention to detail and innovative solutions to ensure the reliability and effectiveness of ultrasonic systems in medical imaging and nondestructive testing applications.

Finding suitable materials (matrix and reinforcement) for backing composites in ultrasonic transducers presents considerable challenges due to several factors. Backing materials often consist of polymer composites infused with metal particles, a popular choice due to their ease of manufacturing and the flexibility to tailor their acoustic properties to specific needs [16]. In traditional designs, heavy metal particles are commonly utilized; in fact, they are preferred for their high density and acoustic impedance properties. Complementing the heavy metal particles are low-impedance polymers like epoxy and rubber, while the concentration of the metal particles loaded into the composite material determines the control of acoustic impedance, phase velocity, and attenuation [17]. These polymers help balance the overall impedance of the composite, ensuring compatibility with adjacent layers. The composite structure typically involves a matrix of heavy metal particles dispersed within a polymer base. This arrangement allows for the manipulation of acoustic impedance while maintaining structural integrity. The selection and proportioning of metal particles and polymers are crucial for achieving the desired acoustic impedance and ensuring efficient transmission of ultrasonic waves through the transducer. In addition, material selection for backing composites must also consider mechanical properties such as stiffness, flexibility, and durability. Researchers have explored various materials as backings for nondestructive ultrasonic transducers, aiming to optimize their performance. Among these materials, tungsten, copper, silver, and other substances have been investigated extensively [18]. These materials offer unique properties such as enhanced sound absorption and compatibility with the active piezoelectric element. However, alumina emerges as a noteworthy candidate due to its favorable properties. Despite its comparatively limited documentation in academic literature, alumina demonstrates promising attributes for backing composites in ultrasonic transducers. Its robust acoustic impedance matching with the active component ensures efficient energy transfer, while its damping properties contribute to minimizing echoes and improving overall signal fidelity. As researchers continue to delve into the realm of ultrasonic transducer design, alumina stands out as a compelling material warranting further exploration and study.

Binxia et al. [19] conducted a theoretical and experimental examination of the sound absorption capabilities of a composite structure consisting of Al_2O_3-polyurethane foam and a microperforated plate. They constructed various configurations of these materials and thoroughly explored the influence of cavity depth, the presence of a perforated plate, and the positioning of the foam on sound absorption properties. Their findings highlighted the significant impact of the perforated plate's placement and the arrangement of resonance structures on sound absorption effectiveness. Yuan et al. [20] prepared flexible polyurethane foam (PUF) and Al_2O_3 nanoparticle composites with a thickness of 20 mm and a diameter of 100 mm by the impregnation method as a sound absorption composite. They examined the sound absorption properties of distinct polyurethane (PU) and Al_2O_3-PU foam specimens. The findings revealed a positive correlation between sound absorption coefficients and frequency amplification within the lower range of 50–1250 Hz. Furthermore, the study demonstrated that the introduction of Al_2O_3 nanoparticles into PU foam structures yielded a notable enhancement in sound absorption efficacy within the aforementioned low-frequency range. Tayyab and colleagues conducted a study to evaluate the impact of an Al_2O_3/PUFs sandwich composite as a reinforcement material, with a particle diameter of 40 nm and weight proportions ranging from 0 to 10 wt%, on enhancing the sound absorption coefficient. They observed a notable enhancement in the damping response and buckling behavior exhibited by the Al_2O_3 sandwich samples. In the current perspective, a notable rise of 38.3% in the damping ratio was ascertained for the specimens reinforced with 2 wt% Al_2O_3 in contrast to the unmodified specimens, while the specimens reinforced with 1 wt% and 3 wt% Al_2O_3 exhibited increases of 31.4% and 26.8%, respectively [21]. Subsequent to analysis, it was noted that the specimens possessing a 10 wt% Al_2O_3 reinforcement ratio demonstrated a non-uniform distribution and agglomeration formation of the alumina particles within the confines of the PUF matrix. In addition, they argued that in order to mitigate the impact of agglomeration and heterogeneous dispersion, particle separation through the use of solvents such as acetone is recommended. Natural fiber/epoxy composites have shown promise as materials for sound absorption applications. Combining the acoustic properties of natural fibers with the damping properties of epoxy resin, these composites offer a sustainable and effective solution for sound absorption in various settings [22]. Das and Biswas [23] investigated the physical, mechanical, and water absorption behavior of epoxy composites reinforced with coir fibers and filled with Al_2O_3 particulates. The experimental findings indicated that the composite properties are enhanced with the inclusion of Al_2O_3 particulates. Furthermore, an enhancement in the mechanical properties of the composites with Al_2O_3 filler is observed compared to those without filler.

Although polymer–metal composites have been widely studied for backing layers in ultrasonic transducers, most research focuses on single-layer structures that often face challenges such as limited sound absorption, uneven particle distribution, and bubble formation. While alumina-reinforced composites have shown promising acoustic properties in other applications, there is a lack of systematic study on functionally graded composites (FGMs) as backing layers. In particular, the combined influence of alumina particle size and volume fraction on both mechanical performance and ultrasonic wave attenuation has not been thoroughly investigated. This gap underscores the need for optimized FGM designs that can enhance sound absorption while maintaining structural integrity and minimizing fabrication defects. The purpose of this study is to develop epoxy resin-based composites reinforced with Al_2O_3 powders using an FGM structure to optimize their acoustic and mechanical properties. The study aims to create a high-performance backing layer for ultrasonic transducers that minimizes acoustic reflections and enhances energy dissipation through improved sound absorption. By varying alumina particle sizes and volume percentages, the research investigates the effects on sound attenuation, hardness, and modulus of elasticity, with a focus on maximizing performance while mitigating fabrication challenges such as particle agglomeration, uneven distribution, and the formation of bubbles or cavities. The findings aim to demonstrate the potential of FGMs as a superior alternative to traditional single-layer composites, advancing material design for engineering applications in nondestructive testing and ultrasonic imaging technologies.

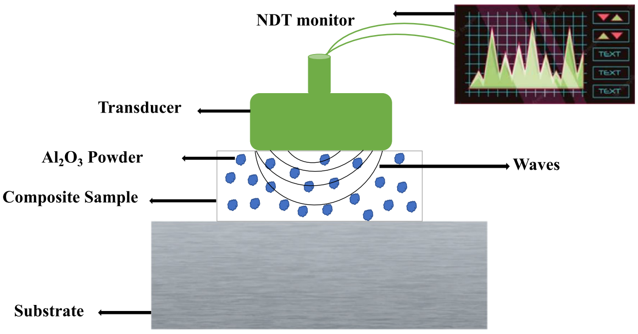
2. Material and Method

In this study, the composite material as a sound absorption structure for ultrasonic transducers were prepared with epoxy resin (LR620), 1.17 g/cm^3 density, 3 kg·cm^{-2}·s^{-1}×10^5 acoustic impedance, hardener Eponate 520 (purity of 99% purchased from Iran Composite Company), and alumina powder with >99% purity was obtained from Merck as an additive with 3.86 g/cm^3 density and 35 kg·cm^{-2}·s^{-1}×10^5 acoustic impedance by single-layer and FGM structure. A series of composite samples was prepared to investigate the effects of alumina particle size and volume fraction. Three different particle sizes (50, 100, and 200 μm) were used, and for each particle size, composites with nine different volume percentages were fabricated. Single-layer composites without alumina were also prepared and used as control samples to provide a baseline for comparison. The fabrication method of composites consists of two steps. First, in order to optimize either the volume percentage or the particle size of alumina powders, backing specimens were fabricated. In the second step, utilizing the best acoustic and mechanical results achieved from the first step, the backing material with FGM structures was created. In the preparation process, alumina powders with standard sieves were classified into 50, 100, and 200 μm. Then, epoxy resin with different contents of powders was mixed, and in order to ensure complete dispersion of the additive inside the resin, an automatic mechanical mixing device (RQ-40 Plus, REMI Group, India) with different speeds of 50, 70, and 90 rpm for a total of 30 min was used. In order to combine the raw materials and reduce the bubbles in the structure, first, the raw materials were mixed together at room temperature and mixed for 15 min. Next, the mixture was placed in a container of 70 °C water and mixed at a speed of 90 rpm for 20 min. Then the container containing the ingredients was placed in a −4 °C container, and the stirring speed was reduced to 50 rpm. At the end, the composition was cast in the prepared mold by hand. Figure 2 presents the fabrication processes of the samples schematically.

Figure 2
The fabrication process of composites

In desiring to study the uniform distribution of the alumina powders, cavity, and bubble presence, as well as the wettability of the additive on the substrate in single-layer and FGM samples, a scanning electron microscope (SEM) supplied by VEGA/TESCAN (Czech) was used. The hardness properties of composites with the KOOPA model UV1 device (KOOPA Company, Iran) with 1 kilogram-force in a 10-s time application were studied. The modulus of elasticity with the ZWICK/ROELL model Z100 device (ZwickRoell GmbH & Co. KG, Germany) with 18N force according to ASTM D790 standard was used. Wettability and contact angle measured based on ISO 17025 standard. In this study, due to the lack of availability of an impedance tube device for determining the sound absorption coefficient for high frequency, an alternative method was utilized, and a 2.25 MHz ultrasonic transducer (HUATEC Company, China) (transmitter–receiver, Tru-Sonics) and a detector Masterscan D-70 (HUATEC Company, China) were used. Figure 3 illustrates the methodology employed for quantifying sound attenuation.

Figure 3
Schematic of the process of measuring the sound absorption of composite samples reinforced with aluminum particles

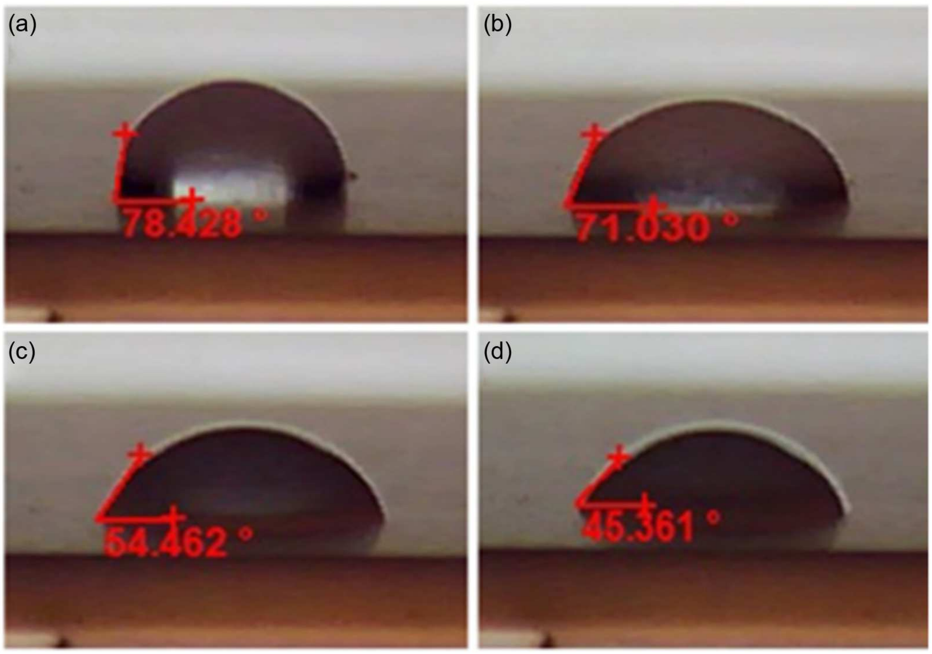


3. Results and Discussion

3.1. Contact angle

Figure 4 presents the contact angle of epoxy resin on the alumina substrate, which was measured to be approximately 62°. This contact angle indicates a moderately wetting regime, which is particularly favorable for particle-matrix systems where complete spreading is not required, but stable interfacial adhesion is essential. From a materials engineering perspective, this level of wettability represents a balance between sufficient resin spreading and controlled interfacial interaction. The observed contact angle confirms that the epoxy resin can adequately wet the alumina surface, enabling strong interfacial bonding without excessive resin penetration that could lead to particle agglomeration or phase separation. Such interfacial properties are critical for load transfer efficiency in particulate-reinforced composites, as insufficient wetting would result in weak interfaces and premature failure under mechanical or acoustic loading [24–26]. More importantly, in the context of backing materials for ultrasonic transducers, interfacial wettability plays a decisive role in acoustic energy dissipation and impedance tailoring. A contact angle of 62° facilitates uniform dispersion of alumina particles within the epoxy matrix, which directly contributes to a more homogeneous microstructure [27]. This homogeneity is essential for achieving stable acoustic impedance and minimizing internal scattering and reflection losses during ultrasonic wave propagation [28]. Furthermore, the moderate wetting behavior observed in this system supports the formation of functionally graded structures, where controlled particle distribution is required to tune acoustic attenuation and mechanical damping properties across the backing layer. Therefore, the measured contact angle is not merely a surface property but a key parameter governing the mechanical integrity, acoustic performance, and long-term reliability of epoxy–alumina functionally graded composites used in ultrasonic transducer applications.

Figure 4
Wettability of alumina powder in contact angle and SEM image. (Left) Sequence of dropping an epoxy resin dropped on the alumina substrate (angle of *a* = 78.43°, *b* = 71°, *c* = 54.46°, and *d* = 45.36°). The SEM image of the epoxy resin and an alumina powder



3.2. Scanning electron microscope (SEM)

Figures 5, 6, 7, and 8 present SEM micrographs illustrating the dispersion state of alumina particles within the epoxy matrix for both single-layer and functionally graded composite samples. The microstructural observations clearly demonstrate that particle size plays a critical role in governing dispersion uniformity and agglomeration behavior. As expected, smaller particles exhibit a higher tendency toward agglomeration due to increased surface energy and interparticle attraction, whereas larger particles are more susceptible to point-contact clustering when insufficient mixing energy is applied. As shown in Figure 5, samples containing well-dispersed, non-agglomerated alumina particles display a homogeneous microstructure, indicating effective particle-matrix interaction. In contrast, samples incorporating alumina particles with an average size of 100 µm exhibit localized point-connected clusters, which are characteristic of agglomeration phenomena. Such microstructural heterogeneities are undesirable, as they can act as stress concentrators and acoustic scattering centers, ultimately degrading both mechanical integrity and ultrasonic performance. The effectiveness of the proposed fabrication strategy is evident in its ability to significantly reduce particle agglomeration and promote uniform distribution across the epoxy matrix. This outcome confirms that appropriate control of processing parameters such as mixing force, rotational speed, and mixing duration is essential, particularly at higher alumina volume fractions. At elevated filler contents, the epoxy–alumina mixture exhibits increased viscosity, leading to a semi-gel state that restricts particle mobility and enhances the likelihood of agglomeration and void entrapment.

Figures 6 and 7 further illustrate these processing-induced challenges, including bubble migration, cavity formation, and localized particle clustering, which become more pronounced with increasing alumina content. These defects are of particular concern in ultrasonic backing materials, as trapped air voids and particle clusters introduce acoustic impedance discontinuities, resulting in increased signal attenuation and reduced energy absorption efficiency. Figure 8 demonstrates the successful

Figure 5
Uniform distribution of alumina powders in epoxy resin substrate in single-layer samples. (a) 100 µm and (b) 200 µm

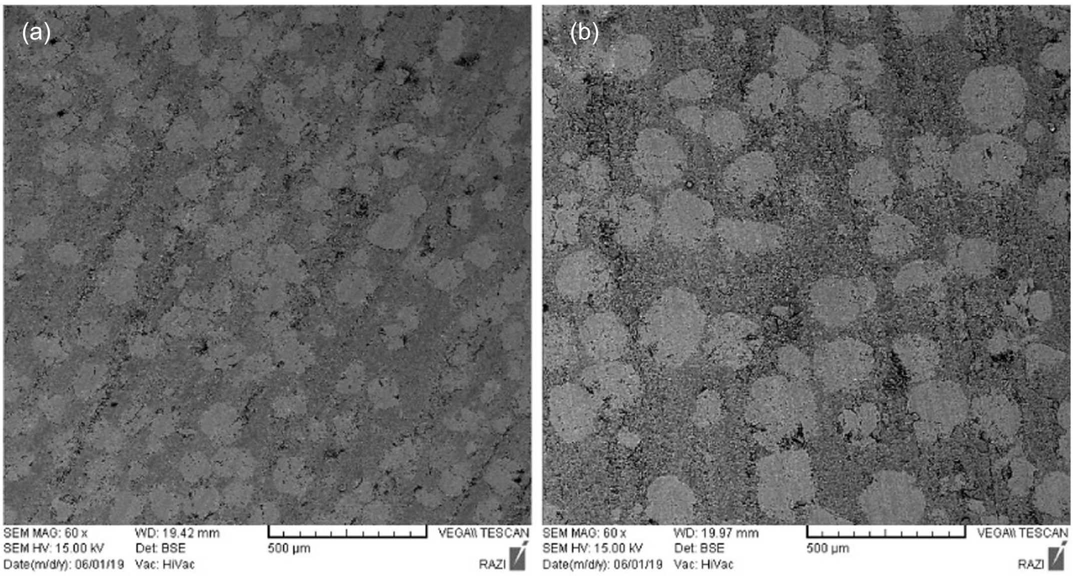


Figure 6
SEM images of the single-layer 31 Al 200 sample showing microstructural defects: (a) bubbles distributed on the surface and (b) cavities formed within the matrix

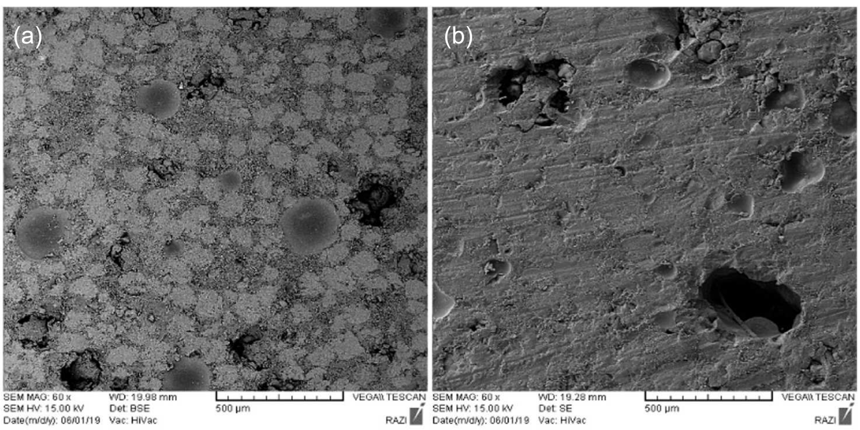


Figure 7
The SEM images of the bubble (red) and cavities (white) of the (a) 23 Al 200 sample and (b) 31 Al 200 sample

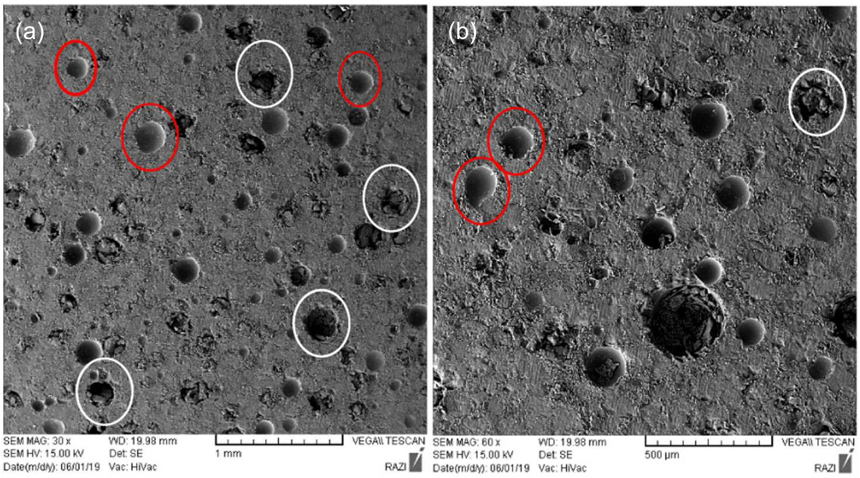
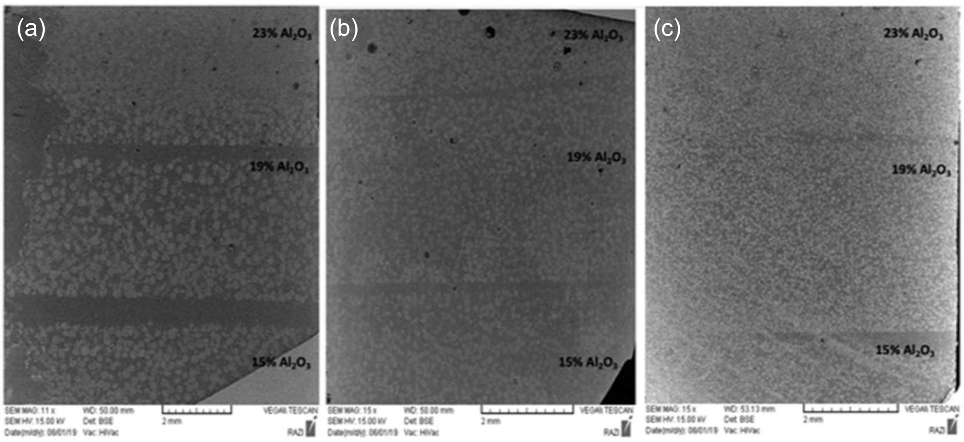


Figure 8
The FGM structure samples with diverse volume percentages and particle sizes. (a) 200 µm FGM sample, (b) 100 µm FGM sample, and (c) 50 µm FGM sample. The volume percentage of alumina increased layer by layer. The first layer of all samples contains 15% Al_2O_3, the second 19%, and third 23%



fabrication of functionally graded material composites incorporating alumina particles in the size range of 50–200 µm with controlled volume fraction variation. The resulting graded microstructure confirms that the adopted processing route enables precise control over particle distribution, which is essential for tailoring acoustic impedance gradients and damping properties. Consequently, the SEM results provide strong microstructural evidence that the developed fabrication approach is suitable for producing epoxy–alumina FGMs with the structural uniformity and reliability required for ultrasonic transducer backing applications.

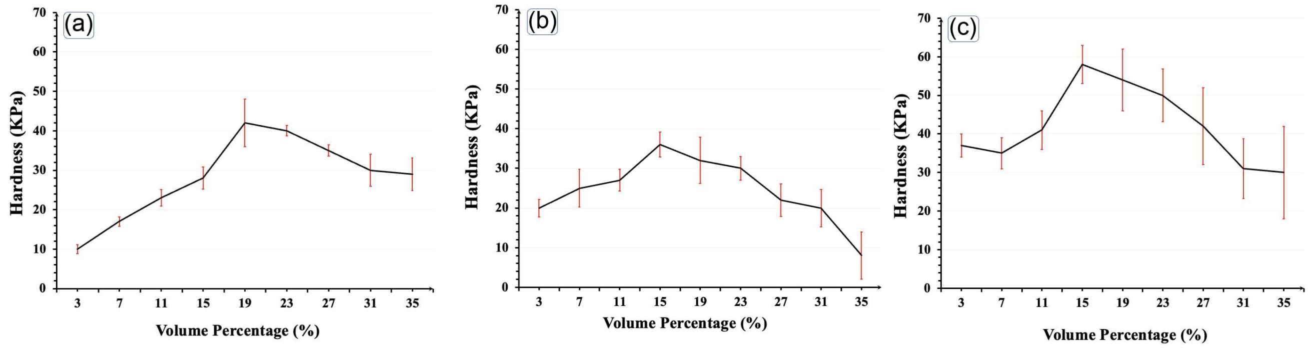
3.3. Mechanical properties

3.3.1. Hardness

Figure 9 shows the hardness of the composite specimens reinforced with 50,100, and 200 µm alumina powders with various volume percentages. The hardness value of the composites reinforced with alumina raised due to the increasing volume percentage of the reinforcing phase in the epoxy resin substrate so that the hardness amount of the polymer sample without reinforcing powders alumina from 16.1 kPa reached the highest value of 60 kPa. The first reason for this improvement is that the alumina particles, being harder and more rigid than the epoxy resin matrix, act as reinforcements within the composite. When the composite cures, the alumina particles become embedded in the resin, creating a network of reinforcement that enhances the overall hardness of the material [29].

In addition, the strong interfacial bonding between the alumina particles and the epoxy resin matrix is crucial for maximizing the reinforcement effect [30]. When the particles are well-bonded to the matrix, they effectively resist deformation and enhance the overall hardness of the composite material [31]. The volume fraction of alumina particles in the composite also plays a significant role. Higher volume fractions typically lead to greater reinforcement and, consequently, increased hardness. However, there is an optimal range for volume fraction beyond which further increases may result in diminishing returns or even decreased mechanical properties due to agglomeration or poor dispersion. The significant result is that at volume percentages above 19%, the hardness values of the composites in all three particle sizes of 50, 100, and 200 µm have reduced. The SEM images (Figure 7)

Figure 9
Hardness of composites reinforced with alumina powders with different average particle sizes. (a) 50, (b) 100, and (c) 200 μm



taken at 23% indicate that at high volumetric bubble and cavity in the structure were created. The optimum amount of alumina powders as a reinforcement material in epoxy resin is 19%. The reason for decrement is related to some different phenomena. First, the bubbles and cavities create voids or empty spaces within the composite material. These voids interrupt the continuity of the material and act as stress concentrators, making the composite more susceptible to deformation and reducing its overall hardness [32]. Second, they can disrupt the interfacial bonding between the alumina particles and the epoxy resin matrix. In regions where voids are present, there is less contact between the reinforcement and the matrix, leading to weakened load transfer and reduced mechanical properties, including hardness [33]. In addition, they tend to concentrate stress in localized regions of the composite material. When subjected to mechanical loading, these stress concentrations can lead to premature failure or deformation of the material, resulting in reduced hardness [34]. Furthermore, they effectively occupy space within the composite material without contributing to its mechanical properties. As a result, the effective volume fraction of reinforcement decreases, leading to a reduction in the overall reinforcement effect and, consequently, hardness.

3.3.2. Modulus of elasticity

Table 1 shows the modulus of elasticity of the composites with different volume percentages. As the volume percentage of the reinforcement phase increases in the epoxy resin substrate, the modulus of elasticity increases. As the volume percentage increases, the reinforcement phase has an increasing trend of up to 15% of the modulus of elasticity, reaching 160 kPa at the highest value. Adding alumina powder to epoxy boosts stiffness, strengthens the material, improves load transfer, enhances bonding, restricts polymer chain movement, and optimizes particle distribution, resulting in a stiffer, more rigid composite with a higher modulus of elasticity. Utilizing alumina powder in the epoxy resin matrix restricts polymer chain mobility, reducing resin deformation under stress and yielding a stiffer composite with a higher modulus of elasticity [35]. In addition, effective dispersion and bonding of alumina particles with the epoxy resin matrix are vital for maximizing reinforcement. Robust interfacial bonding facilitates efficient stress transfer, reducing localized deformation and improving overall modulus of elasticity [36]. Furthermore, Al_2O_3 powders are tougher and more rigid than the epoxy resin matrix, serving as strengthening agents within the composite, so if the amount of alumina powder rises, more of these rigid particles are present in the composite. This reinforcement boosts the material's overall rigidity, resulting in a greater modulus of elasticity, and they improve load transfer by distributing stress more effectively than the resin alone, resulting in a higher modulus of elasticity [37].

At values greater than 15% by volume of the reinforcement phase, the modulus of elasticity of the samples decreases. The occurrence of agglomerations in the composite systems results in an inhomogeneous distribution and subsequently amplifies the interaction between the filler and polymer matrix. An agglomeration of alumina powders in an epoxy resin composite leads to inhomogeneous distribution, poor stress transfer, weak interfacial bonding, increased porosity, localized deformation, and microstructural defects. These factors collectively impair the reinforcing effect of the alumina particles and reduce the stiffness of the composite, resulting in a decreased modulus of elasticity. The present study has found a reduction in the elastic modulus

Table 1
The modulus of elasticity of the composite specimens with different volume percentages (Vol%). The reported values are the mean of three independent measurements. The uncertainties are characterized by the standard deviation (σ), and the values are presented as mean $\pm$ σ

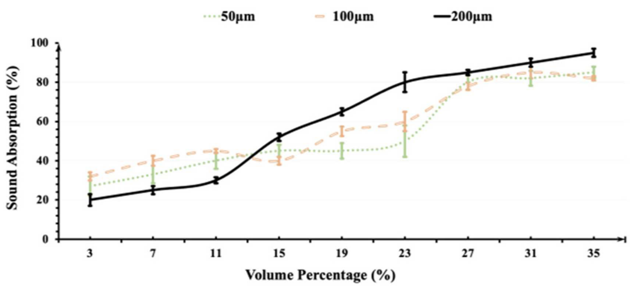
	Volume percentages (%)								
Particle size, μm	3	7	11	15	19	23	27	31	35
	Modulus of elasticity								
50	50.0 ± 2.0	56 ± 2.62	53 ± 2.01	160 ± 4.32	81 ± 2.68	94 ± 2.47	63 ± 0.25	43 ± 1.21	46 ± 0.12
100	33 ± 3.0	59 ± 0.47	67 ± 0.94	132 ± 2.49	101 ± 1.25	65 ± 2.95	67 ± 1.23	60 ± 2.22	43 ± 1.00
200	55 ± 1.25	66 ± 1.70	65 ± 0.82	68 ± 0.47	50 ± 0.47	52 ± 3.01	59 ± 0.34	44 ± 1.92	45 ± 0.23

of the composites due to structural changes. The results demonstrate that the optimal volumetric percentage of the reinforcement phase is 15%, as observed in particles of sizes 50, 100, and 200 μm, respectively.

3.4. Acoustic properties

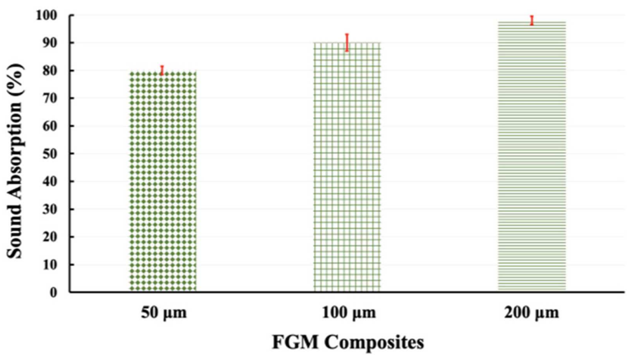
Figure 10 illustrates the sound absorption of ultrasonic waves of composite samples with an average size of various alumina particle sizes. The sound absorption analysis of the specimens reveals an exponential relationship between the volumetric proportion of alumina and the absorption of ultrasonic waves within the structure. At a 3% concentration of Al_2O_3, ultrasonic wave absorption is at its lowest, at 25%. However, as the concentration of alumina increases, the absorption rate significantly rises to 95%. This increase in alumina powder within the epoxy resin matrix has clearly enhanced damping properties. The primary reason for sound absorption and damping in the composite is the epoxy resin's viscoelastic properties, which allow it to both deform elastically and dissipate energy viscously [38]. Using Al_2O_3 particles enhances these properties, improving the composite's ability to dampen and absorb sound [38]. Additionally, alumina has a different acoustic impedance than epoxy resin, creating an impedance gradient that aids in sound absorption and attenuation [39]. The increased density and mass from the alumina powder also improve sound absorption by providing greater resistance to sound wave propagation [40]. Uniformly dispersed alumina particles scatter incoming sound waves, reducing their energy and enhancing absorption, especially at higher concentrations [41]. Moreover, the interaction between the resin and alumina particles increases internal friction, converting more acoustic energy into heat and further enhancing sound absorption.

Figure 10
Sound absorption of ultrasonic waves in composite samples of various average sizes of alumina particles



A significant rise in the absorption rate of all samples is noticed once the volumetric percentage of alumina reinforcement exceeds 23%. This sudden increase in the slope of aberration in composite specimens beyond the 23% threshold can be explained by the presence of air pockets within the composite structure, which is clearly visible in the SEM images. Figure 9(b) depicts bubbles inside the structure in the 31 Al 200 composite sample. In general, increasing the volumetric percentage of the alumina-reinforcing phase in the epoxy resin substrate has led to the formation of bubbles due to the mixing process [33]. This phenomenon has further amplified the absorption intensity. Higher Al_2O_3 content can lead to an increase in microstructural features such as small voids or porosity at the interfaces between the resin and particles, so these microstructural features can trap and dissipate sound waves, contributing to improved sound absorption. However, it is crucial to balance this effect as excessive porosity might compromise the structural integrity of the composite. Figure 11 shows the sound absorption of the composite samples with an FGM structure. According to the graph, the sound absorption of gradients compared to single-layer specimens (Figure 10) has increased dramatically. The main reason for this increase is the use of optimized single-layer composite samples with particle size and volume percentage of the reinforcement phase. The second reason for increasing the damping of composite specimens with a gradient structure is the increase in thickness of the backing layer to 6 mm, and this causes the scattering, absorption, and damping mechanisms of the waves to occur at a higher thickness, as a result of which, the waves lose their energy and attenuate. As seen in the results, the functional gradient structure causes the absorption and attenuation of ultrasonic waves at the highest value to reach 98%, which can greatly affect the efficiency of the backing.

Figure 11
Sound absorption of ultrasound waves of composite samples with FGM structure. FGM samples consist of 3 layers, whose volume percentages gradually increase to 15%, 19%, and 23 %, respectively



4. Conclusion

In the present study, the composite networks of epoxy resin and Al_2O_3 were prepared by using the functionally graded structure with different ratios of epoxy resin/alumina. SEM results showed the distribution of the additive in epoxy resin, and in high volume percentage of alumina, there are some bubbles and cavities so that effects on sound absorption properties and mechanical properties. The sound absorption coefficient results demonstrated that the formation of a functionally graded structure significantly enhanced the acoustic performance of the composite. This improvement is attributed to the increased additive content, which intensifies wave–particle interactions and promotes the conversion of acoustic energy into thermal energy, thereby improving the sound absorption capability of the composite.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Majid Mohammadi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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