Improvement in battery performance due to structure: spiral structure

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Abstract: This paper discusses the performance enhancement brought by the application of spiral structures in batteries, which enhances aspects such as battery contact surface area and ion transport channels, thereby improving the performance and cycle life of solid-state batteries. Solid-state batteries have garnered significant interest because of their substantial energy density, strong safety, and long cycle life advantages. Addressing issues such as low temperature stability and low ion transport rate, current research primarily focuses on material modification and the development of new materials, with structure also being a key factor influencing performance. The spiral structure, with its unique form, gains many advantages and plays an important role in enhancing battery performance.

1. Introduction

With the world's reliance on oil remaining at a high level, we are depleting oil reserves at a rate of approximately 4 billion tons per year, and it is predicted that by 2053 [1], all known oil reserves will be completely exhausted. This poses a significant threat to industries that are centered around oil, and environmental issues caused by the combustion of oil are becoming increasingly severe. In the face of energy crises and environmental pollution caused by energy consumption, it is especially important to actively develop clean and efficient new energy sources. Lithium batteries have become a focus of widespread attention due to their high energy density, long lifespan, and low environmental impact. Although liquid electrolytes in traditional lithium batteries may leak under certain conditions, posing safety risks, solid-state batteries with solid electrolytes fundamentally solve this safety issue. Moreover, solid-state batteries, with their higher energy density, have the potential to alleviate current issues with battery life to a certain extent. Nonetheless, the development of solid-state batteries still faces many challenges, particularly the contact problem at the solid-solid interface, which limits their ionic conductivity. To address this issue, researchers have been dedicated to modifying materials and developing new materials. For instance, studies by Buschmann and others [2-4] on doping garnet-structured electrolytes (LLZO) with aluminum have confirmed that adding aluminum helps to stabilize and improve ionic conductivity. In addition to the intrinsic qualities of the materials, the architectural configuration of batteries also significantly contributes to performance enhancement. This paper will explore the impact of spiral structural design on battery performance, analyze potential challenges, and look forward to future development directions.

2. Preparation of Spiral Structures

The preparation process of spiral structures differs significantly from that of traditional structures, requiring appropriate preparation methods and process optimization for successful application in batteries. Denez and others [5] conducted preliminary experiments by sputtering pure Si and Cu particle raw materials with Ar+, followed by depositing them separately in graphite crucibles. Notably, the primary distinction between spiral and traditional structures lies in the formation of the spiral, which necessitates rotation using a stepper motor when the crucible surface forms an 85° angle with the substrate surface. Moreover, controlling the evaporation rates of Si and Cu to gradually vary the composition along the spiral is essential. On the other hand, Joohyuk Park and colleagues [6] demonstrated an innovative approach by wrapping zinc metal around a stainless steel rod to form a spiral shape and enhancing surface contact by wrapping it with a perforated heat-shrink cable. Liu and others [7] utilized 3D printing technology to directly extrude printing ink, creating an Archimedean spiral solid electrolyte, highlighting the importance of material selection for ensuring a smooth printing process. Regardless of the method used, precise control over the preparation conditions and parameters is crucial to ensure the spiral structure's morphology and size meet requirements, directly impacting electrode performance and stability.

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3. Performance Enhancement Brought by Spiral Structures

3.1. Cycle Life

Spiral structures help mitigate the expansion and contraction of electrode materials throughout the battery's charging and discharging cycles, reducing stress throughout the cycle and prolonging the battery's lifespan. Furthermore, by increasing the contact area of the active material, this configuration aids in slowing down the aging process of electrode materials, thereby further prolonging the battery's lifespan. Spiral structures may help improve the electrochemical performance of batteries because they can provide a more uniform current distribution, reducing battery aging caused by uneven current distribution.

The experimental [7] results demonstrate that spiral carbon nanotubes (CNTs) used as anode materials, exhibit a reversible capacity of 420 mA·h/g at a low current density of 50 mA/g, significantly surpassing that of traditional straight multi-walled carbon nanotubes (MWCNTs) and graphite, which are 370 mA·h/g and 259 mA·h/g, respectively. Notably, even following 100 and 200 cycles at current densities of 50 mA/g and 3 A/g, the spiral CNTs did not show significant capacity loss and maintained a Coulombic efficiency between 98.5% and 100% after the second cycle. This is attributed to the spiral structure creating a self-regulating mechanism that allows for free expansion/contraction along the Z-axis, reducing the stress associated with volume changes during lithium ion absorption and release, thereby ensuring a longer cycle life. Yu and colleagues' research [8] also supports this finding, demonstrating that while the capacity retention rate of carbon nanofibers (CNFs) was 48% when the current density increased from 0.1 A/g to 2 A/g, the retention rate for helical carbon nanofibers (HCNFs) was as high as 87%. Inspired by the DNA helix structure, Qi and colleagues [9] designed the entire battery in a spiral form, showing that even under more than 31,000 cycles of in-situ dynamic mechanical loading, the battery's capacity degradation was less than 3%, significantly enhancing its lifespan.

Therefore, it is clear that the helical structure not only significantly extends the cycle life of batteries in traditional forms but also demonstrates unique advantages in the application of flexible wearable devices.

3.2. Charging and Discharging Rate

Compared to traditional vehicles, the main issue with current new energy vehicles is their insufficient range. Improving the charging efficiency of electric vehicles under existing battery range is an effective solution. Batteries with high-rate performance can charge and discharge rapidly within a short period. This is crucial for fast charging, significantly reducing charging time and enhancing efficiency. Wu et al. [7] demonstrated significant rapid discharge capability of HCNS relative to commercial micrometer-scale graphite and multi-walled carbon nanotubes (MWCNTs). The tortuous path of the helical structure electrode can provide more transmission channels, making it easier for ions to pass through the electrode material, thus accelerating the charging and discharging rates. Additionally, helical structures typically have larger pore spaces, allowing electrolytes to penetrate the electrode material more easily and react with the active material.

3.3. Stability

3.3.1. Thermal Stability

The spiral structure can increase the thermal conduction paths within the battery, allowing heat to be more evenly distributed, thereby enhancing thermal conduction efficiency. Moreover, the heat dissipation design of the spiral structure can reduce local hot spots generated by the battery during charging and discharging processes, thus preventing performance degradation and safety hazards caused by excessive temperatures. Research has shown that improving the thermal stability of batteries can comprehensively enhance their performance [10]. Compared to traditional straight channel systems, helical channels can effectively improve battery temperature [11]. Not limited to traditional flat batteries, helical structures can also serve as effective thermal management in cylindrical batteries. Fei et al. [12] suggested a dual spiral cooling configuration in cylindrical batteries. An aluminum sleeve with double helical grooves on the outer jacket of the cylindrical lithium battery, with coolant added inside the double helical grooves, also provides effective cooling. This is because the rotating fluid in the helical channel can promote fluid mixing, distributing heat more evenly on the surface of the heat source, thereby improving cooling efficiency. Secondly, the rotating fluid in the helical pipeline will increase the turbulent flow effect, which helps to improve heat transfer efficiency. However, when setting up a helical cooling system, attention needs to be paid to the pitch and flow diameter of the helical grooves. These two parameters determine the cooling effect of the helical cooling system, and appropriate numerical values need to be selected through simulation calculations [12], otherwise, opposite heat transfer results may occur.

3.3.2. Mechanical Stability

When batteries are subjected to external mechanical shocks or compression, the lack of sufficient mechanical stability can lead to internal component damage or short-circuiting, which can then cause severe safety incidents such as fires or explosions. Therefore, enhancing the mechanical stability of batteries is one of the crucial methods for ensuring their safety. Compared to the traditional flat structure, the spiral structure significantly improves toughness and strength, providing a promising direction for enhancing the mechanical safety of batteries. Collecting and organizing data from sources [13-17], and using machine learning to predict the importance of factors affecting the strength of the spiral structure, could

offer insights into this area. Figure 1 illustrates the machine learning process and related program design. Figure 2 is the feature importance plot for the XGBoost model, while Figures 3 and 4 display the results obtained from the RF (Random Forest) model. The results indicate that, under the same number of layers, the primary influencing factor is the spiral structure itself. Generally, DH (Double Helix) is stronger than SH (Single Helix), but without matching different inter-layer angles, it could be weaker than SH. Hence, the strength of the spiral structure is closely related to the inter-layer angle. The choice of inter-layer angle affects stress distribution, and an appropriate angle can optimize this distribution, thereby enhancing mechanical performance.

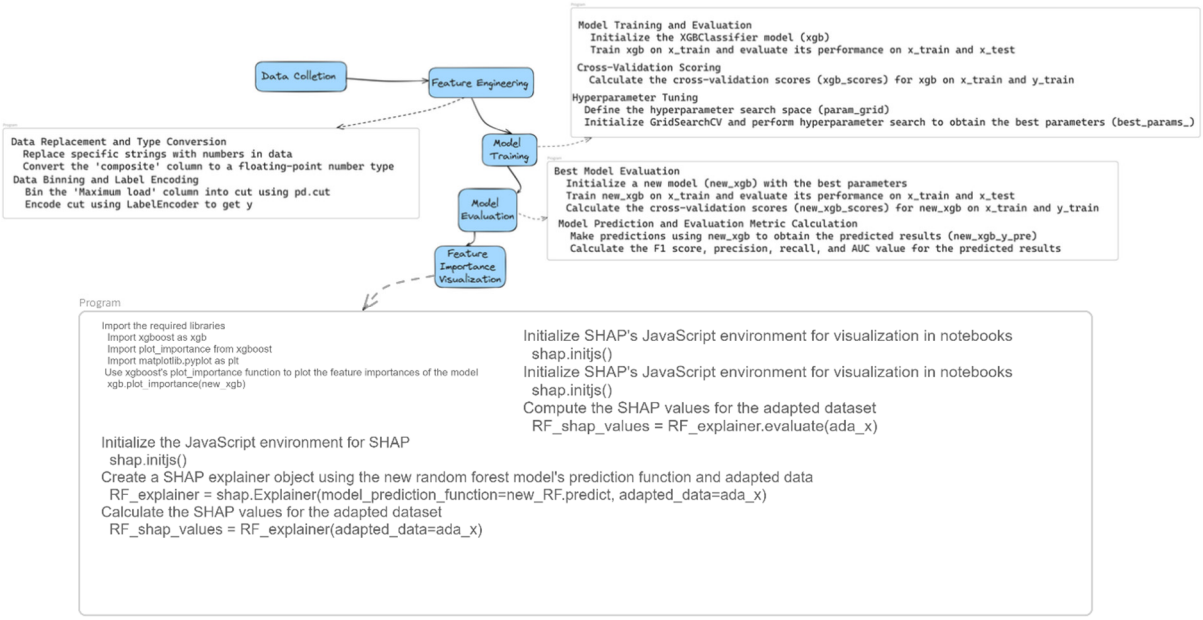

Figure 1. Machine learning process and program design.

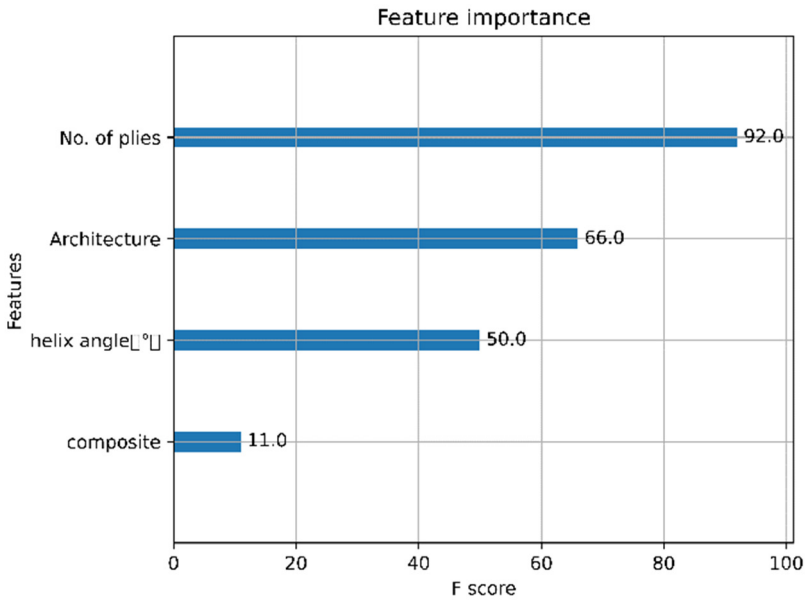

Figure 2. Feature Importance of XGBoost Model

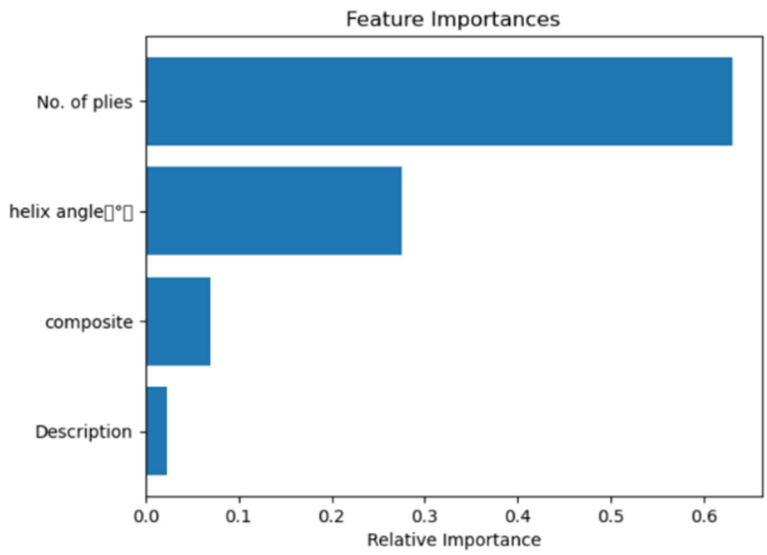

Figure 3. Relative Importance

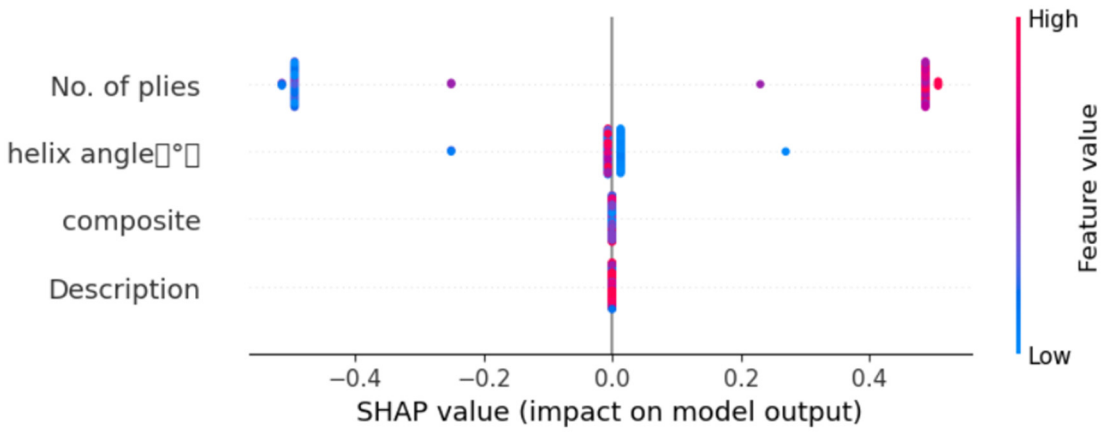

Figure 4. Feature Importance of RF Model

4. Summary and Outlook

The research presented in this paper has demonstrated that spiral structures can significantly enhance the reversible capacity of battery electrodes and maintain stable Coulombic efficiency over extended cycles. This is particularly evident in the use of helical carbon nanotubes and designs inspired by the DNA helical structure, which showcase the potential of spiral structures to enhance battery life under dynamic mechanical loading conditions. Furthermore, the improvement in thermal stability achieved through spiral cooling systems provides a viable solution to the challenges of battery thermal management, which is crucial for maintaining performance and safety. The mechanical stability offered by spiral structures is also a critical aspect, as it ensures the battery's resilience against external impacts, thereby reducing the risk of failure.

However, their application still faces many challenges:

1. Structural optimization: It is well known that helical conductors generate self-inductance when electrified, which may have adverse effects on battery efficiency. Therefore, the reasonable helical angle is crucial. The appropriate angle selection can not only reduce the adverse effects of self-inductance but also ensure good mechanical performance to guarantee structural stability and enhance battery safety.

2. Material selection: Not all materials are suitable for making helical structures. Exploring new materials suitable for helical structured electrodes to improve energy density and cycling stability is necessary.

3. Process optimization: The manufacturing technology is still immature. With the continuous progress of technology and in-depth research, helical structures will play an increasingly important role in solid-state batteries, providing new ideas and approaches for enhance.

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