Dean&Francis
ISSN 2959-6157

Lithium Dendrite Suppression and Safety Enhancement in Lithium-ion Batteries

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Abstract:
Lithium-ion batteries (LIBs) are widely applied in portable electronics, electric vehicles, and large-scale energy storage due to their high energy density and long cycle life. However, the growth of lithium dendrites during cycling poses serious safety hazards, including internal short circuits and thermal runaway, while also reducing battery lifespan and efficiency. This paper systematically reviews the formation mechanism of lithium dendrites, their impacts on safety and performance, and recent strategies to suppress their growth. Approaches such as electrolyte modification, solid-state electrolytes, separator enhancement, and electrode engineering are analyzed with reference to the latest studies. The review highlights that dendrite suppression is essential for achieving safe and durable LIBs. Future research directions include integrating experimental and computational methods, advancing scalable fabrication techniques, and promoting interdisciplinary innovations to accelerate practical applications. It is sure that continuous breakthroughs in lithium dendrite control technologies will sustainably drive the further development of high-performance LIB systems.

Keywords: Lithium-ion batteries; lithium dendrites; battery safety; electrolyte engineering.

1. Introduction

Since they were commercialized in the early 1990s, lithium-ion batteries (LIBs) have emerged as the dominant energy storage technology today because of their high specific energy, long cycle life, and relatively low self-discharge rate. They have since become ubiquitous in portable electronics, electric vehicles and large-scale energy storage systems. Light, high-voltage platform and quick charging for an indispensable role in the worldwide transition of energy to renewables and carbon neutrality.

The pervasiveness of applications has imposed more rigorous requirements on the safety and robustness, as well as the efficiency. Among all challenges, lithium dendrite formation on the anode side is a prominent challenge due to the safety threat and long-term reliability. Internal short circuit due to the penetration of the separators by the dendrites, followed by thermal runaway, which then leads to a catastrophic accident, is one possibility. Lithium dendrite suppression for high-performance batteries: The problem of

ISSN 2959-6157

dendrite suppression has been recognized as a global field of advanced battery research.

Various strategies have recently been proposed to overcome dendrite formation. For example, Shi et al. developed cerium-alloyed, dendrite-suppressed, stable, solid-state lithium batteries with improved interfacial stability and cycling stability [1]. Li et al. also reported a fire-retarding sandwich separator was produced by electrospinning, which not only boosts thermal stability but also effectively suppresses dendrite penetration [2]. Xing et al. also reported in-situ growth of multifunctional interlayers in garnet-type solid electrolytes that could achieve a large-scale high ionic conductivity and dendrite inhibition [3]. These works, as a group, are noted for their emphasis on the role of materials design and microstructural control in suppression of dendrite growth.

The present work is a comprehensive survey on the morphology of the formation of lithium dendrites, the threat it poses to the battery performance and safety, and the most recent state-of-the-art methods for dendrite suppression. This work attempt to help gain a principled understanding of dendrite suppression mechanisms by categorizing, discussing and reviewing techniques including electrochemical optimization, solid electrolyte, separator optimization and electrode design, as well as offering insights for future studies and applications for safe and high-capacity LIBs.

2. Lithium Dendrites and Their Threats to Battery Safety

2.1 Formation Mechanism of Lithium Dendrites

Tree-like dendrites, which formed due to lithium ions deposited on the anode surface during charging of the lithium-ion battery in some cases fail to distribute homogeneously on the surface to form a smooth layer, causing it to be deposited unequally and thus leading to the formation of needle-like thin formations. Dendrites could be easily observed in charge-discharge cycles of a lithium-ion battery [4]. Under conditions where the deposition rate of lithium ions overcomes the diffusion through the solid electrolyte interphase (SEI) layer of an anode, this growth is typically observed, and it is affected by high current densities, high charge inhomogeneity, and low ion conductivity of an electrolyte. The dendrite growth can pierce the separator, resulting in an internal short circuit, which leads to serious safety concerns such as thermal runaway, battery leakage, and even detonation.

2.2 Safety Hazards Associated with Lithium Dendrites

The development of lithium dendrites may be considered as significant safety concerns of lithium-ion batteries. The main danger with them is that they can create short circuits in the battery, and in the event the dendrites penetrate the separator, they can short the anode and cathode by short circuiting them directly together [5]. More likely, short circuiting would quickly increase in temperature, known as a thermal runaway event, which would likely result in a dangerous reaction of some sort, such as combustion or explosion. Moreover, dendrites will make a contributive role to the damages of a battery structure and initiate leakage of the electrolyte or its expansion that causes hazardous reactions. Within a higher severity range, lithium dendrites can cause an unexpected death of a battery, diminishing its performance and longevity, and limiting its use in high-performance context such as electrical vehicles or electronics.

2.3 Influence of Dendrites on Battery Performance and Lifespan

The main failure mode reducing the safety of lithium-ion batteries and decreasing the service life of batteries is Li dendrites. The developing dendrites destroy the smooth surface of the anode thereby becoming a hindrance to the even distribution of charge. Failure in lithium deposition will lead to the degradation in capacity and erosion in the total battery efficiency. After some time, the capacity is likely to reduce; thereby rendering it hard to ensure that the battery retains its charge within a cycle range [6]. The higher internal resistance can lower the battery's energy, charging speed, and lifespan, which is especially concerning for its safe, efficient, and long-term use.

3. Effective Strategies for Suppressing Lithium Dendrite Formation

3.1 Improved Electrolytes

The electrolyte, a typical liquid electrolyte of lithium-ion batteries, highly affects the formation of the lithium dendrites. The liquid electrolyte involves the use of lithium salts that are soluble in organic solvents but have poor ion transport at low temperatures and a greater voltage during cycling. Such an uneven distribution of lithium ions, which is likely to encourage the growth of dendrites. Thus one of the most promising strategies to avoid such an uneven distribution of lithium ions is to modify the electrolyte component [7].

A robust SEI layer on the anode surface can be obtained through the use of electrolytes containing additives to produce a more reliable, robust and protective coating. The SEI layer is necessary to prevent the direct contact between the anode and electrolyte, which reduces the side reactions and enables uniform lithium ion plating deposition. Certain additives, such as the fluoroethylene carbonate (FEC), lithium bis(fluorosulfonyl)imide (LiFSI), etc. assist in creating a more robust and ionically conduction SEI layer that prevents the development of the dendrites.

An alternative option would be GPEs/ionic liquids, in which improved ionic mobility and improved mechanical stability of the electrolytes has been demonstrated. As an example, gel polymer electrolytes can be used to offer both improved stability and improved ionic conductivity compared to the classical liquid electrolytes without compromising the flexibility needed to suppress dendrite. The unique electrochemical properties of ILs non-volatile, high ionic conductivity) can also be more effective in improving the stability of batteries and suppressing dendrite.

One proposal to recommend the use of high-concentration electrolytes, where lithium salt concentration is significantly greater than the standard electrolyte lithium salt concentration, has been put forward. This reduces the chance of the lithiumions depleted region near the anode that may cause the generation of the dendrite. The raise of salts concentration ensure the higher homogeneity of lithium ions distribution and prevent dendritic growth. Bi-Ion electrolytes, in which the lithium intercalation process can be extended to other ions like Na or K, could also potentially mitigate the nucleation and growth of dendrites, by either changing electrochemical interactions at the electrode/electrolyte interface.

3.2 Solid-State Electrolytes

Solid-state electrolytes(SSEs) represents the most viable solution to the question of lithium dendrite formation. Different from liquid electrolytes, they are typically made of ceramics, glass or polymer based materials and hence feature enhanced mechanical strength, thermal stability and a superior dendrite growth resistance. The rigidity of these prohibits fluid-phase instability and significantly lowers the probability of dendrite intrusion into electrolyte.

The ceramic electrolyte, specifically those of the type lithium garnet-type materials(e.g.,Li7La3Zr2O12)or lithium phosphate-based compounds have been receiving growing interest because of their high ionics conductivity and their chemical stability at room temperature. Solid state electrolytes (SSEs) can eliminate Li dendrites since Li cannot diffuse from a solid electrolyte and/or solid electrolyte does not allow Li dendrite to grow into the separator [8].

The solution could be to engineer solidstate polymeric electrolytes(SPEs) having high ionic conductivity and stability at e.g. ceramic fillers or plasticizers, enabling SPEs to take advantage of the flexibility and low density of polymers, and provide ionic transport necessary to achieve high charge transfer rates.

Although promising, solid-state electrolytes encounters the challenge of not being able to achieve the better of the poor electrochemical contact between electrolyte and electrode, resulting in a high resistance and low ionic conductivity, in doing so, research is currently actively in search of techniques to perfect its fabrication and interfacial electrolytes. Notwithstanding this, nevertheless, the mechanical toughness of SSEs provides another advantages in preventing dendrite propagation and making certain long-term battery safety.

3.3 Enhancing Separator Efficiency

A separator is needed in a Li-ion battery to avoid lithium dendrite short circuits because it will block the penetrating path. This requires separator is able to isolate anode and cathode, but still allow ions to transfer across. In order to implement a dendrite supression strategy, an improvement of separator capability is necessary.

Another approach to modifying separator components involves improving their mechanical strength and porosity in order to prevent punctures or deformation caused by dendrites, which can lead to short circuits between the electrodes. The part separators have been made of polyethylene(PE)and polypropylene(PP), but are commonly insufficient to prevent dendrites' infiltration in some cases, nanomaterials or coatings(e.g. ceramic particles) should be used to prevent this. Accordingly, Al2O3 can be introduced into the separator to enhance the mechanical strength and dendrite resisting ability of the separator.

Composite separators, which allow incorporating the material properties of more than one material with a view to strengthen the electrolyte holding capacity and mechanical integrity include, for example, using inorganic particles (e.g. silica or alumina) into the separator for stronger and thermally stable matrix allowing more resistance towards the dendrite penetration. These composites increase the conductivity of separator through these composites, thus reduced resistance to the transport of lithium ions.

A suitable solution could be to implement electrolyte-drenched separators. In such a design the separator is impregnated with solid electrolyte material or ionic liquid thereby creating a safer ionic conduction path. The ionic flow is uniform, preventing the dendrite formation and preventing the creation of local high current density areas which would favor the dendrite growth. Further work of complicated separators with multi-layers or conductive coatings are introduced for further improving the suppres-

ISSN 2959-6157

sion ability.

3.4 Electrode Modification

Anode is the mostly common place for lithium dendrites evolution and the place of such detrimental phenomenon of lithium deposition unevenness. To ensure this path, anode structure must be optimized, preventing the growth of the dendrites. There is plethora of methods to this end.

One way to increase the homogeneity of the Li plating is to use a simple modification as the application of porous or three-dimensional structures, which could lead to a better control of the Li plating as well. Hence, decreasing the likelihood to obtain the formation of dendrites. These geometries provide a bigger area for deposition and a more uniform current distribution thus preventing local high concentrations of current that lead to dendritic growths. Anode materials have been suggested consisting of carbon nanotubes, graphene or mesoporous carbon because their nanostructured surfaces enable, in fact, lithium ion deposite deposition, hence the formation of dendrites is excluded.

An effective solution is using of protective coatings on anode which is carbon, ceramic or polymer composite and blocks lithium metal from direct contact with electrolyte. Coating can function to regulate flux of lithium ions, stabilizing growths thereby decreasing probability of dendrites production. Stabilizing the SEI layer by coating can assist in suppressing the dendrites. Coatings of LiPON (lithium phosphorus oxynitride)- a film of lithiumconductive ceramic – on the anode surface can stabilize dendrite growth by stabilizing the local environment and facilitating smoother deposition.

The introduction of surface functionalization processes including chemical or plasma modification, by modifying the electrodes energy surface, can thus result in the creation of a better interface for planar lithium deposition. The surface properties of the electrode may be altered by such treatment and thereby make the electrode more compatible with the electrolyte and reduce the growth of the dendrites due to more uniform distribution of the lithium ions.

As a battery will cease to function if the electrode undergoes damage over the course of cycling (i.e., if dendrites grow and cause a short circuit), one must adopt a modification route in which the nucleation and growth of lithium is regulated to avoid the formation of lithiated dendrites.

4. Conclusion

Lithium dendrites formation still remain a significant barrier to the safe and reliable operation of lithium-ion battery. In this paper, it is summarized that these dendrites not only pose high risk of safety due to the formation of internal short circuit and therm runaway but also damage the battery performance in terms of fading capacity, reduced cycling stability as well as reduced life time. Researchers have developed various methods to address these difficulties, such as multifaceted electrolyte mixtures, the integration of solidstate electrolytes, improvements in separator, and the surface of electrodes. The need of a multidisciplinary solution of the materials design, interface control, and structural innovation by each of those approaches points to the need of the multidisciplinary solution.

This analysis of the data herein illustrates why dendritic growth suppression is not merely of vital importance to assure LIB security, but is also essential to achieve full utilization of lithium ion batteries in electric vehicles, small and large batteries in portable electronics and large storage applications.

Further research must be done on reconciling computational simulations with experimentation to illuminate the coupled, multi-level structure formation and growth of dendrites. The last way ahead will need to be to overcome dendrite related problems in the long term in order to realize the truly sustainable, safe and high-performance energy storage system. Scalable manufacturing procedures, lower-cost materials and cross-functional solutions (e.g. AI design) are likely to be required to successfully bridge the gap between the laboratory and real world industries.

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