Materials Science Innovations

RESEARCH PAPER

Utilization of Gallium-Based Liquid Metal Silicone Composites in Battery Pack Design for Electric Vehicles

Yourun Lin[1], Jinfeng Cai[1], Hongji Chen[1], Jinchuan Liu[1], Shuiyan Liu[2], Jinzhu Zhang[2], Xin Ge[1,*]

1 School of Automobile and Transportation Engineering, Guangdong Polytechnic Normal University, 510450 Guangzhou, China
2 Guangzhou Highteen Plastics Co., Ltd., Guangzhou 510800, China
*Correspondence author: gexin@gpnu.edu.cn

Abstract: This study explores the development and application of gallium based liquid metal silicon composite materials in battery packs, addressing their mechanical, electrical, and electromagnetic shielding properties. The rapid development of electric vehicles and renewable energy technologies requires improving the performance and safety of battery systems. Gallium based liquid metals are renowned for their excellent conductivity and thermal properties, but they face challenges such as oxidation and flow control. To alleviate these issues, we studied a composite material of gallium and silicon, which is a polymer known for its insulation and heat resistance. The preparation process involves mixing gallium with silica gel and carbon black, followed by a systematic mold creation and curing process. Characterization techniques such as scanning electron microscopy (SEM), electrical signal analysis, and mechanical testing are used to evaluate the microstructure and properties of composite materials. The results showed that the integration of gallium significantly improved the tensile strength and elongation at break, with the best performance observed at the Ga6 mass fraction. In addition, composite materials exhibit responsive electrical behavior under pressure and strain, indicating their potential for real-time monitoring applications in battery systems. Electromagnetic shielding assessment reveals strong protection against electromagnetic interference over a wide frequency range, highlighting the multifunctionality of composite materials in different operating environments. Overall, gallium based liquid metal silicon composite materials are expected to improve the safety, reliability, and performance of battery packs, paving the way for future research on optimizing the material composition of advanced energy storage solutions.

Keywords: Battery pack, Liquid metal, Silicone

1. Introduction

In recent years, the rapid development of electric vehicles and renewable energy technologies has heightened the focus on the performance and safety of battery packs, which serve as crucial components for energy storage and conversion [1,2]. Liquid metal materials, particularly gallium-based liquid metals, have emerged as a promising research area due to their excellent conductivity, thermal conductivity, and flexibility [3-5]. Gallium's low toxicity, favorable fluidity, and adaptability highlight its potential in enhancing thermal management and electrical connections within battery packs [5,6]. However, the practical application of pure liquid metals is hindered by issues such as susceptibility to oxidation and challenges in fluidity control [8,9].

To address these limitations, researchers have begun to explore the composite of gallium-based liquid metals with polymer materials like silicone. Silicone, known for its excellent insulation and high-temperature resistance, can significantly enhance the stability and mechanical strength of the composite materials. Additionally, the fluidity of gallium can improve the thermal conductivity of silicone to some extent, thereby

Received: Oct. 02, 2024
Revised: Oct. 22, 2024
Accepted: Oct. 25, 2024
Published: Nov. 01, 2024

increasing the cooling efficiency of battery packs.

This study systematically investigates the application of gallium-based liquid metal silicone composite materials in battery packs, analyzing their advantages and shortcomings in conductivity, electromagnetic shielding, and mechanical properties. Through experimental and data analysis methods, we aim to delve into the performance of this composite material under various conditions, providing both theoretical basis and experimental support for the design and optimization of battery packs. The findings suggest that these composites can effectively enhance the safety and reliability of battery systems, thereby promoting the broader application of liquid metal composites in electric vehicles and other energy storage systems.

2. Experimental Part

2.1 Materials

In this study, the silicon rubber was obtained from Highteen Plastic Company Co., Ltd., China, which consists of two components (A:B = 1:1), where A is silicone oil and B is a curing agent. The curing time is about 1 hour. Carbon black (CB), with a density of 1.7−1.9 g/cm³, was obtained from Orion Engineered Carbons Co., Ltd., China. Liquid metal Ga (99.9%) was procured from Guangzhou Dingtai Metal Co., Ltd, China.

2.2 Preparation of Gallium-Based Liquid Metal Silicone Composite Materials

In this research, the preparation process of gallium-based liquid metal silicone composite materials mainly includes several key steps: mixing the solution, pouring into the mold, vacuum extracting, and heating curing. As shown in Figure 1, at room temperature, A type silicone and liquid metal are mixed in a sealed mechanical stirrer in a certain proportion for at least 30 mins to achieve uniform dispersion.

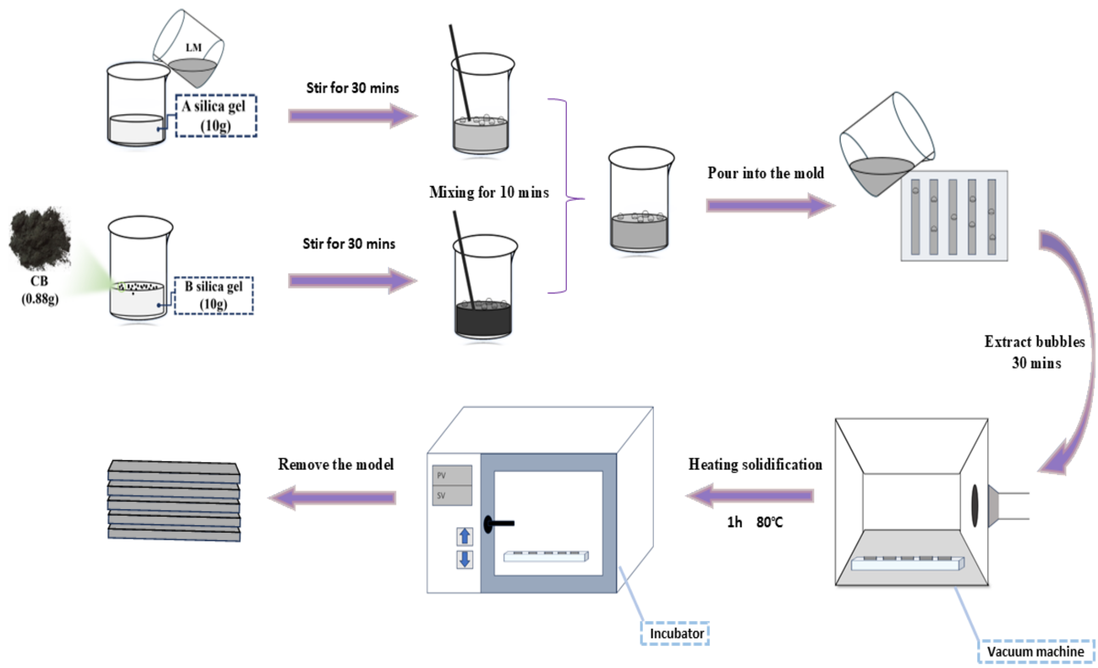

Figure 1. Preparation process of gallium based liquid metal silicone composite material.

Meanwhile, prepare a container with 10 g of B type silicone, and add 0.88 g of carbon black (CB) to it, then mix them in another sealed mechanical stirrer for at least 30 mins until the carbon black is uniformly dispersed. Next, mix the two components in a third sealed stirrer for 10 mins until they are fully mixed and uniform.

Finally, pour the mixed solution slowly into the mold to form a long strip, ensuring the surface is smooth.

Then, place the mold in a vacuum drying oven, and perform vacuum degassing at room temperature to remove air from the mixture. After multiple vacuum extractions, ensure that no more bubbles are produced, and then place the mold into an oven at 80 ºC to cure for 1 hour. After demolding, the sample is obtained.

2.3 Battery Pack Design

In this study, the design process of battery packs involves multiple key steps, including design modeling, 3D printing, mold making, flip molding, and coating. As shown in Figure 2, the scale type and design requirements of the battery pack were first established, and professional modeling software was used for 3D design to generate an 18650-battery pack model that meets the specifications.

Next, PETG material is selected as the printing medium, and the designed 18650 battery pack model is printed out using a high-precision 3D printer. PETG materials are widely used in such engineering due to their excellent mechanical properties and thermal stability. After printing is completed, use sandpaper to finely polish the printed part to remove surface defects and improve the quality of subsequent mold forming. Subsequently, apply Vaseline evenly on the surface of the printed part as a release agent to ensure the smooth progress of the subsequent release process.

After preparing the mold frame, place the processed battery pack model inside and pour in the flip mold silicone. This process requires ensuring that the silicone fully covers every detail of the model to capture its shape and structural features. After the silicone is fully cured, manual demolding is performed to obtain the mold for the 18650-battery pack.

Finally, carefully pour the AB resin material into the already made mold. During the resin curing process, it is necessary to maintain appropriate temperature and humidity to ensure its physical properties and chemical stability. After the AB resin is completely cured, a high-precision 18650 battery pack flipping model can be obtained. After obtaining the model, coat the gallium based liquid metal silica gel mixture solution obtained in the process of Figure 1 onto the model. Through this systematic design process, the structure and performance of battery packs can be effectively optimized, laying a solid foundation for subsequent applications and testing.

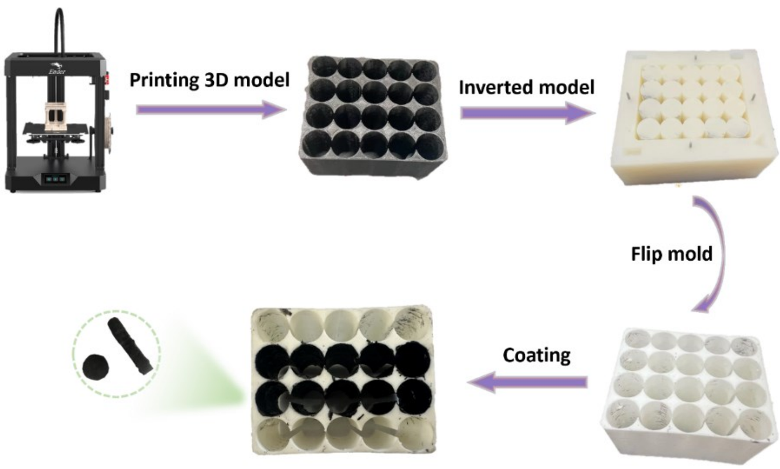

Figure 2. Integrated design of gallium-based liquid metal silicone composites in electric vehicle battery packs.

2.4 Characterizations

In this study, scanning electron microscopy (SEM) was utilized to examine the cross-sections of samples using a Carl Zeiss microscope (Germany). The samples were prepared by cutting them with a suitable blade, as they exhibited elasticity even after being treated with liquid nitrogen. This phenomenon may relate to the supercooling of liquid metal and the absence of crystalline nuclei [10,11]. Characterization was performed at an accelerating voltage of 10 kV, with a gold layer sputtered onto the surfaces to improve microstructural analysis.

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were conducted with a temperature increase of 10 K/min, ranging from 23 ºC to 800 ºC, under a nitrogen atmosphere. The mechanical properties were evaluated using a tensile testing machine (EUT5105) linked to a Keithley 6487 picoammeter. Specimens measuring 100 mm in length and 10 mm in width were securely fastened in isolation fixtures, with a gauge length of 40 mm, and stretched uniaxially at a rate of 60 mm/min until fracture. Data on mechanical and electrical properties were simultaneously recorded for a comprehensive assessment of the electromechanical characteristics, with at least five specimens analyzed for each experiment.

Electromagnetic shielding effectiveness was tested in the X-band frequency range (8.2-12.4 GHz) using an Agilent E5071c device with waveguide techniques. Samples were cut to dimensions of 22.5 × 10.0 mm^2 to fit the waveguide holders. The obtained s-parameters were calculated using the following formulas [11-13]

$$SE_R = -10\log(1 - |S_{11}|^2) \quad \text{(Eq. 1)}$$

$$SE_A = -10\log(|S_{21}|^2/(1 - |S_{11}|^2)) \quad \text{(Eq. 2)}$$

$$SE_T = SE_R + SE_A \quad \text{(Eq. 3)}$$

Coaxial methods using an Agilent E5071c device were employed to obtain the electromagnetic parameters (real dielectric constant ε', imaginary dielectric constant ε'', real permeability μ', and imaginary permeability μ'') of the samples in the 2–18 GHz range, and simultaneous calculations for the attenuation constant α, impedance match IM, and reflection loss RL were performed using the following equations [15-17]

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu'\varepsilon'' + \mu''\varepsilon')^2 + (\mu''\varepsilon'' - \mu'\varepsilon')^2}} \quad \text{(Eq. 4)}$$

$$IM = |Z_{in}/Z_0| = \sqrt{|\mu'/\varepsilon'|}\tanh\left[j\left(\frac{2\pi fd}{c}\right)\right]\sqrt{\mu'\varepsilon'} \quad \text{(Eq. 5)}$$

$$RL = 20\log|(Z_{in} - Z_0)/(Z_{in} + Z_0)| \quad \text{(Eq. 6)}$$

Here, f denotes frequency, c is the speed of light, d represents the specimen thickness, and Z_{in} and Z_0 are the input and free space impedances, respectively.

3. Results and Discussion

3.1 Morphological Study of Gallium-Based Liquid Metal Silicone Composite Materials

The microstructure of the gallium-based liquid metal silicone composite materials was studied using SEM (Figure 3), revealing its unique microstructure and morphology. As shown in Figure 3A, there is a smooth and continuous interface between the gallium-based liquid metal and the silicone matrix, indicating that a good interfacial bonding can be formed between the two, which is crucial for enhancing the material's electrical and thermal conductivity. Figure 3B provides an enlarged view of the area where the gallium-based liquid metal combines with the silicone matrix. The image shows that the gallium droplets are uniformly distributed within the silicone matrix, indicating successful dispersion of the liquid metal. The droplets are spherical, suggesting low interfacial tension between gallium and silicone. The size of the droplets ranges from 1 to 5 μm, which is consistent with the particle size required for optimal electrical conductivity. This excellent dispersion not only contributes to enhancing the mechanical properties of the material but also effectively improves its heat dissipation ability within the battery pack, reducing the risk of temperature rise and thereby extending the battery’s lifespan.

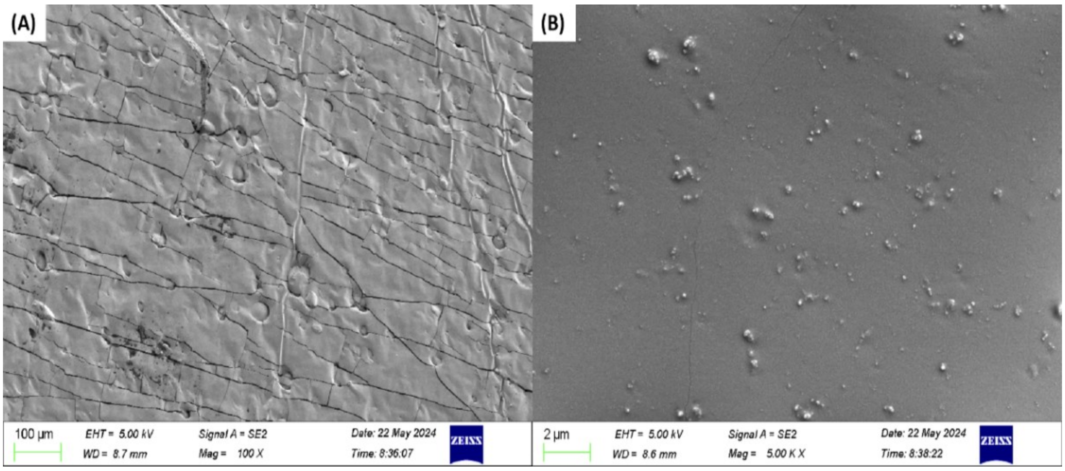

Figure 3. Scanning electron microscopy images of gallium based liquid metal silicone composite materials.

3.2 Mechanical Properties of Gallium-Based Liquid Metal Silicone Composite Materials During Uniaxial Tension

Figure 4A shows the stress-strain curves of silicone gel composites with different gallium mass fractions. The stress-strain curve intuitively illustrates the deformation behavior of the material under external forces, with the results of pure silicone gel represented in purple. In contrast, as the gallium mass fraction increases, both the tensile strength and the elongation at break of the material improve, with the most notable effect observed at the Ga6 sample. This indicates that the introduction of gallium not only enhances the plasticity of the material but also increases its overall strength. This enhanced stress-strain performance enables gallium-based liquid metal silicone gel composites to have better compressive and impact resistance in battery pack applications.

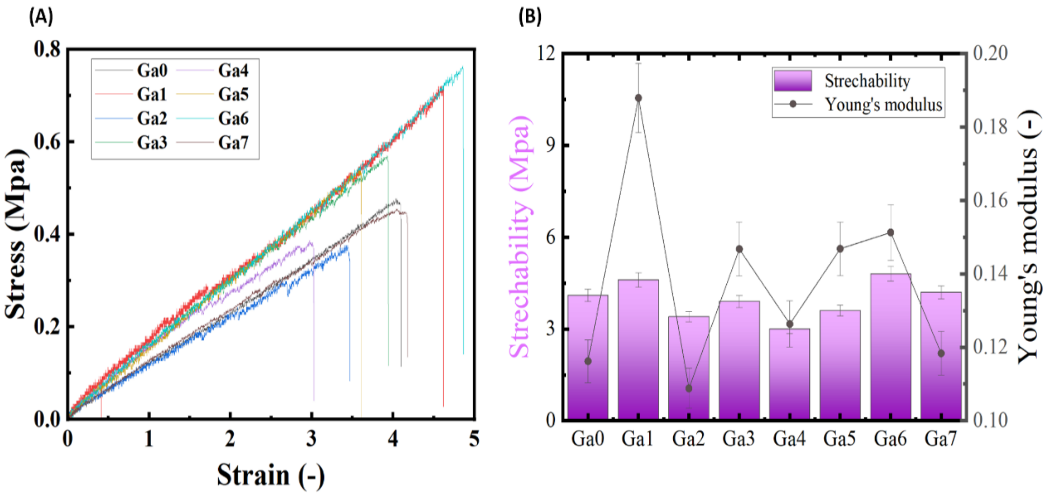

Figure 4. (A) Stress strain curves of silicone composites with different Ga mass fractions; (B) The relationship between tensile properties (left axis) and Young's modulus (right axis) of silicone composite materials and Ga mass fraction.

Figure 4B displays the tensile properties and Young's modulus of silicone gel composites with different gallium mass fractions. From Figure 4B, it can be seen that with the increase in gallium mass fraction, both the tensile properties and Young's modulus of the samples change. However, it is noteworthy that some samples with higher gallium content showed a decline in tensile performance and Young's modulus. This phenomenon may be related to the interaction between the gallium content and the internal structure of the material.

Thanks to their superior mechanical properties, gallium-based liquid metal silicone gel composites have the potential for successful application in battery packs. The high ductility and adjustable strength characteristics of these materials make them an ideal choice for battery pack materials, contributing to improved performance and safety in working environments.

3.3 Electrical Behavior of Gallium-Based Liquid Metal Silicone Composite Materials

Figure 5 shows the electrical signal curve of the material subjected to 20 cycles of cyclic impact under external force with a strain of 30%. From Figure 5, we can observe that the conductivity undergoes significant changes (peak values) within each cycle, and the fluctuation pattern is clear and concise. This phenomenon indicates that the conductivity of gallium based liquid metal silicone composite materials shows an increasing trend when subjected to external forces, which may be related to structural changes and enhanced fluidity within the material.

With the change of external force, the rise of signal peak not only reflects the changes in mechanical properties and conductivity inside the material, but also implies the potential application of the material as a sensing element in battery packs. A higher peak indicates that the material can effectively sense external pressure changes, which is crucial for the safety monitoring and performance evaluation of battery packs under various operating conditions.

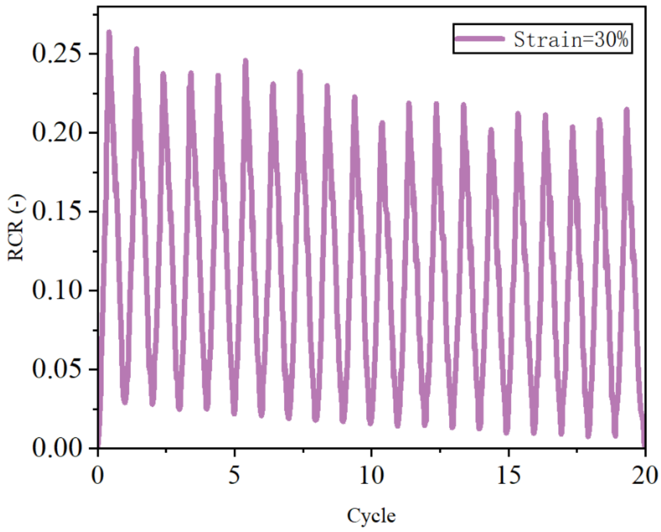

Figure 5. Electrical signal changes of gallium based liquid metal silicone composite material under external force in 20 cycles.

3.4 Electromagnetic Shielding Performance of Gallium-Based Liquid Metal Silicone Composite Materials

In this study, we assessed the electromagnetic interference (EMI) shielding performance of gallium-based liquid metal silicone composite materials, presenting the variation trends of total shielding effectiveness (SE_T), reflection shielding effectiveness (SE_R), and absorption shielding effectiveness (SE_A) at three different gallium mass fractions in relation to frequency (GHz).

From Figure 6, it can be observed that as the gallium mass fraction increases, the total shielding effectiveness (SE_T) of the material exhibits significant improvement over a wide frequency range. Specifically, higher gallium content effectively enhances the reflection and absorption capabilities against electromagnetic waves, indicating superior EMI shielding performance in the high-frequency range. However, we found that the total shielding effectiveness of the sample with 80 g Ga mass is slightly lower than that of the sample with 50 g Ga mass, which may be attributed to increased viscosity and reduced fluidity of the material, leading to performance degradation in certain frequency bands.

At the same time, the trends in SE_R and SE_A indicate that at low frequencies, the reflection shielding effectiveness is relatively high, while at high frequencies, the absorption shielding effectiveness gradually increases. This dual-optimized shielding mechanism enables gallium-based liquid metal silicone composite materials to provide flexible EMI protection in various working environments, ensuring the safety and stability of battery packs under diverse conditions. These test results confirm the feasibility of using gallium-based liquid metal silicone composite materials in battery packs, suggesting that optimizing the gallium mass fraction and designing material components rationally will provide strong support for the electromagnetic compatibility of battery packs.

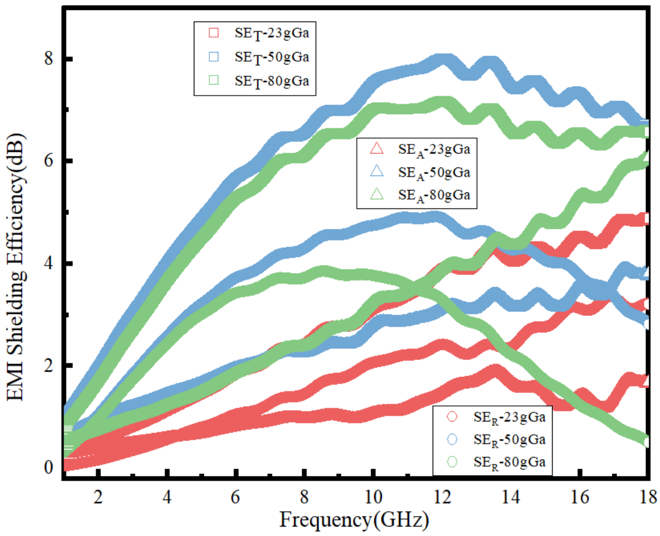

Figure 6. Shielding efficiency of gallium based liquid metal silicone composite materials at different electromagnetic frequencies.

4. Conclusion

In this study, we investigated the application of gallium based liquid metal silicon composite materials in battery packs, with a focus on their mechanical, electrical, and electromagnetic shielding properties. The results indicate that the addition of gallium significantly improves the mechanical properties of the composite material, which can be demonstrated by increasing the tensile strength and elongation at break, especially when the optimal gallium mass is 6 g. These enhancements contribute to the material's excellent compressive and impact resistance, making it suitable for harsh conditions within battery packs.

In addition, the electrical behavior of composite materials indicates that their conductivity has a positive response to external pressure and strain, suggesting that they may be used as sensing elements in real-time monitoring applications. These findings emphasize the ability of materials to effectively detect changes in external conditions, which is crucial for ensuring the safety and performance of battery systems.

In addition, the evaluation of EMI shielding performance emphasizes that composite materials provide strong EMI protection capabilities over a wide frequency range. The dual optimization of reflection and absorption shielding effects proves their universality in various operating environments, ensuring the stability and reliability of the battery pack.

Overall, gallium based liquid metal silicon composite materials exhibit promising application characteristics in battery packs, combining enhanced mechanical properties, responsive electrical behavior, and effective EMI shielding. These findings pave the way for further research on optimizing material composition and exploring its potential in improving the safety and performance of advanced battery systems.

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

References

[1] Nykvist, Björn, and Måns Nilsson. "Rapidly falling costs of battery packs for electric vehicles." *Nature climate change* 5.4 (2015): 329-332.

[2] Dunn, Bruce, Haresh Kamath, and Jean-Marie Tarascon. "Electrical energy storage for the grid: a battery of choices." *Science* 334.6058 (2011): 928-935.

[3] Jiang, Yunpeng, and Xilong Ding. "On the effective thermal conductivity of gallium-based liquid metal filled elastomers." *Materials Today Communications* 39 (2024): 108954.

[4] Yan, Yuhao, et al. "Experimental investigation on optimization of the performance of gallium-based liquid metal with high thermal conductivity as thermal interface material for efficient electronic cooling." *International Journal of Heat and Mass Transfer* 226 (2024): 125455.

[5] Wang, Jiuyang, et al. "Pressure induced thermal conduction paths in liquid metal-boron nitride fillered thermal interface materials with high thermal conductivity." *Composites Communications* 47 (2024): 101881.

[6] Majidi, Leily, Dmitry Gritsenko, and Jie Xu. "Gallium-based room-temperature liquid metals: Actuation and manipulation of droplets and flows." *Frontiers in Mechanical Engineering* 3 (2017): 9.

[7] Shen, Yifeng, et al. "Magnetically Responsive Gallium-Based Liquid Metal: Preparation, Property and Application." *ACS nano* 18.31 (2024): 20027-20054.

[8] Zhang, E., et al. "Study on the tolerance of cell inconsistencies in high-capacity liquid metal battery parallel modules." *Journal of Energy Storage* 101 (2024): 113856.

[9] Xiang, Jun-Xiang, and Ze Liu. "Observation of a Large Slip Effect in the Nanoscale Flow of Highly Viscous Supercooled Liquid Metals." *Langmuir* 39.32 (2023): 11224-11230.

[10] Zheng, Jiashu, et al. "Paste-like recyclable Ga liquid metal phase change composites loaded with miscible Ga2O3 particles for transient cooling of portable electronics." *Applied Thermal Engineering* 213 (2022): 118766.

[11] Yan, Ding-Xiang, et al. "Structured reduced graphene oxide/polymer composites for ultra-efficient electromagnetic interference shielding." *Advanced Functional Materials* 25.4 (2015): 559-566.

[12] Shen, Bin, et al. "Compressible graphene-coated polymer foams with ultralow density for adjustable electromagnetic interference (EMI) shielding." *ACS applied materials & interfaces* 8.12 (2016): 8050-8057.

[13] Al-Saleh, Mohammed H., and Uttandaraman Sundararaj. "Electromagnetic interference shielding mechanisms of CNT/polymer composites." *Carbon* 47.7 (2009): 1738-1746.

[14] Liu, Zunfeng, et al. "Reflection and absorption contributions to the electromagnetic interference shielding of single-walled carbon nanotube/polyurethane composites." *Carbon* 45.4 (2007): 821-827.

[15] Wang, Xihua, et al. "Reduced graphene oxide/carbon nanofiber based composite fabrics with spider web-like structure for microwave absorbing applications." *Advanced Fiber Materials* 4.5 (2022): 1164-1176.

[16] Song, Limeng, et al. "Multifunctional SiC@ SiO2 nanofiber aerogel with ultrabroadband electromagnetic wave absorption." *Nano-Micro Letters* 14.1 (2022): 152.

[17] Zhao, Pei-Yan, et al. "Electrospinning fabrication and ultra-wideband electromagnetic wave absorption properties of CeO2/N-doped carbon nanofibers." *Nano Research* 15.9 (2022): 7788-7796.