Current Approaches Enhancing the Elimination of Dendrite Formation in Batteries

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Abstract. Dendrite formation poses a substantial challenge to the advancement of high-energy-density batteries, especially those utilizing lithium-metal anodes. Irregular metal deposition throughout successive electrochemical cycles causes acicular dendrite formation, causing internal short circuits, diminished capacity, and significant safety risks, including thermal runaway. This paper analyses the essential mechanisms of dendrite nucleation and development, their implications in lithium-metal, lithium-sulfur, lithium-air, and sodium-based batteries, and contemporary tactics for suppression. Strategies encompass the development of sophisticated electrolytes, the alteration of anode surfaces, and the use of nanotechnology to improve separator efficacy and solid electrolyte interphase (SEI) stability. Along with the recent significant progress exhibiting feasible approaches towards dendrite growth, obstacles concerning material expenses, manufacturability and long-term stability persist. Emerging technologies like hybrid electrolytes and real-time diagnostics are crucial to the next generation of safe and efficient energy storage systems.

Keywords: Dendrite growth; Battery; Material.

1. Introduction

The fast proliferation of electrification in numerous industries has heightened the worldwide need for sophisticated energy storage systems that are characterized by high performance, efficiency, safety, and sustainability. In this context, next-generation batteries, especially those utilizing lithium metal, have emerged as viable contenders to exceed the energy constraints of traditional lithium-ion batteries. In contrast to graphite anodes employed in conventional systems, lithium metal anodes present a markedly superior theoretical specific capacity (3,860 mAh/g) and high voltage, rendering them exceptionally appealing for applications necessitating high energy density and compact configurations, such as electric vehicles (EVs), drones, and aerospace systems [1]. Nonetheless, despite their theoretical benefits, the commercialization of lithium metal and associated batteries has been markedly impeded by a continual and perilous occurrence: dendrite formation.

Dendrites are needle-shaped or tree-like metallic appendages that develop on the anode's surface during successive charge-discharge cycles. These patterns arise from non-uniform metal ion deposition, frequently instigated by variations in current density, mechanical stress, or surface imperfections on the electrode [2]. Dendrites, when they grow into the electrolyte, may ultimately penetrate the separator—a porous membrane that electrically isolates the anode from the cathode—resulting in internal short circuits. This internal failure mechanism may result in significant repercussions, including localized heating, thermal runaway, fires, and potential explosions [3]. The dendrite problem is significantly discovered especially in commercially available lithium metal batteries, as the strong reactivity of lithium anodes with standard liquid electrolytes hastens the development and proliferation of dendrites.

The significance of managing dendritic development transcends safety issues. Dendrites negatively impact the overall efficiency and lifespan of batteries by elevating internal resistance, facilitating side reactions and inducing fast deterioration of active materials, hence batteries experience efficiency degradation and shortened cycle life with time [4]. These concerns extend beyond lithium metal batteries alone. Other nascent battery chemistries—such as lithium-sulfur (Li–S), lithium-air (Li–O_2), and sodium-based batteries—confront analogous issues with dendrite development, but with causes and repercussions distinct to each material.

Consequently, mitigating dendritic development is both a technological need and a pathway facilitating the next generation of high-performance energy storage devices. Investigations into materials design, electrolyte engineering, interfacial chemistry, and advanced manufacturing processes are swiftly advancing to mitigate dendrite development and stabilize the electrode–electrolyte interface. A comprehensive knowledge and effective management of dendrite formation are essential for realizing the full potential of future battery technologies, allowing safer, more durable, and energy-dense storage solutions across many applications.

This review seeks to deliver a comprehensive overview of the processes that govern dendrite formation and their influence on battery performance and safety within intriguing chemistries. This analysis delves into contemporary mitigation strategies, encompassing electrolyte and anode engineering as well as nanotechnology applications for solid electrolyte interphase (SEI), while assessing persistent challenges and prospective pathways for realizing stable, high-performance energy storage systems.

2. Discussion

2.1. Mechanism of Dendrite Formation

The development of dendrites in lithium-based batteries is a complex electrochemical phenomenon mainly driven by the irregular deposition of lithium ions on the anode surface during repeated charge and discharge cycles. During charging, lithium ions should traverse from the cathode through the electrolyte and uniformly deposit onto the anode. In real systems, particularly those employing lithium metal as the anode, the deposition process often demonstrates irregularity. This behavior can be ascribed to several variables, including variations in current density, the surface shape of the anode, and changes in ionic flow at the electrode-electrolyte interface. Irregular lithium deposition is a critical phase in this process, since it initiates the creation of tiny protrusions or "nuclei" on the anode surface [5]. In succeeding cycles, these protrusions demonstrate anisotropic development, evolving into pointed, needle-like formations known as dendrites (**Figure 1**). Dendrites penetrate the electrolyte and may eventually contact the separator, creating a conductive pathway between the anode and cathode. This might result in internal short circuits, greatly compromising the safety and efficacy of the battery.

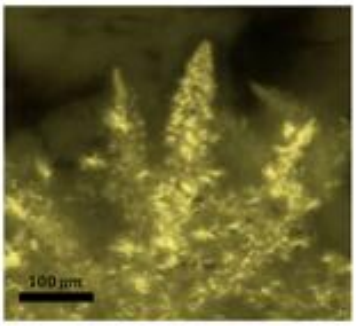

Figure 1. Photograph of lithium dendrites on electrodes with electrochemical deposition of lithium [6].

The composition and characteristics of the electrolyte are essential to this occurrence. Electrolytes with limited lithium-ion conductivity or inadequate durability are more susceptible to dendritic development. The consistency of lithium-ion deposition is affected by factors such as ion transport number, viscosity, solvation structure, and interfacial compatibility with lithium. Electrolytes that cause unequal ion mobility can lead to localized lithium saturation, hence encouraging the development of protrusions rather than enabling a smooth, flat deposition [7].

The circumstances of charge and discharge cycling, especially the current density, profoundly affect dendritic development. At high current densities, lithium ions are deposited onto the anode at an increased rate, often exceeding the capacity for uniform incorporation into the electrode structure

[8]. The fast deposition exacerbates uneven development and leads to increased nucleation of dendritic formations. In these conditions, the system fails to attain the requisite temporal and energetic equilibrium for the lithium to spread uniformly across the electrode surface, therefore facilitating dendrite growth [9]. Aggressive cycling protocols can undermine the integrity of the SEI layer, which is crucial for stabilizing lithium deposition, hence worsening the issue.

Dendrite production arises from intricate interplay between electrochemical kinetics, material characteristics, and operational parameters. A comprehensive knowledge of these processes is essential for developing techniques to impede dendritic formation and improve the dependability, safety, and lifetime of next-generation lithium-based batteries.

2.2. Consequences of Dendrite Formation in Conventional Lithium Metal Batteries

The formation of dendrites in lithium metal batteries (LMBs) poses considerable obstacles to achieving their complete electrochemical potential. These metallic filaments, arising from uneven lithium-ion deposition during charging and discharging cycles, result in two notably adverse effects: the depletion of active lithium and the potential for catastrophic battery failure owing to internal short circuits.

The principal consequence of dendrite development is the permanent loss of active lithium. As dendrites develop and ultimately achieve electrical isolation from the anode, they cease to engage in the electrochemical cycling process. The phenomena termed "dead lithium" generation gradually diminishes the available lithium inventory in the cell, resulting in a quantifiable reduction in capacity over time. The persistent depletion of electrochemically active material diminishes the battery's cycle life and compromises its energy efficiency and dependability, especially under rigorous use scenarios like rapid charging. A significant impact is the heightened probability of internal short circuits. As dendrites extend within the cell, they may penetrate the separator—a porous insulating layer intended to avert direct contact between the anode and cathode. When a dendrite penetrates this barrier, it establishes a conductive pathway that facilitates the unimpeded flow of electrons between the electrodes, circumventing the external circuit. This produces a localized short circuit that creates significant heat owing to resistive losses [10]. In severe instances, such thermal occurrences may result in thermal runaway, marked by an unregulated increase in temperature, the emission of combustible gases, flames, or perhaps explosions [11]. The intrinsic instability of lithium metal amplifies these dangers, rendering dendritic development a major safety issue in sophisticated battery systems.

2.3. Impact on Next-Generation Batteries

Despite its great energy potential, dendritic development is not only crucial to the conventional lithium batteries, but also the next generation batteries, endangering their safety and lifespan. Li–S and Li–O_2 batteries with metal anodes are susceptible to dendrite-induced deterioration. Dendrites and polysulphide shuttle effect destabilize Li–S electrode interfaces. Dendrites in Li-O_2 batteries hinder oxygen delivery, increase short-circuit danger, and significantly lower performance [12].

Dendritic difficulties plague sodium-ion batteries, which are cheap and abundant. Despite its lower plating tendency than lithium, sodium's higher ionic radius and unique deposition behavior still cause dendrites under high currents or prolonged cycling, threatening battery integrity [13].

Zinc and magnesium batteries are also vulnerable. Though magnesium's divalent ions help smooth deposition, impurities and excessive current can cause dendritic development. Zinc-based aqueous batteries, however safer, frequently generate dendrites due to hydrogen evolution and uneven plating during deep or rapid cycles [14].

Dendrite formation hinders next-gen battery viability. Advanced materials, ion transport management, and stable electrode–electrolyte interfaces are needed to solve problem.

3. Strategies for Alleviating Dendrite Formation

3.1. Modifying electrolytes

A promising approach to mitigate dendrite growth in lithium metal and next-generation batteries involves the strategic engineering of electrolytes. By modifying the electrolyte into solid-state or high-concentration dual-salt formulations can directly influence lithium-ion flux, deposition morphology, and interfacial stability, which are critical factors for dendrite suppression, as dendrites form at the electrode–electrolyte interface.

3.1.1 Solid-state electrolytes (SSEs)

Solid electrolytes, particularly ceramic or polymer ones, offer robust physical barrier to dendritic intrusion, thus reducing internal short circuits. Unlike liquid electrolytes that promote the formation and spread of lithium dendrites, solid-state electrolytes possess high mechanical moduli, greater than doubled that of lithium metal shear modulus (around 4.2 GPa), which effectively prevent dendrite penetration through the electrolyte matrix [15].

Ceramic-based solid electrolytes, exemplified by garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO), exhibit high lithium-ion conductivity (up to 10^{-3} S/cm) and demonstrate exceptional chemical stability with lithium metal. Their high shear modulus values (around 52 to 64 GPa) enable high mechanical strength, inhibit dendrite growth and facilitate uniform ion transport across the interface. Sulfide-based solid electrolytes, such as $Li_{10}GeP_2S_{12}$ (LGPS), exhibit high ionic conductivities and compatibility with lithium; however, they necessitate further strategies to address air and moisture sensitivity as well as interface engineering [16].

Polymer-based solid electrolytes, including those that utilize polyethylene oxide (PEO), exhibit increased flexibility and ease of processing; however, they generally demonstrate reduced ionic conductivities at room temperature. Hybrid polymer-ceramic composites have been developed to improve their properties, integrating mechanical strength of ceramics with the flexibility of polymers, enhancing dendrite resistance and interfacial contact with electrodes.

3.1.2 High-concentration dual-salt electrolytes

High-concentration electrolytes (HCEs) and dual-salt formulations change lithium-ion solvation structure and deposition morphology. increasing salt concentration modulates ion transport, minimizing concentration gradients that cause uneven plating and dendritic nucleation.

Dual-salt electrolytes (dual-anion electrolyte (HCDE)) typically include lithium bis(fluorosulfonyl)imide (LiFSI) and lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) [17]. The SEI protects the lithium surface, promoting uniform lithium deposition and reducing metal-electrolyte parasitic processes. Ionic liquids and gel polymer electrolytes are incorporated due to their low volatility, thermal stability, and large electrochemical windows. Salts dissociate at distinct rates, facilitating the equalization of lithium-ion concentration gradients next to the anode, inhibiting ion depletion zones where dendrites often nucleate. Dong, N. et al. demonstrated that by incorporating LiFSI, consistent cycling at elevated current densities (1 mA/cm^2) with minor dendrite formation after over 300 cycles was shown [18]. Advancing electrolyte composition using high-concentration or multifunctional liquid media—improves lithium metal and next-generation battery Coulombic efficiency, cycle life, and operational safety by inhibiting dendrite development.

3.2. Alterations of Anode Surface

A vital approach to inhibit dendrite development in lithium-metal batteries is to deliberate alteration of the anode surface, controlling lithium-ion deposition, diminish localized current density hotspots, and stabilize the lithium–electrolyte interface. These solutions encompass pre-fabricated coatings, structural design of nano-materials to get uniform and reversible lithium plating.

3.2.1 Artificial solid electrolyte interphase coatings

A possible approach is the implementation of artificial solid electrolyte interphase layers before battery operation. In contrast to the naturally occurring SEI that develops spontaneously and irregularly upon contact with lithium and electrolyte, artificial SEIs are meticulously designed protective coatings that offer enhanced mechanical integrity and chemical stability. Materials like lithium fluoride (LiF) and lithium nitride (Li_3N) [19] are frequently utilized for their superior ionic conductivity and resistance to dendritic penetration. These coatings regulate the kinetics of lithium-ion transport and promote homogenous nucleation, substantially reducing dendritic development during cycling.

3.2.2 Moldifying lithium metal anode hosts (scaffolds, 3D architectures and nano-structure)

The introduction of 3D structured current collectors or host scaffolds mitigate dendrite development effectively. These permeable, conductive matrices reduce local current densities by enhancing the effective surface area, present designated locations for lithium nucleation, and create a restricted environment for lithium deposition, thereby inhibiting uncontrolled dendritic development. Carbon-based substrates, including carbon nano-fibers and hollow carbon spheres, are extensively investigated for their chemical stability, electrical conductivity, and structural versatility [20].

Nanotechnology provides another approach regulating lithium-ion dynamics at the interface. Nano-structured anodes, consisting of materials like silicon nanoparticles, graphene oxide frameworks, or metal-organic frameworks (MOFs), offer highly adjustable surfaces with many nucleation sites. These features facilitate the homogeneous distribution of lithium ions, hence mitigating the likelihood of dendrite formation resulting from unequal current densities. By managing the volume fluctuations linked to lithium plating and stripping, the anode's long-term mechanical and electrochemical stability are enhanced. MOFs fabricating lithophilic three-dimensional (3D) structures using various substrates (e.g., carbon cloth (CC) and copper mesh) for dendrite-free lithium metal anodes is developed by Zeng et al. The synthesized composite anode, leveraging the lithophilic N-functional groups and LiZn alloy, facilitated an evenly distributed formation of Li, leading to a dendrite-free morphological structure (**Figure 2**). In addition, the 3D conducting carbon framework improved the reaction kinetics and accommodated the measurement fluctuations of the electrode. The anode demonstrated an extended lifespan exceeding 1000 cycles at 5 mA cm−2, accompanied by a minimal over-potential of 19 mV [21].

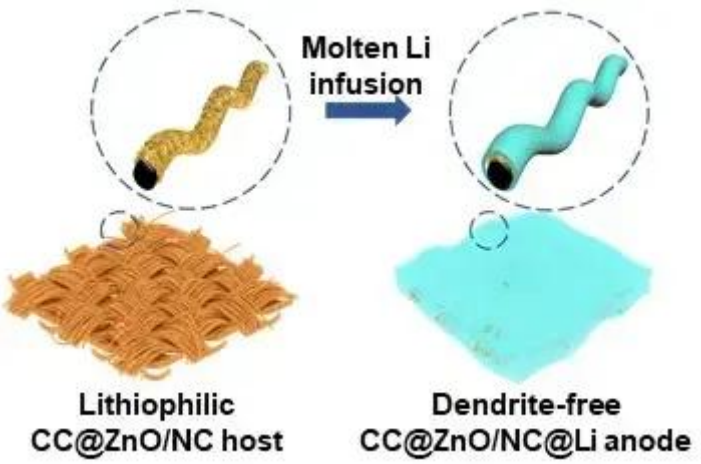

Figure 2. General construction of lithiophilic 3D skeleton for dendrite-free lithium metal anode via a versatile MOF-derived route [21].

3.3. Nanotechnology: Separators

The separator—porous membrane situated between the anode and cathode, is essential in lithium-based batteries preventing direct contact between the electrodes while facilitating ionic transport, particularly when subjected to high current densities or extended cycling. These circumstances induce

dendrites, promoting incorporations of nanotechnology-driven enhancements into the separators. Two main strategies include utilizing nano-composites to strengthen solid electrolyte interphase layers and implementing advanced nanoscale coatings that serve as supplementary protective barriers, which minimize defects and fill voids in the separator material that otherwise serve as initiation points for dendrite growth.

3.3.1 Nano-materials enhancing SEI layers

A key role of separator modification is to aid in the stabilization of the SEI—the protective layer that develops at the anode-electrolyte interface. The SEI is essential for regulating lithium-ion movement and ensuring electrochemical stability. Nonetheless, conventional SEI layers frequently exhibit mechanical weakness and chemical instability, rendering them susceptible to dendritic intrusion. To tackle this issue, innovative separators have been created that utilize nano-composite enhancements, integrating nano-materials like metal oxides (e.g., Al_2O_3, TiO_2, SiO_2) and metal sulfides (e.g., MoS_2) within polymer matrices. The SEI is reinforced both mechanically and chemically by these nano-materials. For instance, Al_2O_3 nanoparticles aids in mitigating dendrite growth by ensuring a more uniform ion flux and enhanced resistance to mechanical stress. In addition, nano-structured sulfides like MoS_2 enhance ion transport and exhibit lithophilic characteristics that promote efficient lithium deposition, thereby minimizing dendrite nucleation. Embedding these nano-fillers into the separator or applying them to the separator surface leads to a notable improvement in the mechanical integrity of the SEI and the overall performance of the cell [22].

An additional approach entails the utilization of ultra-thin protective coatings on separators through meticulous nano-fabrication methods, including atomic layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD). These techniques facilitate the precise deposition of nanometer-scale films, ensuring remarkable uniformity and control. This makes them particularly suitable for improving separator surfaces while maintaining unobstructed ionic transport. Materials like aluminum oxide (Al_2O_3), lithium phosphate (Li_3PO_4), and lithium niobite ($LiNbO_3$) are frequently utilized for these coatings because of their chemical stability and mechanical strength. These coatings act as synthetic buffer layers that inhibit direct interaction between dendrites and the separator, thereby effectively mitigating dendrite penetration [23]. Furthermore, their interaction with the lithium surface can lead to the development of a more stable and robust solid electrolyte interphase, enhancing the overall cyclability and safety of the cell.

4. Conclusion

The persistent challenge of dendrite formation in lithium metal and advanced batteries significantly hinders the development of safer, more durable, and higher energy density energy storage systems. Dendritic growth compromises battery performance and safety by inducing internal short circuits, depleting active lithium, and accelerating capacity degradation, particularly in high-energy chemistries like lithium-sulfur, lithium-air, and sodium-ion batteries. Recent advancements in electrolyte and interface engineering, including solid-state, high-concentration, and hybrid electrolytes, have improved interfacial stability and uniform lithium-ion flux, fostering stable solid-electrolyte interphase (SEI) layers. Engineered anodes, featuring artificial SEIs, three-dimensional porous hosts, and nanostructured current collectors, effectively mitigate dendrite nucleation by reducing local current densities and accommodating volume changes. Additionally, nanotechnology-enabled separators and coatings, such as atomic layer deposition (ALD), provide ultrathin barriers that prevent dendritic intrusion while facilitating ion transport. However, challenges remain in scaling these materials while maintaining mechanical and electrochemical stability over prolonged cycles.

Looking ahead, the integration of hybrid electrolyte solutions, combining polymer matrices with ceramic fillers, offers a promising approach to balancing ionic conductivity, mechanical reinforcement, and dendrite suppression. Real-time diagnostic techniques, such as transmission electron microscopy (TEM) and synchrotron X-ray tomography, coupled with electrochemical impedance spectroscopy (EIS), enhance understanding of dendritic dynamics and improve battery

management systems. Furthermore, life-cycle assessments and green chemistry frameworks are essential to evaluating the environmental and economic impacts of novel materials. By combining cutting-edge materials, real-time monitoring, and sustainability criteria, future research aims to develop scalable, dendrite-free energy storage systems, accelerating the adoption of electric vehicles and renewable energy technologies in the coming decade.

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