Degradation of Lithium-Ion Batteries

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Bachelor’s thesis

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Abstract:

Lithium-ion batteries (LIBs) are a cornerstone of modern energy storage systems, powering applications ranging from electric vehicles to portable electronics. However, their performance and lifespan are impacted by mechanical and thermal degradation, which pose challenges for their reliability and safety. This literature review explores the key mechanisms of degradation in LIBs, focusing on mechanical stresses such as pressure, vibration, and thermal cycling, and their effects on electrode integrity, separator stability, and casing durability. This thesis also examines mitigation strategies, including materials-based innovations like polymer-brush electrolytes and two-dimensional materials, as well as advanced design and manufacturing improvements such as stack pressure optimization and embedded sensing technologies.

Real-time monitoring techniques, including differential thermal voltammetry and predictive hybrid models, are highlighted for their role in early degradation detection and lifespan prediction. Comparative case studies of LIB degradation in electric vehicles and portable electronics illustrate how application-specific stresses influence battery performance. The review concludes with future research directions, emphasizing the need for intelligent regeneration techniques, hybrid modeling approaches, and sustainable recycling practices to address existing gaps.

By combining multidisciplinary strategies, LIBs can achieve greater durability, efficiency, and sustainability, ensuring their continued role as a key technology for better energy systems. This thesis underscores the importance of a comprehensive approach to LIB development to meet the growing demands of modern energy applications.

Keywords: Lithium-ion batteries (LIBs), degradation mechanisms, mechanical stress, thermal cycling, electric vehicles (EV), portable electronics, electrode delamination, separator failure, polymer-brush electrolytes, two-dimensional materials (2D materials), thermal management, predictive modeling, battery lifespan, sustainable recycling, energy storage systems.

Table of contents

1 Introduction

Lithium-ion batteries (LIBs) have reestablished modern energy storage systems, becoming a cornerstone of numerous technologies due to their high energy density, relatively long lifespan, and low self-discharge rates. Since their commercialization in the 1990s, LIBs have seen widespread usage across industries from portable electronics to electric vehicles (EVs) and large-scale renewable energy storage systems.

In portable electronics, LIBs enable compact and light designs with extended runtimes, making them the preferred choice for smartphones, laptops, and other devices. Meanwhile, in the automobile industry, the transition to EVs has been driven largely by improvements in LIB technology, offering energy-efficient and environmentally friendly vehicles. On the other hand, in renewable energy, LIBs play an important role in storing excess power generated by solar and wind systems which ensures a stable and reliable energy supply.

Despite these advantages, a key challenge remains when relying too much on LIBs. Their performance degrades over time because of mechanisms like electrochemical reactions, thermal stresses, and mechanical forces. Degradations not only reduce battery capacity and efficiency but also impacts safety and operational lifespan. For instance, a mechanical stress such as vibration and pressure during driving conditions aggravates structural failures which then leads to premature aging. Similarly, thermal cycling caused by temperature fluctuations in both portable electronics and renewable energy systems poses a great challenge to the durability of LIB components.

1.1 Research objectives

This thesis aims to explore how LIBs degrade over time, focusing specifically on the impacts of mechanical stresses like pressure, and vibration, and the impacts of thermal cycling. These stresses are major contributors to the aging and failure of key battery components such as electrodes, separators, and casings. When combined with electrochemical and thermal degradation, they can lead to serious performance issues and reduce the lifespan of the battery. To address these challenges, this thesis incorporates insights from twenty-three (23) recent studies to answer three key questions:

- How do mechanical stresses contribute to the aging and failure of LIB components?

- What strategies are currently effective in mitigating mechanical and thermal degradation in LIBs?
- How can advances in materials science and manufacturing improve the mechanical resilience of LIBs?

The focus is to provide a comprehensive understanding of these degradation mechanisms and investigate practical guidance for designing more durable batteries. By focusing on well-known applications like electric vehicles (EVs) and portable electronics, this work aims to contribute to the ongoing development of robust and reliable energy storage technologies.

1.2 Structure of the thesis

The thesis begins by introducing degradation mechanisms in LIBs, covering chemical, thermal, and mechanical factors that contribute to battery aging. This sets the stage for a better understanding of mechanical stresses like pressure, vibration, and expansion/contraction, which impact key battery components, such as electrodes, separators, and casings. The next section explores the role of thermal cycling, highlighting how temperature fluctuations can exacerbate structural weaknesses and accelerate capacity fade. From here, the review transitions to mitigation strategies by showcasing innovative materials like polymer-brush electrodes and two-dimensional composites, as well as advancements in battery design and manufacturing techniques. These strategies aim to increase the durability and resilience of LIBs.

The thesis then advances into monitoring and prediction methods by discussing real-time monitoring tools like differential thermal voltammetry and predictive hybrid models that combine both physics-based and data-driven approaches. These methods provide insights into prolonging battery lifespan and ensuring safety during various operations. Finally, the thesis closes by looking at real-life applications by comparing degradation patterns in electric vehicles (EVs) and portable electronics. The review concludes with discussion of future research directions for improving LIBs even more, as well as environmental concerns. Through this structure, this thesis provides a comprehensive view on LIB degradation, emphasizing the role of mechanical stresses while offering insights for overcoming current challenges and advancing the field of energy technology.

2 Degradation Mechanisms in Lithium-Ion Batteries

LIBs performance and lifespan are vastly limited by various degradation mechanisms. Understanding these mechanisms is important to improve their reliability and durability. This chapter focuses on primary factors contributing to LIB degradation, highlighting the interplay between chemical, thermal, and mechanical stresses that collectively impact battery efficiency and performance. These mechanisms often overlap, creating a cumulative effect that accelerate degradation.

2.1 Chemical degradation

Chemical degradation is primarily driven by side reactions between the electrolyte and electrode materials. These reactions lead to the formation of solid-electrolyte interphase (SEI) layers and consumption of active lithium ions [1]. Over time, the growth of the SEI layer increases internal resistance, reducing the battery's capacity and efficiency. Additionally, repeated cycling can cause electrolyte decomposition and particle fracture within electrodes, further exacerbating capacity fade. [1][2]

2.2 Thermal degradation

Thermal degradation occurs when the battery is exposed to elevated temperatures or undergoes frequent thermal cycling. High temperatures accelerate side reactions, degrade electrolyte stability, and cause structural changes in the electrodes. [3] Thermal cycling, particularly in applications such as electric vehicles and renewable energy storage, induces repeated expansion and contraction of materials, weakening the internal structure. [1][3]

2.3 Mechanical degradation

Mechanical degradation involves stresses such as pressure, vibration, and shock. These stresses acting as forces derive during battery assembly, cycling, and real-world operation, especially in applications like electric vehicles or portable electronics. The problem is that mechanical stresses can deform electrodes, damage separators, and disrupt the electrode-electrolyte interface, leading to capacity fade and potential safety hazards. [3] The interaction between mechanical, chemical, and thermal degradation is important. For instance, mechanical pressure exacerbates thermal cycling effects by inducing stress concentrations, while chemical degradation weakens the structural integrity of electrodes, making them more susceptible to mechanical failure. [1][3] Each of the degradation mechanisms individually harms the battery lifespan and performance, but the interactions between them vastly makes the situation worse overtime.

2.4 Mechanical and thermal stress-induced degradation

As already mentioned, mechanical and thermal stresses are significant contributors to LIB degradation, often overlapping to undermine performance and lifespan. Recent studies have provided valuable insights into how these stresses work and impact battery performance.

2.4.1 Mechanical stresses: vibration and pressure

Mechanical stresses, such as pressure and vibration, can severely degrade LIBs. For instance, higher stack pressure, which is the compressive force applied to the layers of a LIB during assembly or operation, accelerates capacity fade due to mechanical-chemical coupling. This occurs as localized deformation in the separator, disrupting lithium-ion transport. This then causes a nonuniform lithium plating and loss of active material. [4] Similarly, prolonged exposure to vibrations can lead to mechanical failure in the separator, which increases the risk of internal short circuits and therefore degrades the electrode-electrolyte interface [5]. This indicates that long-term vibrational loads reveal critical degradation mechanisms that may not be apparent during short-term standard testing. Interestingly, not all mechanical stresses are detrimental. Controlled application of small stack pressures can help prevent electrode delamination, maintaining consistent contact between layers and improving performance over extended cycling [1].

2.4.2 Thermal cycling and its amplification by mechanical stresses

Repeated expansion and contraction of battery materials due to temperature fluctuations is another significant factor in LIB degradation. This is known as thermal cycling. Mechanical stresses amplify the effects of thermal cycling by creating stress concentrations at interfaces, increasing the likelihood of structural damage. This interaction leads to the separator deformation and contributes to nonuniform lithium plating, which accelerates capacity fade. [4] Applications like electric vehicles and renewable energy storages exacerbate these issues due to constant temperature variations during operation. The combined effect of mechanical and thermal stresses creates a feedback loop where one type of stress worsens the effects of the other, leading to accelerated degradation.

Overall, chemical, thermal, and mechanical degradation mechanisms each have unique impacts on the performance and lifespan of LIBs, but it is their interplay that makes them particularly challenging to address. Chemical degradation steadily diminishes battery capacity through side reactions and SEI layer formation, increasing resistance and reducing efficiency. Thermal degradation further exacerbates the decline by destabilizing materials at higher temperatures and inducing structural changes during thermal cycling. Meanwhile, mechanical degradation adds another layer of complexity, namely stresses such as vibration and pressure, that damage the internal components and compromising the electrode-electrolyte interface. What makes all these mechanisms even more critical is the interplay between them. Chemical degradation weakens the structural integrity, while at the same time mechanical stresses can exacerbate thermal effects. These feedback loops highlight the inseparable nature of these mechanisms, as addressing one often requires considering its impact on the others.

3 Impact of Mechanical Stresses on Battery Components

As mentioned before, mechanical stresses can severely impact components of LIBs. These stresses are very much present in applications such as electric vehicles (EVs) and portable electronics, where mechanical loadings are common. This chapter focuses on the effects of mechanical stress on electrodes, separators, and battery casings, with insights derived from studies on high-volume-change electrode materials, separator failure mechanisms, and casing deformations.

3.1 Electrode degradation

Electrode degradation due to mechanical stress is most prominent in materials with higher volume of change during the phase of lithiation or delithiation. For example, silicon-based anodes experience a lot of stress since they can expand up to 280 % when fully lithiated. As predicted, this causes huge amounts of structural instability. This massive volume of 280 % charge causes surface cracking and structural instability, which then hinders the long-term cycling performance. [6] When silicon anodes get repeatedly expanded and contracted, it leads to the initiation of cracks, particle pulverization, and eventual loss of electrical connectivity [7]. Also, mechanical stresses within electrodes arise from uneven lithium-ion transport and stress response. This causes crack propagation, because localized tensile stress during lithiation eventually leads to formation of cracks, and from there the propagation in high-volume-change electrode materials leads to reduced electrode integrity and lifespan. [8] So, it is particularly clear that high-volume-change electrodes, especially materials made of silicon are very susceptible to various mechanical stresses. Volume expansion and tensile stress are key causes of crack propagation and pulverization, leading to capacity loss and reduced lifespan.

3.2 Structural failures of separators

Separators are important safety components of LIBs, since they prevent direct contact between the anode and cathode while allowing ion transportation. However, mechanical stresses such as pressure and vibration can cause problems with its structural integrity, leading to potential failures that increase the risk of internal short circuits. Mechanical stresses below the materials yield strength can cause creep deformation, which then leads to localized closure and uneven lithium-ion transportation. When creeping gets prolonged, the pressure reduces separator porosity, which impedes the movement of ions and creates current distribution that is inhomogeneous. Not only does this lead to uneven transportation but it also increases the internal resistance over time which then affects the performance of battery. [9] On the other hand, vibrational stresses are shown to cause damage because the stresses cause harm to the separator. Combined with vibration, the nonuniform solid-electrolyte interphase (SEI) growth exacerbates uneven lithium deposition and potential internal short circuits [10]. A healthy separator is a key component of LIB since the combination of mechanical pressure and vibration weakens the separator’s mechanical integrity, making it more prone to deformation and tearing, and in extreme cases, this can lead to direct contact between electrodes, causing potential safety hazards.

3.3 Casing and external structural failures

Battery casing is used to provide mechanical support and protection for internal components. However, mechanical stresses such as buildup of pressure and repeated cycling can compromise the structural integrity of casing, especially in cylindrical and pouch cells. This can lead to problems such as electrolyte leakage and reducing the battery’s ability to maintain mechanical stability during tasks. [11] Real-world vibration tests found out that due to vibrational stress, the mandrel displacement (a deformation or movement of the central supporting structure of the battery that secures the jelly roll inside the casing) punctured the casing, leading to direct contact with the jelly roll. This can potentially cause a catastrophic failure. [3] These problems highlight the importance of designing casings to withstand various mechanical loads and changes in internal pressure.

As it is now understood that mechanical stresses greatly impact LIB components, each with unique failure mechanisms. High-volume-change electrodes, such as silicon anodes, are prone to crack formation and pulverization under tensile stresses. Pressure and vibration can lead to short circuits in separators, since deformation and tearing occurs. Finally, casing failures can occur due to the buildup of internal stresses and external mechanical loadings. Understanding these mechanisms helps to improve mechanical resilience and safety of LIBs in real-world applications and, from there, leads to design of new and improved materials.

4 Thermal Cycling and Its Influence on Degradation

Previously, it was briefly explained that over time thermal cycling causes degradation in LIBs. Thermal cycling is characterized by repeated expansion and contraction of battery materials due to fluctuations of temperature. These temperature driven changes disrupt the mechanical integrity of electrodes, causing compromised ion transportation, and fading capacity. This chapter focuses on thermal expansion and contraction in electrodes and broader impact of temperature fluctuations affecting the degradation of LIBs.

4.1 Thermal expansion and contraction in electrodes

Regarding the high-volume-change materials, thermal cycling exerts a lot of stress on electrodes. This happens because after each cycle of lithiation and delithiation, electrodes undergo rapid dimensional changes which causes structural damage over time. In situ synchrotron X-ray tomography reveals that thermal cycling exacerbates morphological changes which then leads to electrode cracking, delamination, and void formation in already discussed silicon-based anodes. [7] Regarding the void formation, silicon expansion during lithiation is the primary reason why this repetitive expansion and contraction creates these voids within electrodes matrix. Over extended cycles, these voids lead to the pulverization of electrodes, causing a loss of electrical conductivity. [7] So, high-volume-change materials are clearly vulnerable to thermal cycling-induced mechanical stresses, and therefore this stress contributes to crack formation and strain localization, which over period leads to electrode failure [8]. These effects perfectly underscore the role of thermal cycling in growing electrode degradation, especially in advanced electrode materials that experience a lot of volumetric change.

4.2 Temperature fluctuations and capacity fade

Temperature fluctuations during tasks not only impact electrode materials but also compromise the overall performance and lifespan of LIBs. Repeated exposure to varying temperatures creates reversible and irreversible changes in the dimension of electrodes, which then compromises the structural stability and transportation of ion pathways [12]. Temperature gradients within the battery boost these effects by inducing heterogeneous strain distributions, further amplifying the rate of degradation of electrode matrix. Also, the accumulation of strain due to thermal cycling promotes local delamination within composite electrode structures. [13] This delamination disturbs the continuity of the electrode-electrolyte interface, which then reduces active material utilization and increases the resistance. As a result, the battery experiences profound capacity fade, especially in applications that have a fluctuating temperature change, for example, energy storage systems.

Thermal cycling impacts the degradation of LIBs by inducing mechanical and structural changes in materials of electrodes. The repeated expansion and contraction of high-volume-change materials like silicon leads to morphological changes, including cracking, delamination, and void formation. These effects usually result in pulverization of electrodes and a loss of electric conductivity, which then directly impacts the battery’s ability to function properly over periods of cycles. Because of these, thermal cycling poses a lot of challenges for advanced electrode materials that undergo volumetric changes during operation. In addition to these localized mechanical effects, temperature fluctuations introduce larger challenges that compromise the overall stability and performance of LIBs. The creation of both reversible and irreversible dimensional changes in electrode structures disrupts the integrity of ion transport pathways, diminishing the battery’s efficiency. Furthermore, temperature gradients within the cell amplify degradation by causing uneven strain distributions, accelerating damage in specific areas of electrode matrix. These gradients not only boost delamination within electrodes but also exacerbate resistance and reduce the usage of active materials, leading to profound capacity fade. The cumulative effect of thermal cycling and temperature fluctuations underscore the importance of addressing these issues in real-world applications. Developing materials and designs that can withstand thermal cycling stresses is critical to enhance the reliability and lifespan of LIBs.

5 Mitigation Strategies for Mechanical and Thermal Degradation

As LIBs need more durability in high-demanding applications, mitigation strategies are important to enhance their mechanical and thermal qualities. This chapter looks at the advancements in materials science, design improvements, real-time monitoring, and predictive modelling aimed at addressing key challenges regarding mechanical stress, thermal cycling, and capacity degradation.

5.1 Materials-based approaches

Innovative materials have a potential to improve mechanical and thermal durability of LIBs. Among these advancements, polymer-brush electrolytes and two-dimensional (2D) materials have demonstrated interesting potential for enhancing stress resistance and extending the lifespan of batteries.

5.1.1 Polymer-brush electrolytes

Polymer-brush electrolytes introduce a novel class of electrolytes designed to withstand cyclic mechanicals stress. These electrodes demonstrate notable mechanical resilience under cyclic stress while maintaining ion conductivity, while contributing a pathway to extend the lifespan of battery in environments consisting of higher stresses [14]. One key advantage of these polymer-brush electrolytes is their ability to form a highly flexible interface with electrode surface. This flexibility allows them to accommodate repeated expansion and contraction cycles that occur during the operation of a battery. It also seems that these types of electrodes exhibit superior adhesion properties, and therefore reduces the risk of delamination and structural failure under repeated expansion and contraction. [14]

5.1.2 Two-dimensional materials

2D materials like graphene have gained attention for their ability to provide mechanical flexibility as well as structural integrity. These 2D materials provide superior mechanical flexibility and structural stability, effectively mitigating degradation caused by thermal and mechanical stresses. [15] Another advantage of these materials is the ability to improve thermal management within the battery. Materials like graphene and similar have excellent thermal conductivity, which allows for better heat dissipation. This reduces the localized effect and helps to prevent electrode degradation. In addition to enhancing already mentioned qualities, two-dimensional materials provide protective layers to suppress the growth of dendrites, which is a common issue in LIBs. [15]

5.2 Design and manufacturing improvements

Besides material innovations, designing and manufacturing are suitable strategies for improving the mechanical resilience of LIBs. Optimizing component configuration and integrating real-time monitoring systems are valuable options.

5.2.1 Stack pressure optimization

During the process of manufacturing, optimizing stack pressure is one key element to better the performance of LIBs. It reduces electrode delamination, while also enhancing uniform stress distribution. This in return significantly improves the lifecycle of a battery. With this controlled stack pressure, the minimization of internal stresses can be achieved, which could otherwise lead to separator deforming or electrode cracking. [1] This optimization not only extends the lifespan of battery but also enhances their safety in demanding applications.

5.2.2 Embedded sensors for real-time monitoring

Real-time thermal and mechanical condition monitoring is another promising way of mitigating degradation. For example, fiber-optic sensors that are distributed in LIBs enable real-time monitoring of internal components such as temperature and stress, allowing early detection of degradation. With these sensors, manufacturers can identify issues such as nonuniform temperature distributions and localized stresses during the process of operation. [16] This in turn improves the battery’s performance and safety. Embedded sensors, combined with other innovations, enable adaptive thermal management strategies to reduce the likelihood of failures.

5.3 Monitoring and predictive modelling

Real-time monitoring techniques and predictive modeling approaches play an essential role in addressing mechanical and thermal degradation challenges. These tools enhance the ability to detect early degradation and provide insights for predicting battery performance and lifespan under different conditions.

5.3.1 Real-time monitoring techniques

Recent advancements in real-time monitoring have allowed researchers and manufacturers to better understand failure mechanisms in LIBs and further develop mitigation strategies. Among these, differential thermal voltammetry (DTV) and coupled electrochemical-thermal-mechanical modeling are prominent techniques. DTV tracks temperature-related changes in battery, providing detailed analysis of degradation. This happens during battery's charge and discharge cycles. By correlating thermal events with specific electrochemical reactions, DTV's can detect early thermal runaway. [17]

A coupled electrochemical-thermal-mechanical modeling approach integrates all these degradation factors, providing a comprehensive framework for real-time analysis. This coupled model can simulate the exchange of electrochemical reactions, heat generation, and mechanical deformation, predicting important aspects of degradation with high accuracy. [18] Also, as noted in the previous chapter, fiber-optic sensors can provide repeated temperature and stress monitoring by enabling detection of localized degradation in advance [16]. So, it seems that there's a quite few technologies that can allow adaptive thermal management strategies for reducing the likelihood of failures.

5.3.2 Predictive lifespan assessment modeling

Predictive models are important tools for estimating the lifespan of LIBs under various stressful conditions. These models combine empirical data and simulations, providing accurate predictions of battery performance over time. One approach focuses on using fatigue-based models to predict capacity fade due to accumulated damage. This accumulation provides a potent framework for estimating the battery lifespan under cyclical loads by incorporating mechanical and thermal stressors. [19] This method is very useful, since it accounts the cumulative effects of repeated cycling, offering valuable insights into long-term battery performance.

Machine learning and data-driven approaches are becoming vastly popular for battery degradation predictions. Data-driven models use large datasets to predict the battery life with high precision, outperforming standard physical approaches by managing nonlinear degradation patterns [20]. There's also something called hybrid models, which combines physic, and data-driven approaches for creating models that balance accuracy and computational efficiency. These hybrid models can capture complex combinations of electrochemical, thermal, and mechanical degradation mechanisms by providing litigable insights for extending the lifespan of batteries [18]. These models are well suited for applications that require precise precision overtime, like grid-scale energy storage systems.

Addressing the mechanical and thermal degradation challenges of LIBs requires a comprehensive approach that integrates advanced materials, design innovations, real-time monitoring, and predictive modeling. These strategies work together to enhance the durability, safety, and reliability of batteries, meeting the growing demands of modern applications. Advanced materials, such as polymer-brush electrolytes and 2D materials like graphene, play an important role in improving the mechanical resilience and thermal stability of LIBs. Polymer-brush electrolytes reduce risks of delamination and structural failure through their flexibility and adhesion properties, while 2D materials provide superior heat dissipation, suppress dendrite growth, and stabilize internal components during mechanical and thermal stresses. These innovations extend battery lifespans in demanding environments.

Design and manufacturing improvements further mitigate degradation. Optimizing stack pressure during assembly ensures uniform stress distribution, preventing internal failures like separator deformation or electrode cracking. Real-time embedded sensors, such as fiber-optic systems, enable continuous monitoring of temperature and stress by allowing early detection of localized issues and reducing the likelihood of catastrophic failures. Real-time monitoring techniques, including DTV and coupled modeling frameworks, enhance the ability to detect and analyze degradation mechanisms as they occur. These tools provide accurate insights into temperature-related changes and mechanical deformations, enabling timely interventions. Predictive lifespan models, such as fatigue-based and data-driven approaches, offer long-term assessments of battery performance. By integrating physics-based and machine-learning methodologies, hybrid models deliver accurate predictions of capacity fade and degradation trends, making them particularly useful for applications requiring high reliability.

In summary, these strategies collectively address the key challenges of LIB degradation. Advanced materials improve resilience and performance, while design and monitoring innovations enhance reliability and safety. Predictive modeling ensures long-term operational insights, reducing maintenance costs and optimizing battery usage. Together, these approaches pave the way for durable, efficient, and sustainable energy storage solutions in diverse industries.

6 Applications and Case Studies in Real-World Environments

Differences in operational demands, environmental conditions, and design constrains means that degradation in LIBs varies across applications. Two of the most known applications today are, for example, electric vehicles (EVs) and portable electronics which both uses LIBs extensively. This chapter briefly highlights the unique stresses faced in both.

6.1 Electric vehicles (EVs)

LIBs in EVs are subjected to mechanical and thermal stresses because of their automotive operations. Vehicle movements like acceleration, deceleration, and other driving conditions expose batteries to constant vibration and temperature fluctuations. Due to these, EVs operate under higher mechanical and thermal stresses than portable electronics. [21] It seems that the most prominent degradation mechanisms in EVs are losses of active lithium, as well as electrolyte decomposition and electrode delamination. Temperature fluctuations during cycles of charging and discharging exacerbates the degradation even more. This is exacerbated with thermal gradients within EV battery. Also, variations in cell-to-cell performance may lead to uneven capacity fade and decreases safety. [21] To tackle these problems, manufacturers can incorporate thermal management systems to mitigate these challenges. However, such systems are not yet bulletproof, leaving room for improvements on material selection and battery design.

6.2 Portable electronics

LIBs in portable electronics operate under less mechanically intense conditions in comparison to EVs. However, high cycling rates, deep discharges, and the demand for compact designs still possess enough stress to make a difference, resulting in the growth of solid electrolyte interphase (SEI) and lithium plating [22]. Portable electronics also operate at lower temperatures than EVs, which reduces the rate of electrolyte decomposition, but the higher energy density requirements often result in a similar structural failure in electrodes. Likewise, portable electronics rely on the inherent stability of battery materials to ensure longevity, which means that cost constraints limit the implementation of advanced thermal management systems. [22]

While both EVs and portable electronics rely on LIBs for storing energy, their operational environments create recognizable challenges. EVs are largely affected by mechanical and thermal stresses, requiring precise thermal management and durable battery design. On the other hand, portable electronics face higher rates of degradation due to cycling and structural failures. Therefore, new innovations in electrode materials and energy storage systems are required. By looking at these comparisons, it is easy to see the importance of application-specific strategies for mitigation battery degradation. For EVs, advancements in thermal management and structural durability are important. For portable electronics, improving material stability and energy density will remain key priorities.

7 Conclusion

LIBs are important in energy storage technology, supporting advancements in electric vehicles, portable electronics, and other energy systems. Despite their efficiency and versatility, LIBs face a lot of challenges from mechanical and thermal degradation standpoint, which limits their lifespan and performance. This thesis has looked up on the degradation mechanisms, mitigation strategies, and a couple of real-world applications of LIBs, providing key insights into improving their durability and reliability.

7.1 Summary of key findings

Findings of LIB degradation mechanisms have revealed the interplay between mechanical and thermal stressors. Mechanical degradation such as pressure, vibration, and cycling-induced expansion disrupts electrode and separator integrity, leading to capacity fading and potential safety risks. Similarly, thermal degradation caused by temperature fluctuations and gradients accelerates chemical reactions, exacerbates stress, and weakens structural components. Mitigation strategies have focused on both material-based innovations and manufacturing improvements. Polymer-brush electrolytes and two-dimensional materials improve stress resistance, while stack pressure optimization and embedded sensing technologies reduce the rates of degradation and improve operational safety. Real-time monitoring techniques like differential thermal voltammetry, as well as predictive models, including hybrid physics-based and data-driven approaches have further strengthened the ability to detect and mitigate early degradation. These findings conclude the importance of an integrated approach combining materials science, design optimization, and advanced monitoring techniques to extend both the lifespan and performance of LIBs.

7.2 Future research

While a lot of progress has been made, there are gaps remaining in understanding LIB degradation, as well as in mitigating these problems. For instance, this thesis did not take into consideration the environmental impact of LIBs and how to mitigate strategies related to these problems. Some studies on intelligent regeneration of cathode materials suggest that these materials can restore performance at the same time, while reducing environmental impact [23]. This seems to be one way of integrating circular economy principles to LIB-based environmental problems. This could be a very interesting thesis topic for the future. Also, research into more efficient and cost-effective thermal systems will remain a priority for the future. This could include exploring phase-change materials and advancements in cooling technologies could help by mitigating the impact of thermal cycling and even extend the lifespan of battery.

7.3 Final thoughts

This thesis provided a comprehensive look at the complex challenges posed by mechanical and thermal degradation in LIBs. While these degradation mechanisms may be persistent, they are not completely impossible to fix. The innovative solutions presented in this thesis show that progress in materials science, predictive modelling, and advanced design strategies can extend the durability and performance of LIBs a lot. Mechanical stresses like pressure, vibration, and cycling-induced expansion highlight the need for robust materials which are capable of withstand repetitive deformation. Likewise, thermal cycling and temperature gradients emphasize the importance of effective thermal management to maintain the stability of electrochemical structure. Addressing these challenges not only require innovative materials like polymer-brush electrodes or two-dimensional composites, but also advancements in battery design, including stack pressure optimization and embedded sensors.

Looking forward, the way to having efficient and durable LIBs lies in the combination of multidisciplinary approaches. By combining real-time monitoring, predictive hybrid models, and intelligent material design, manufacturers can develop not only stress resilient batteries, but also adaptable ones to various operational demands. Moreover, focusing on sustainable practices, like briefly mentioned cathode regeneration as a circular economy approach gives hope for reducing environmental impact of LIBs and address possible resource limitations.

The role of LIBs in the future is looking bright. From enabling the transition to electric vehicles to supporting renewable energy storage, their application spans a wide range of industries. However, achieving even better usage of LIB technology requires ongoing collaboration between researchers, engineers, manufacturers, and policymakers. Investments in research, combined with sustainability commitment, ensures that LIBs continue to evolve as a cornerstone of energy sector innovations. This work underscores the importance of a comprehensive approach to LIB development. By addressing challenges highlighted in this thesis, LIBs can not only meet but exceed the demands of modern energy systems, showing the way for a sustainable, more efficient future.

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