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Progress of Using Nanotechnology in Electric Vehicle Batteries

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Abstract:

The global new energy vehicle industry is developing rapidly the bottlenecks of traditional lithium-ion batteries in terms of energy density, charging and discharging efficiency, cycle life and safety are difficult to meet the needs of electric vehicles, and nanotechnology provides a new path to break through these limitations. This paper review the application of nanotechnology in the field of automotive batteries in recent years, summarize the mechanism of nanotechnology in improving energy density, optimizing charging and discharging speeds, prolonging cycle life and enhancing safety, and summarize the current technological advances and challenges. Nanotechnology can optimize the performance of key battery components by regulating the microstructure and interfacial properties of materials, such as nano-electrode materials to enhance lithium storage capacity and reaction kinetics, nano-coated diaphragms to inhibit lithium dendrite growth, and nano-structural design to promote the development of solid-state electrolytes. In addition, nanotechnology also shows potential in battery thermal management, which can optimize the internal thermal conductivity efficiency and improve the performance stability at extreme temperatures, providing reference for subsequent related research.

Keywords: Nanotechnology; battery; electric Vehicle; safety.

1. Introduction

With the rapid development of the global new energy vehicle industry, the performance improvement of automotive batteries has become a core issue to promote the progress of the industry. The bottlenecks in energy density, charge/discharge efficiency, cycle life and safety of traditional lithium-ion batteries have made it difficult for them to meet the demand for long range, fast charging and high stability of electric vehicles [1]. Nanotechnology, with its unique advantages in material microstructure regulation, provides a new solution to break through the battery performance limitations. The introduction of nano-materials can significantly optimize the performance of key battery components. For example, nanoscale electrode materials(e.g., nano-silicon, nano-lithium iron phosphate) can effectively improve the lithium

storage capacity and reaction kinetics of the electrodes by increasing the specific surface area and shortening the ionic diffusion paths [2], while nano-coated diaphragms can inhibit the growth of lithium dendrites and reduce the risk of short-circuiting, thus improving the safety of batteries [3]. In addition, nanostructure design shows great potential in the development of solid-state electrolytes, which is expected to solve the problems of liquid leakage and high-temperature runaway caused by liquid electrolytes [4]. The current application of nanotechnology in automotive batteries has demonstrated the potential of multi-dimensional breakthroughs, for example, in the modification of electrode materials, the balance of high capacity and high stability can be achieved simultaneously through nanoscale structural design, and some of the nanocomposite electrode materials have been used to increase energy density by more than 30% at the laboratory level; in the aspect of the battery thermal management assistance, the introduction of nano-thermal conductive materials to optimize the efficiency of heat conduction within the battery, and indirectly improve the performance at extreme temperatures. The introduction of nano thermal conductive materials can optimize the heat conduction efficiency inside the battery and indirectly improve the performance stability under extreme temperature. The synergistic development of these technological directions is driving the performance of automotive batteries in the direction of being more suitable for the practical needs of new energy vehicles.

In this paper, by combing the application research of nanotechnology in the field of automotive batteries in recent years, it review the mechanism of nanotechnology in terms of energy density enhancement, charging and discharging speed optimization, cycle life extension, and safety enhancement, and summarize the current technological advances and challenges, in order to provide references for the direction of the subsequent research.

2. Nanotechnology Enhances Electric Vehicle Batteries in three Key Areas

2.1 Enhancements in Security

Nanotechnology has shown irreplaceable value in enhancing the safety of electric vehicle batteries by precisely regulating the microstructure and interfacial properties of battery materials, and its applications have covered core components such as battery diaphragms, thermal management materials and electrode materials.

Battery diaphragm is the key barrier to prevent positive and negative short-circuiting, and diaphragm puncture caused by lithium dendrite growth is a major safety hazard. The interfacial super-assembled carbon nanocomposite diaphragm developed by the team of CPSM and Fudan University realizes the orderly transport of lithium ions and effective inhibition of lithium dendrite growth by constructing a silicone-polymer carbon nanocoating on the surface of the traditional diaphragm. Experimental data show that the Coulombic efficiency of the modified diaphragm increased from 67%(without nanocoating) to 85% after 1,000 cycles at 25°C, and from 10%(without nanocoating) to 93% after 150 cycles at 45°C, which significantly extends the safe service life of the battery. The polyimide-based ion management membrane developed by the Chinese Academy of Sciences' Modern Physics Institute [5], which achieved 1200 hours of stable lithium plating/stripping at 1 mA/cm² while maintaining a uniform lithium deposition morphology. Additionally, Enjie Holdings' nanoanti-dendrite coated separator demonstrated a 30% reduction in lithium dendrite penetration depth at 10°C compared to conventional ceramic separators, with cycle life improvements of 40% in low temperature applications. In the field of battery thermal runaway protection, nano aerogel materials have become the core solution due to their unique microstructure. 3D nanoporous aerogel thermal barrier materials developed by Aspen Aerogels, with a thickness of only 1-4 mm, can build a highly efficient insulation layer that reduces the rate of thermal runaway spreading of the battery pack by 70%, while at the same time, its negative impact on the energy density of the battery is reduced by 40% compared to the traditional insulation solutions, realizing a balance between safety and performance [6]. Solutions include the Paraffin@SiC nanowire/aerogel composite developed by the University of Science and Technology of China [7], which created a 602°C temperature gradient with just 2 mm thickness while limiting energy density loss to 0.79%. Industry adoption is also evident in BYD's 2024 EV models [8], where aerogel thermal barriers reduced pack level thermal runaway propagation speed by 65% while maintaining a 500 Wh/L volumetric energy density. The thermal stability of electrode materials directly affects battery safety boundaries. The NCM 811 high nickel single crystal anode material developed by Ningde Times optimizes the crystal structure through atomic level nano doping technology, which improves the thermal stability of the material by 20%, and the cycle life reaches 2500 times(far exceeding the requirement of 1500 times of the national standard); the supporting nano ceramic composite diaphragm improves the temperature resistance to 180℃, and the thermal runaway spreading time exceeds 48 minutes in the pinning experiment, far higher than the national standard of ≥5 minutes. Sinoma Science & Technology's

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ceramic coated separator for solid-state batteries achieved 1800 cycles at 60°C with a 92% capacity retention rate, outperforming conventional polyolefin separators by 30%. These advancements collectively demonstrate the multi-layered strategies employed to enhance battery safety across material, structural, and system levels.

Nanotechnology provides a systematic solution to improve the safety of electric vehicle batteries by solving the core safety problems of battery short circuit and thermal runaway from the material level. With the maturity of the nano-preparation process, its application in the field of battery safety will be further deepened.

2.2 Enhancement in Battery Cycle Life

Nanotechnology provides a key solution to enhance the cycle life of electric vehicle batteries by precisely regulating the structure and interfacial properties of battery electrode materials, and its application has made significant breakthroughs in the fields of positive electrode materials, negative electrode materials and interface modification.

Nano-structuring of cathode materials is an important path to extend cycle life. Shenzhen Defang Nanotechnology team used self-heating evaporation liquid phase synthesis method to prepare lithium iron phosphate nanoparticles, combined with discontinuous graphene coating and ion doping technology to optimize the conductivity and structural stability of the material. Experimental data show that the cycling performance of the nano-treated $LiFePO_4$ battery is significantly improved and far better than similar products in the market, which can fully meet the demand for long-life electric vehicle power batteries [9]. Previous Research such as the polyaniline-derived porous carbon-coated LiFePO4 nanocrystals developed by the Chinese Academy of Sciences' Institute of Physics, which achieved 166.9 mAh/g capacity at 0.2C with 92.7% carbon content and maintained 128.4 mAh/g at 5C over 250 cycles [10]. Additionally, Tsinghua University's demonstrated a 2wt% Li-La-Ti-O-coated $LiMn_2O_4$ composite cathode that retained 115 mAh/g at 55°C under 1C cycling, outperforming uncoated materials by 30% in high-temperature stability.The nano-composite design of anode materials effectively solves the volume expansion problem of traditional materials. The hard carbon-tin nanocomposite anode developed by Pohang University of Science and Technology in collaboration with the Korea Energy Research Institute retains the high lithium storage capacity of tin by embedding tin nanoparticles in a hard carbon matrix and reduces the volume expansion effect with the help of buffering effect of hard carbon. Tests show that lithium-ion batteries with this composite anode can achieve more than 1500 cycles under 20-minute fast charging conditions, with a breakthrough in cycle life and energy density(1.5 times that of conventional graphite anode batteries) [11].Solution include the silicon-carbon yolk-shell nanostructure developed by Stanford University, which exhibited 93% capacity retention after 400 cycles with 1120 mAh/g specific capacity at 1C, leveraging hollow carbon shells to mitigate silicon's 400% volume expansion [12]. Similarly, MIT's silicon-titanium dioxide core-shell anode demonstrated 842.6 mAh/g capacity at 2A/g over 1000 cycles, combining TiO_2 passivation with carbon reinforcement [9]. Interfacial nanocoating technology provides long-lasting protection for electrode materials. The nickel-magnesium composite nano-coating developed by researchers at the University of Queensland, Australia, can effectively inhibit material decomposition and interfacial side reactions during charging and discharging by tightly wrapping the surface of the anode material with strong adhesion. The performance of lithium batteries treated with this coating remains stable after 1000 charge/discharge cycles, and the number of cycles is more than doubled compared with that of untreated batteries [13]. include Harvard University's silicon-encapsulated lithium metal anode, which achieved 80% capacity retention over 6000 cycles by confining lithium plating within silicon micropores, reducing dendrite formation by 90%. Meanwhile, Tianjin University's graphene-wrapped Ni/NiO core-shell structure demonstrated 750 mAh/g reversible capacity with 86% porosity, enabling 1200 cycles at 1C through dual-phase stress dissipation [14]. These advancements collectively demonstrate the multi-layered strategies employed to enhance battery longevity across material, structural, and interfacial engineering.

Nanotechnology can significantly extend the cycle life of EV batteries by optimizing the electrochemical performance of batteries from the dimensions of material structure and interface regulation. With the large-scale application of nanopreparation process, its value in the field of long battery life will be further highlighted.

2.3 Enhancement in Charging Speed

Nanotechnology has become a core technical means to break through the bottleneck of fast charging of electric vehicle batteries by optimizing the ion transport path and electrode reaction kinetics of batteries, and substantial progress has been made in the fields of diaphragm modification and electrode structure design.

Nanostructure modification of battery diaphragm can significantly improve the ion conduction efficiency. The graded covalent organic framework porous diaphragm (PAN/AM-COF) designed by the team of Prof. Yaozu Liao from Donghua University, with the precise screening

effect of lithium-friendly microporous channels and graded linkage pore structure, the ionic conductivity reaches 3.33 mS cm^{-1}. Lithium iron phosphate batteries equipped with this diaphragm can be filled up in only 12 minutes at 30C ultra-high rate, and the capacity degradation is only 0.0025% per cycle. The team further proposed the concept of all-nanofiber covalent organic framework battery(ANCB), in which the positive and negative electrodes and the diaphragm are fabricated simultaneously with the same type of nanoporous materials, and the energy density reaches 517 Wh/kg while the power density soars to 9771 W/kg, realizing the ultra-fast charging in 56 seconds. This approach aligns with recent advancements such as the anion-functionalized covalent organic framework(Bd-COF) developed by Tsinghua University, which achieves 0.153 mS/cm ionic conductivity through electrostatically induced lithium-ion desolvation, enabling stable cycling of Li-metal batteries for over 1000 hours. The design of nanopore electrode structure provides a new interface solution for fast charging. The nanopore structure battery developed by the University of Maryland team stores the electrolyte in micropores, and enables rapid charge migration between nanotube electrodes by shortening the ion diffusion distance and increasing the electrode-electrolyte contact area, which is measured to complete the full-charged state in 12 minutes without significantly affecting the cycling stability. Solutions include the metal-organic framework(MOF)-based anode optimized via machine learning by Tytlabs, which reduces charge transfer resistance by 40% and enables 10-minute fast charging while maintaining 92% capacity retention after 500 cycles [15]. Nanocoated materials, on the other hand, assist in enhancing fast-charging feasibility through thermal management. German scientists developed an ultra-thin diamond nanofilm, using its excellent thermal conductivity(thermal conductivity is 5 times that of copper) and insulating properties, can reduce the local heat load during charging by 10 times, effectively alleviating the problem of temperature surge caused by fast charging, and the integration of which can increase the charging speed of electric vehicles by 5 times . Similarly, Fraunhofer USA's flexible diamond nanomembrane, with 5x higher thermal conductivity than copper, reduces local heat accumulation during fast charging by 10-fold, allowing EVs to achieve 5x faster charging speeds without compromising energy density.In addition, the optimization of the morphology of nanoscale anode materials directly improves the efficiency of lithium storage. The high specific surface area nanoanode material synthesized by a Korean team can theoretically enable modern electric vehicles to finish charging within 6 minutes by increasing the active sites for lithium ion adsorption and shortening the diffusion path, and the volume expansion rate of the material is controlled within 20%, which solves the structural stability problem of traditional high-capacity anodes. Previous achievements include Zhengzhou University's single-walled carbon nanotube(SWNT)-reinforced SiOx anode, which mitigates 400% volume expansion through strain-induced interfacial Si-C bond formation, delivering 685 mAh/g capacity over 1000 cycles with 82% retention [10].

Nanotechnology breaks through the technical limitations of fast charging from the multi-dimensional aspects of ion transport, interfacial reaction, and thermal management.

3. Conclusion

Nanotechnology holds immense application value in the field of electric vehicle batteries. This paper systematically explores its optimization effects on three core battery performance metrics-safety, cycle life, and charging speed-while outlining technological advancements and challenges. Regarding safety, nanotechnology enhances separator performance by precisely controlling the microstructure and interfacial properties of battery materials, thereby suppressing lithium dendrite growth to prevent short-circuit risks. It slows the propagation speed of thermal runaway within battery packs using the unique structure of nano-aerogel materials. Simultaneously, techniques like atomic-level nano-doping optimize the thermal stability of electrode materials, enabling multidimensional safety risk management from the material to the component level. Regarding cycle life, nanotechnology addresses material structural degradation during charging/discharging by reducing internal stress from volume changes through nanostructured cathodes buffering active material expansion with nanocomposite anodes suppressing interfacial side reactions via nanocoatings These synergistically enhance structural stability and significantly extend cycle endurance. For charging rate optimization, nano-modified separators create efficient ion transport channels to reduce migration resistance. Nano-porous electrode designs increase electrode-electrolyte contact area while shortening ion diffusion paths. Nano-thermal materials assist in mitigating heat accumulation during fast charging, collectively overcoming technical barriers to rapid charging. Nanotechnology provides a critical pathway for breakthroughs in electric vehicle battery performance. As nanomanufacturing processes mature and scale up, they will better align with the practical demands of new energy vehicles. This also clarifies the direction for future in-depth research on nanotechnology in battery applications, driving the advancement of the new energy vehicle industry.

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