applied sciences

Review

Multifunctional Integrated Underwater Sound Absorption Materials: A Review

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Abstract: Rapid improvements in underwater vehicle technology have led to a significant increase in the demand for underwater sound absorption materials. These materials, unlike their counterparts utilized in air, must have high hydrostatic pressure resistance, corrosion resistance, and other advantageous attributes. This necessitates the development of innovative, composite sound-absorbing materials with multifunctional properties, which presents substantial challenges for researchers. In this comprehensive review, we systematically analyze and categorize the mechanisms governing underwater sound absorption, hydrostatic pressure resistance, and corrosion prevention while considering related research advances. Furthermore, we provide an extensive overview of research advancements, existing challenges, and potential solutions pertaining to multifunctional and integrated underwater sound-absorbing materials. This review aims to serve as a valuable resource for future investigations into the development and optimization of multifunctional integrated underwater sound-absorbing materials, thereby contributing to the advancement of underwater vehicle technology.

Keywords: multifunctional materials; underwater sound absorption; anti-corrosion; high hydrostatic pressure resistance

Citation: Chen, X.; Meng, L.; Liu, Z.; Yang, F.; Jiang, X.; Yang, J. Multifunctional Integrated Underwater Sound Absorption Materials: A Review. *Appl. Sci.* **2023**, *13*, 5368. https://doi.org/10.3390/app13095368

Academic Editor: Lamberto Tronchin

Received: 23 March 2023
Revised: 20 April 2023
Accepted: 24 April 2023
Published: 25 April 2023

1. Introduction

In recent decades, advancements in underwater vehicle technology have led to significant improvements in their overall performance. As a result, there is an increasing research interest regarding underwater sound absorption materials (USAM). This is because sound waves can travel long distances (up to ten thousand meters in the ocean), whereas electromagnetic waves quickly decay when propagating through the water. There are two primary applications for USAMs to prevent detection by sonar systems: (i) active control noise reduction materials, which reduce the noise radiated from underwater vehicles, with a sound absorption frequency range from 50 Hz to 10 kHz; and (ii) passive control noise reduction materials, which reduce the acoustic target strength of underwater vehicles, with a sound absorption frequency range from 1 kHz to 30 kHz [1]. Passive control noise reduction materials have received more attention than active control noise reduction materials due to their high performance-to-cost ratio, ease of fabrication, and reliable service. Normally, USAMs are placed on the surface of vehicles, particularly those that travel in the depths of the ocean [2–4]. As a result, the materials required for acoustic absorption in water differ from those used for air. Consequently, research on sound-absorbing materials with high hydrostatic pressure resistance, corrosion resistance, and other important properties faces increasingly serious challenges. To date, there have been only a few reviews on the topic of USAMs applied in underwater vehicles [1,5,6].

USAMs typically fall into one of four categories: polymer-based [7], metal-based [8], ceramic-based [9], or acoustic metamaterials [10], as shown in Figure 1. However, to the best of our knowledge, no relevant review paper exists on multifunctional sound-absorbing materials for underwater sound absorption, particularly those with high hydrostatic pressure resistance and corrosion resistance. Given the difficulties involved in preparing metamaterials and materials with singular performance, this review aims to fill this gap in the literature and serve as a beneficial reference for the study of USAMs. This review focuses on the following topics and their relevant research advances:

- The mechanism of acoustic absorption in underwater environments and the various factors that impact the performance of USAMs;
- The corrosion mechanism of USAMs, as well as crucial factors and methods for achieving corrosion resistance;
- The hydrostatic pressure resistance mechanism of USAMs, and key factors and methods to enhance the hydrostatic pressure resistance.

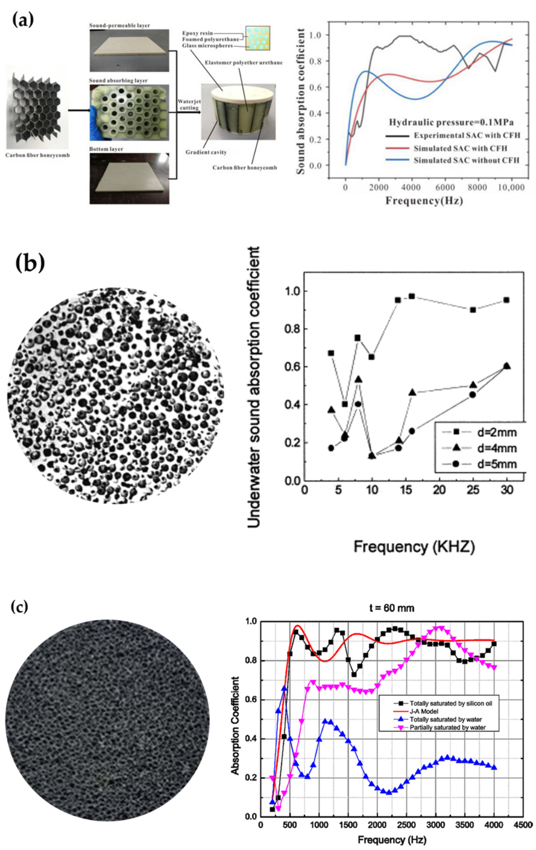

Figure 1. *Cont.*

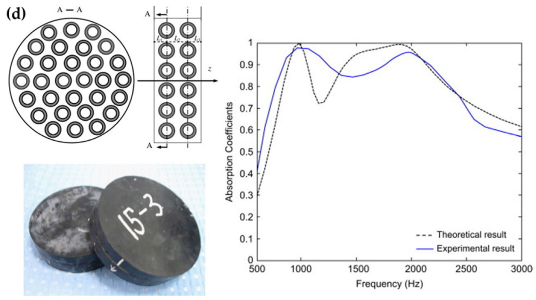

Figure 1. Schematic of (**a**) polymer-based composite USAM (the carbon fiber honeycomb is incorporated into the sound-absorbing periodically arrayed structure) and sound absorption performance [7]; (**b**) metal-based USAM (porous aluminum) and sound absorption performance [8]; (**c**) ceramic-based USAM (SiC foam) and sound absorption performance [9]; and (**d**) underwater sound absorption metamaterials (host rubber) and sound absorption performance [10].

Lastly, we present an overview of the recent research progress in the field of USAMs integrated with hydrostatic pressure resistance, corrosion resistance, existing challenges of multifunctional integrated underwater sound-absorbing materials, and proposed solutions.

2. Underwater Acoustic Absorption Mechanisms and Research Advancements in This Area

2.1. Underwater Acoustic Absorption Mechanism and Impact Factors

The Schematic of sound propagation as shown in Figure 2. The sound absorption coefficient α is defined as the ratio of absorbed sound energy to total incident sound energy, which is a critical parameter for quantifying the sound absorption capability of materials [6]. α is:

$$\alpha = \frac{E_\alpha}{E_i} = \frac{E_i - E_r - E_t}{E_i} = 1 - \frac{E_r + E_t}{E_i} = 1 - \left| \frac{Z_s - \rho c}{Z_s + \rho c} \right|^2 \tag{1}$$

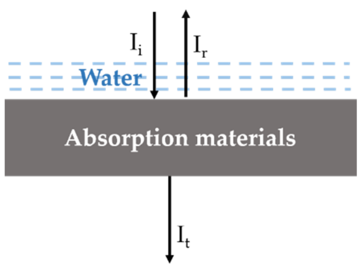

Figure 2. Schematic of sound propagation: I represents the incident wave, r is the reflected wave, t is the transmitted wave, and I represents sound intensity [6].

The absorbed sound energy is denoted by E_a, the total incident sound energy is denoted by E_i, E_r is the reflected sound energy, and E_t refers to the transmitted sound energy. Z_s represents the surface impedance, and ρ and c denote the density and speed of sound, respectively.

In general, the sound absorption coefficient is a measure of sound energy consumption. As underwater acoustic materials continue to develop, there are three methods that can be utilized to enhance the sound absorption coefficient. The first principle involves the conversion of sound energy to heat energy, which is then dissipated through the vibration and friction of molecules in the porous sound absorption materials with pore walls when sound waves penetrate these materials. The second principle relies on matching the surface impedance of the materials with the water impedance to increase the absorption coefficient through the dissipation of sound energy at the interface of different media. The third principle involves local resonance sound absorption [11–13]. For porous materials, the main factors that influence sound absorption are flow resistance, porosity, curvature, the thermal characteristic length, the sticky feature length, Young's modulus, bulk density, Poisson's ratio, loss factor, thickness, shape, layered structure, and boundary features [14–17]. Generally, the JCA model and Biot-Allard model are utilized to study these factors [18,19]. Furthermore, in the case of viscoelastic polymer materials, the sound absorption performance of USAMs is primarily influenced by interface characteristics of the element components and internal structure [1,20–25]. The principal calculation methods typically utilized in this field are the finite element method, transfer matrices, and the finite difference time domain [26–32]. Furthermore, based on different requirements and purposes, the underwater sound absorption properties can be obtained through various testing methods: full sea trial, acoustic water tank, dynamic mechanical test, compressive test [1], transmission method [33], waveguide method [34,35], et al.

2.2. Research Advancements in Underwater Sound Absorption Materials

Figure 3 shows the research history of USAMs, which can be traced back to the early 20th century. Early studies focused on natural materials such as sponges and corals, but these materials had an unstable sound-absorbing performance and poor durability. In the 1960s and 1970s, synthetic materials such as polyimides and polystyrene gradually became a popular research topic. These materials have a good sound-absorbing performance but are expensive and require complex preparation processes. After the 1980s, researchers began to use new porous, fiber, and multi-layer structure materials, and explored new preparation methods and technologies, such as polymer foaming and ultrasonic preparation. These materials have a good sound-absorbing performance, low cost, and simple preparation, and thus have been widely used and promoted. In recent years, with the emergence of new materials and technologies, such as nanomaterials, metamaterials, and biomimetic materials, research on underwater sound-absorbing materials has continued to advance. Researchers have not only made breakthroughs in sound-absorbing performance using these new materials and technologies, but have also made vast improvements to the durability and stability of such materials, opening up wider opportunities for the application of underwater sound-absorbing materials.

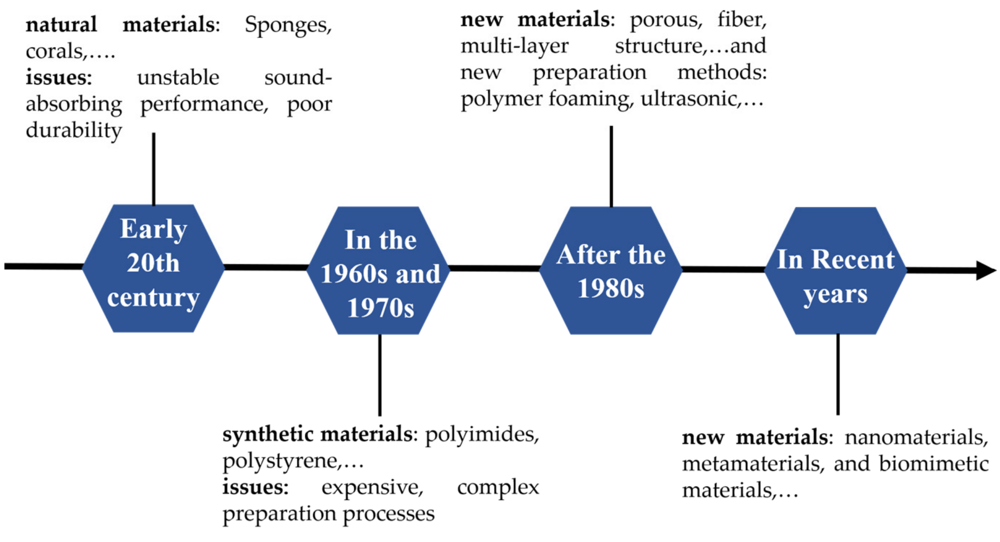

Figure 3. The schematic of research history of USAMs.

In general, USAMs can be classified into four main categories based on their composition: polymer-based, metal-based, ceramic-based, and acoustic metamaterials.

2.2.1. Polymer-Based

Polymer-based absorption materials offer several advantages, including a low cost, easy fabrication, and a close acoustic impedance (1,568,970 Rayls) to water [32]. Some polymer-based materials also exhibit damping properties, making them ideal for use in USAMs. The loss factor δ, defined as the ratio of the imaginary part to the real part, is critical for determining the sound absorption coefficient in underwater environments. The equations for calculating the sound absorption coefficient are provided below:

$$\tan\delta = \frac{E''}{E'} \tag{2}$$

$$E^* = E' + E''j \tag{3}$$

Herein, E' is storage modulus, E'' is loss modulus, and E^* is the complex dynamic modulus. E' is a measure of elastic energy stored, and E'' represents the equivalent energy loss during the collision [1,36]. The dynamic mechanical property E^* of a material can be evaluated via its damping and absorption capability. A higher loss factor $\tan\delta$ indicates better damping properties. When sound propagates through polymer-based materials, the polymer chains are alternately compressed and elongated on a micro/nanoscale [1]. This phenomenon has led to the development of polymer-based underwater absorption materials, which are known for their better damping properties and mechanical strength. These include polymer-based USAMs, such as foam plastics, polyurethane foam, polyethylene, polystyrene, polycarbonate, and polypropylene [5]. Of these materials, polyurethane (PU) foam is the most widely used [37] due to its good sound absorption performance and mechanical properties.

Polymers with an impedance match have limited performance for underwater sound absorption because of their low loss factor [1]. To address this, a new method was developed that combines two or more polymers into a physical network connected by a cross-link [38,39]. For example, Cao, R. prepared composites of *Eucommia ulmoides* gum (EUG)/styrene-butadiene rubber (SBR). The diagrammatic morphology of the sample is shown in Figure 4a, which have excellent pressure resistance and sound absorption coefficients in the low-frequency range from 3 kHz to 8 kHz. The SBR/EUG (70/30) has an absorption coefficient 24.23% higher than that of SBR alone [40]. Fu, Y. et al., developed a hybrid material composed of carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) in a polydimethylsiloxane (PDMS) matrix. The SEM images of the sample is shown in Figure 4b. The GNPs formed junctions with air micro-voids, and the material showed a significant increase in hydrostatic pressure from 0.4 MPa to 1.0 MPa in a frequency range from 1500 Hz to 7000 Hz, compared to materials containing only CNTs or GNPs [41].

To overcome the limitations of homogeneous materials, gradient impedance polymers have been proposed [7]. However, the thickness of the wedge material is typically large, limiting their applications and increasing their cost. To address this problem, nanofibrous membranes with a high porosity and high airflow resistivity were manufactured, and carboxyl functionalized multi-walled carbn nanotubes (MWCNT-COOH) were added to polydimethylsiloxane (PDMS) with a dispersant to enhance its underwater acoustic properties. The picture of sample is shown in Figure 4c. The addition of MWCNT-COOH and surfactant improved the sound absorption coefficient from 1500 Hz to 7000 Hz under normal pressure (0 MPa) to above 0.75 [42]. Kabir, I. I. et al., prepared nanocomposite films for underwater sound absorption applications via spin coating. The addition of 2 wt% of MWCNT-COOH to the PDMS matrix significantly improved the elastic modulus by 48% compared to pure PDMS, and the PDMS/MWCNT-COOH/surfactant nanocomposite exhibited a sound absorption coefficient of 0.25, which was much higher than that of pure PDMS. The addition of surfactant decreased Young's modulus by 34% compared to pure PDMS, but this was an advantage because it helped to avoid acoustic impedance mismatch [32]. Ayub, et al., found that a 3 mm thick layer of CNTs can provide up to 10%

acoustic absorption within the frequency range from 0.125 kHz to 4 kHz [43]. Sharifi, M. J. investigated the underwater sound absorption of polyurethane elastomer in the frequency range from 2 kHz to 18 kHz, and found that it was affected by different molecular masses of polypropylene glycol [37]. Li, Y. et al., prepare graphene/SBR nanocomposites and its SEM images of graphene/SBR nanocomposites as shown in Figure 4d. The sample had a Young's modulus that was over 30 times higher than that of rubber. These nanocomposites exhibited excellent underwater sound absorption, with an average absorption coefficient of over 0.8 at 6–30 kHz. The absorption performance increased with increasing water pressure [44].

In deep water, high hydrostatic pressure causes the polymer's elastic modulus to increase, making it less effective at converting acoustic elastic energy, which leads to a reduction in the sound absorption coefficient. Additionally, polymers are susceptible to rotting in water and lack high-temperature resistance, which limits their practical applications.

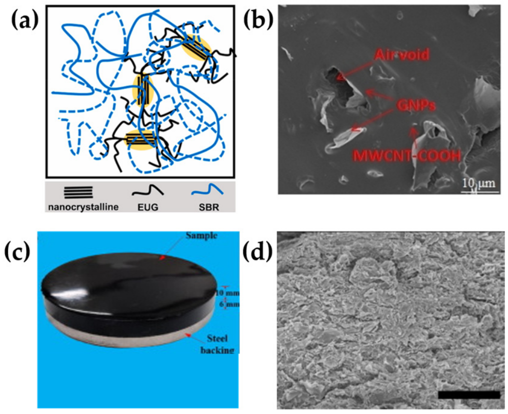

Figure 4. (**a**) Diagrammatic morphology of SBR/EUG composite [40]; (**b**) SEM images of PSM05+PG30 in high magnification [41]; (**c**) picture of sample of the multi-walled carbon nanotubes (MWCNT-COOH) added to polydimethylsiloxane (PDMS) with steel backing [42]; and (**d**) SEM images of graphene/SBR nanocomposites [44].

2.2.2. Metal-Based Porous Materials

The acoustic absorption that occurs in metal-based porous materials is caused by viscous losses and thermo-elastic damping as the sound propagates through numerous air cavities within the material. Porous aluminum with a controllable pore structure was prepared, demonstrating that sound absorption coefficients increase with decreasing pore size and increasing sample thickness; the optimal sound absorption occurs at porosities between 75% and 80% [8]. Lu, T. J. prepared aluminum foams with semi-open cells that improve sound absorption by adjusting processing parameters such as infiltration pressure, which is equivalent to increasing particle size or decreasing surface tension. Figure 5a shows the typical microstructure and Figure 5b shows the sound absorption varies with the effect of air cavity between two 10 mm thick aluminum foam. The results demonstrate that a sound absorption coefficient larger than 0.8 was recorded in the frequency range of 800–2000 Hz [45].

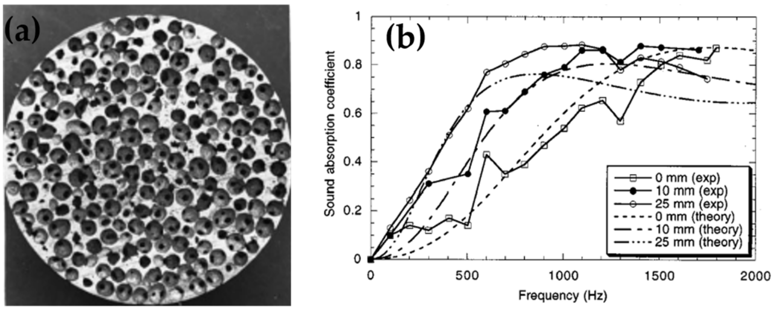

Figure 5. (**a**) Typical microstructure of semi-open aluminum foam; and (**b**) effect of air cavity between two 10 mm thick aluminum foam. The error of measurement is on the order of 5–10% [45].

Although non-metallic sound absorption materials are developing rapidly, metal-based materials remain critical when dealing with complex marine environments. They can withstand high pressure underwater and maintain their physical characteristics when exposed to chemical atmospheres or high-speed airflows. Metal-based foam is also required to meet the lightweight requirements of underwater vehicles. The aluminum foam has limited mechanical strength. To overcome this challenge, Liu, R. X. prepared an impedance gradient underwater sound-absorbing composite with multiphase composites (IGCM) with polyether polyurethane and metal powders such as iron powder, tungsten powder, and mixtures of iron powder and tungsten powder with varying mass density gradients. The sound absorption frequency ranges were concentrated between 6 kHz and 10 kHz under normal incident conditions [46].

2.2.3. Ceramic-Based Foams

To enhance the corrosion resistance of materials, researchers have turned to ceramic foams. These materials have high chemical stability, corrosion resistance, stiffness, and good mechanical properties, making them ideal for sound reduction in critical environments. However, there are few studies on the underwater sound absorption properties of ceramics, particularly in high-pressure environments. Du, Z. et al., developed porous silicon nitride ceramic foams to reduce underwater noise and found that porosity, pore size, and thickness were contributing factors to better sound absorption across almost all frequencies, achieving a sound absorption coefficient higher than 0.99 by inserting an air gap [47–49]. Xu, W. et al., prepared the open-celled SiC foams and its photograph of a section of SiC foam sample and SEM photographs of the cell structure are shown in Figure 6a,b shows the underwater acoustic absorption coefficient varies with the frequency. The result shows that the underwater acoustic absorption coefficient was mainly observed over the low- and middle-frequency range (200–4000 Hz) [50].

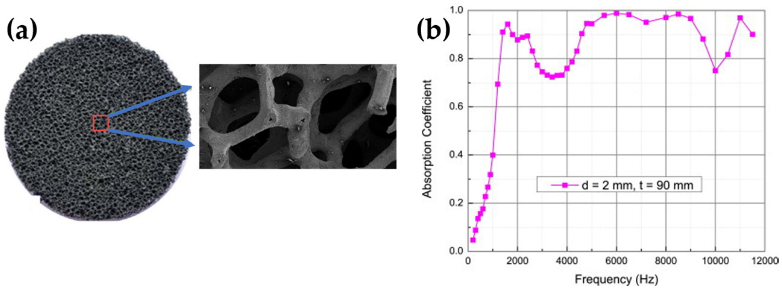

Figure 6. (**a**) Photograph of a section of SiC foam sample and scanning electron microscope photographs of the cell structure; and (**b**) underwater acoustic absorption coefficient of the sample with thickness of 90 mm and pore size of 2 mm over a wide frequency band [50].

One limitation of these materials is their brittleness, which restricts their applications. However, recent research by Zhang, J. et al., utilized silicon nitride with plastic deformability, covalently bonded via bond switching at coherent interfaces [51]; such research shows great potential for addressing current limitations.

2.2.4. Metamaterials

In recent years, acoustic metamaterials have become a popular topic for researchers in the field of acoustics. The purpose of these materials is to design structures with unique properties that are not present in natural materials [52]. The concept of metamaterials originated in the field of electromagnetics. Veselago discovered that the dielectric properties and the permeability of electromagnetic materials could have negative values [53]. This is distinct from conventional materials with positive material parameters, and thus the concept of electromagnetic metamaterials was theoretically proposed. Later on, this theory was applied to the study of optical metamaterials. In the case of natural materials, material parameters such as mass density, Young's modulus, and Poisson's ratio are positive [54]. However, with artificial construction, it is possible to achieve effective material parameters that are negative within specific frequency ranges. Acoustic metamaterials can manipulate and control sound waves by modulation of their structures, which can result in a zero, or even negative, refractive index for the control of sound at subwavelength scales [55]. Numerous reports have shown the influence of various factors, such as the structure of materials (e.g., conical cavity [56], hole-shape materials [57], and locally resonant phononic woodpiles [58]), geometric and material parameters [59,60], and localized resonances [61] on acoustic absorption. Chen, H. et al., have successfully achieved invisibility cloaking in acoustic waves through the use of conductivity equations. These equations are derived from the similar concept of "transformation media," which was originally applied to manipulating electromagnetic waves to achieve invisibility cloaking [62,63]. Iannace, G. et al., conducted a study to investigate the sound attenuation of an acoustic barrier made with metamaterial. In their study, the authors constructed a 1:10 scale model consisting of cylindrical wooden bars, measuring 30 cm high and 1.5 cm in diameter. Different alternating rows of cylindrical bars were arranged with an empty space to form regular geometries. The results suggest that barriers made with metamaterials can be effective substitutes for traditional barriers in mitigating noise [64]. However, there have been relatively few reports on the use of metamaterials for underwater sound absorption. Meng, H. et al., designed a sound absorption slab that utilized locally resonant acoustic metamaterials, resulting in broadband (800–2500 Hz) absorption of the underwater sound [10]. Zhong, H. et al., designed an underwater honeycomb-type acoustic metamaterial (AM) plate composite. Its structure is shown in Figure 7a, which had a thickness of 20.25 mm, and achieved an underwater sound transmission loss (STL) over 20 dB higher than that of homogeneous materials with the same area density. Under a hydrostatic pressure of 3 MPa, this structure still achieved an average STL of 10 dB in the frequency range from 2 kHz to 10 kHz [65]. Using several detuned multi-order micro-perforated panels with a backing cavity (MPPB) basis, an 11-unit meta-structure with a thickness of only 75 mm was developed, as shown in Figure 7b, achieving almost a 100% maximum absorption coefficient and an average absorption coefficient of 80% at frequencies ranging from 1380 to 3150 Hz. This is caused by the precise adjustment of the parameters of micro-perforated panels, which are arranged in parallel with a backing cavity [66]. This method also achieved a high underwater sound absorption coefficients of over 0.9 in the range of 12−30 kHz, with a compressive strength of over 5 MPa in "phononic glass", the model simplification process of phononic glass is shown in Figure 7c [67].

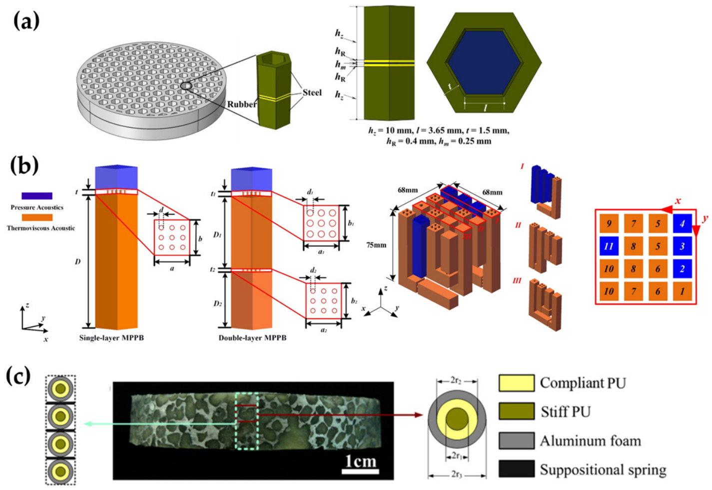

Figure 7. (**a**) Proposed overall structure and unit cell of acoustic metamaterial [65]. (**b**) The schematic diagram of single-layer MPPB and double-layer MPPB and metamaterial composed of 11 MPPBs in parallel array [66]. (**c**) The model simplification process of phononic glass [67].

Metamaterials have significant advantages over traditional acoustic materials, with strong design capabilities that allow them to surpass the physical limitations of conventional materials in low-frequency broadband sound absorption for small-sized and lightweight structures. However, the production of underwater metamaterials is still limited by current crafting techniques, and they have yet to be effectively applied in underwater environments.

The development and increasing requirements of underwater vehicle equipment have created an increased demand for multifunctional sound absorption materials related to hydrostatic pressure resistance and corrosion resistance. However, complex and incompatible manufacturing methods have limited the development of materials that can simultaneously meet all of these requirements for specific applications, such as underwater vehicles and ships. Hence, it is crucial to investigate high-performance multifunctional sound absorption materials that can integrate the advantages of different materials, including polymer-based, metal-based, ceramic-based, and metamaterials. By adjusting the element design, preparation process parameters, and structural cross-scale design, it may be possible to develop a feasible solution for multifunctional sound absorption materials research.

3. Corrosion Resistance and Hydrostatic Pressure Resistance Mechanisms of USAMs

3.1. Corrosion Resistance Mechanism of USAMs and Research Advancements

The USAMs are required to withstand harsh environments when underwater vehicles are operating at great depths beneath the ocean. There are three recognized main causes of corrosion. (1) Atmospheric corrosion is caused by the interaction between a material and its surrounding atmospheric conditions, such as temperature, humidity, irradiance, chloride ion concentration, salinity, and pollutants. (2) Seawater is a highly corrosive electrolyte solution containing significant amounts of salts, including sodium chloride and salts containing potassium, bromine, iodine, and other elements. (3) Hydrostatic pressure restricts the corrosion mechanism in materials [68–73]. As a result, marine corrosion causes structural damage and material decay, which impacts the sound absorption coefficient and reduces the underwater vehicle's service life. Therefore, investigating the suitability of sound absorption materials with anti-corrosion properties in harsh environments holds considerable promise for marine equipment applications.

The protection of underwater vehicles against corrosion is essential to ensure their longevity and performance. Several methods have been utilized to achieve corrosion resistance, including coating protection [74–78], cathodic protection [79,80], pitting corrosion method [81], joint protection act [82,83], and selecting multifunctional materials with anti-corrosion properties. Engineers often integrate sound-absorbing materials and anti-corrosion materials to meet requirements. Gu, B. et al., prepared a multiwall carbon nanotube addition with a polyurethane coating on phosphate steel, and studied the anti-corrosion and underwater acoustic absorption properties [84]. However, this integration can lead to a substantial increase in cost, weight, and performance issues. Based on current research, ceramic matrix composite materials have shown strong resistance to corrosion compared to ordinary metal materials, resulting in better performance. He, C. et al., prepared a porous sound-absorbing ceramic matrix that showed a 28.9% increase in sound absorption coefficient for low- and middle-frequency ranges and anti-corrosion properties [85]. Foam glass-ceramics materials were prepared by Yan, Z. et al., and demonstrated effective sound absorption and corrosion-resistant characteristics. All sintered samples have a noise reduction coefficient of 0.41, and the percentage change in mass was less than 0.4% after soaking for 35 days in a dilute sulfuric acid with at pH 5 [86].

3.2. Hydrostatic Pressure Resistance Mechanism of USAMs and Research Advancements

As underwater vehicles operate at increasing depths, the hydrostatic pressure-resistant equipment must possess greater strength and stability to withstand the harsh environment. This hydrostatic pressure can cause structural damage and material deformation, leading to a decrease in sound-absorbing coefficient and anti-corrosion performance, ultimately shortening the equipment's lifespan. The key approach to enhancing the strength and stability of hydrostatic pressure-resistant equipment lies in the rational selection of high-strength materials with higher yield strength, higher elastic modulus, and suitable pressure-resistant structural designs. Currently, the materials used in deep-sea pressure-resistant equipment can be broadly categorized as metallic and non-metallic materials. Non-metallic materials, such as resin matrix composite materials [87–89] and structural ceramic materials [90], are more resistant to seawater corrosion than metal materials. Ceramic-based materials exhibit high strength, elastic modulus, corrosion resistance, wear resistance, and effective high-temperature resistance, as well as having a lower density compared to conventional metal materials [91]. However, the brittle nature of ceramics such as silicon carbide [92,93] and silicon nitride [47,94] restricts their range of applications, despite the significant progress in advanced research of ceramic materials. The research on ceramic toughening has also made great strides, popularizing the application of ceramic materials [95]. It is hoped that, via structures and element design optimization, ultra-strong and anti-pressure materials can be developed for high-hydrostatic-pressure-resistant usage.

4. Summary of Research on USAMs with Hydrostatic Pressure Resistance and Corrosion Resistance

4.1. Preparing Multifunctional USAMs with Hydrostatic Pressure Resistance and Corrosion Resistance

In recent years, multifunctional USAMs with hydrostatic pressure resistance and corrosion resistance have attracted increasing attention and experienced rapid development. These materials have various applications in underwater acoustics, such as in underwater communication systems and oceanographic research. Figure 8 illustrates the preparation process of these materials, which requires interdisciplinary research in materials science, acoustics, physics, electricity, mechanics, and other fields. The preparation of multifunctional USAMs with hydrostatic pressure resistance and corrosion resistance typically involves a multi-step process that may vary depending on the specific material being developed. The general steps involved in the preparation of such materials are as follows: firstly, a selection of suitable intrinsic acoustic materials, which should be able to resist corrosion and the filler materials, should provide the necessary strength and stiffness to resist hydrostatic pressure. Secondly, material characterization must be considered. Before the actual preparation of multifunctional USAMs, the intrinsic materials should be characterized to determine their properties, such as mechanical strength, acoustic properties, and corrosion resistance. This will help to determine the ideal composition and processing conditions for the material. Thirdly, the fabrication process should be optimized to ensure that the final product has the desired properties and is free from defects. Fourthly, the final

USAMs must then be subjected to a series of tests to evaluate their performance, including hydrostatic pressure resistance, corrosion resistance, and sound absorption properties. This may involve subjecting the material to simulated underwater conditions and measuring its acoustic properties under various conditions. Finally, based on the test results, the composition and processing conditions of the material may be optimized to improve its performance. The material can then be scaled up for production and further testing in real-world applications.

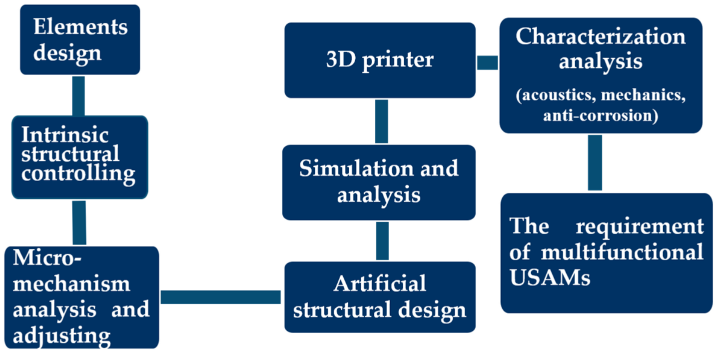

Figure 8. Preparation process of multifunctional USAMs.

4.2. Research Challenges and Methods of Improvement

One of the main challenges in the development of these materials is achieving a balance between sound absorption performance, hydrostatic pressure resistance, and corrosion resistance. The following are some of the challenges of current research:

Limited sound absorption performance: Most of the materials with good hydrostatic pressure and corrosion resistance do not have good sound absorption properties. Normally, ceramic- and metallic-based materials possess excellent mechanical properties, but they have lower acoustic absorption coefficients compared to polymer-based materials. However, polymer-based materials have a poorer corrosion resistance than ceramic materials.

Complex fabrication processes: The fabrication processes for these materials are often complex and require specialized equipment, which makes them difficult to manufacture on a large scale. For example, the fabrication of metallic foams requires multiple manufacturing steps, such as melting, foaming, solidification, and post-processing, which often involve complex processes. The fabrication of metal–organic frameworks involves multiple synthetic steps, including solvothermal synthesis, post-synthesis activation, and shaping, which make them challenging to scale up.

The cost of these materials is often high due to the complex fabrication processes and the use of expensive materials. Metal matrix composites are expensive due to the cost of the reinforcing materials, the complexity of the manufacturing process, and the need for specialized and expensive equipment.

In summary, the main challenges in this field are incorporating additives, optimizing microstructure, using innovative fabrication techniques, and using low-cost materials.

Methods for addressing the above challenges are as follows:

Composite materials consist of a matrix material, such as rubber or polymer, reinforced with filler materials, such as carbon nanotubes or graphene oxide. Additive materials can provide the necessary strength and stiffness to resist hydrostatic pressure, while the matrix material can provide corrosion resistance.

The optimization of microstructures is a crucial aspect of enhancing the sound absorption performance of materials. This can be achieved by controlling various factors such as pore size, density, porosity, and thickness. The simultaneous control of these factors can help to create an optimal microstructure that enhances sound absorption performance.

Innovative techniques such as 3D printing and electrospinning can be used to fabricate these materials with complex structures and high precision. Nanoparticles, such as metal oxides and carbon nanotubes, can be added to the matrix material to improve its mechanical and acoustic properties.

The use of low-cost materials such as natural fibers and recycled materials can help to reduce the cost of these materials while maintaining their properties.

5. Conclusions

This review provides an introduction to the mechanisms of USAMs, high-pressure and corrosion resistance in underwater environments, and the research progress on materials that can serve such functions. It also gives a comprehensive review of USAMs with high-pressure resistance and corrosion resistance. The materials discussed include polymer-based, metal-based, and ceramic-based materials and metamaterials. However, there are still several challenges to be addressed in the development of USAMs with hydrostatic pressure resistance and corrosion resistance. These challenges include studying cost-effective preparation technology, low-frequency and wide-frequency range requirements, achieving lightweight materials, and other limited performances. Methods of improvement are also proposed in this review.

Overall, much more research is necessary to develop multifunctional USAMs with hydrostatic pressure resistance and corrosion resistance for a range of applications. The use of composite materials, innovative techniques, and nanotechnology is promising, and further research in these areas may lead to the development of new and innovative materials in the future.

Author Contributions: X.C. and L.M. contributed equally to this work. Conceptualization, X.C. and L.M.; methodology, X.C. and L.M.; validation, X.C. and L.M.; formal analysis, X.C. and L.M.; investigation, X.C. and L.M.; resources, X.C. and L.M.; data curation, X.C. and L.M.; writing—original draft preparation, X.C. and L.M.; writing—review and editing, X.C., L.M., Z.L. and X.J.; visualization, X.C.; supervision, J.Y.; project administration, F.Y. and J.Y.; and funding acquisition, X.J., Z L., F.Y. and J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by an open project of the State Key Laboratory of Sound Field Acoustic Information of the Chinese Academy of Sciences under Grant SKLA2022114, in part by the National Natural Science Foundation of China under Grant 62171438, in part by Youth Innovation Promotion Association of the Chinese Academy of Sciences under Grant 2018027, and in part by IACAS Frontier Exploration Project QYTS202111. Acknowledge the financial support part from the China Postdoctoral Science Foundation of (Grant No. 2022M711805) and the National Natural Science Foundation of China (Grant No. 52205209).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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