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Multiphysics Analysis of Impact of Vibrations on the Formation of Dendrites in Lithium-Ion Batteries

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Abstract: This paper introduces a multiphysics simulation framework for examining the impact of mechanical vibrations on lithium dendrite formation in lithium-ion batteries. We connected the lithium-ion battery, solid mechanics, and phase field physics interfaces using a custom model in COMSOL Multiphysics. The central aspect of our methodology is a stress-dependent diffusion mechanism, wherein mechanical stress induced by vibrations increases lithium-ion diffusivity within the anode, resulting in non-uniform plating and the nucleation and growth of dendrites. The simulation is conducted on a simplified one-dimensional geometry to examine this electro-chemo-mechanical coupling. A significant discovery is a non-monotonic frequency response: dendrite growth is most rapid within a mid-band frequency range of 150-250 Hz and most sluggish near 350 Hz. These results are compared to Faradaic deposition rates and give a detailed look at the conditions that can speed up battery degradation and failure. The method provides a repeatable, unit-safe way to study how dynamic degradation works, and understanding this mechanism can improve battery design and operational strategies to enhance safety and lifespan. These insights suggest that controlling vibration frequencies during battery operation could mitigate dendrite formation, informing both manufacturing standards and real-time monitoring protocols for enhanced battery safety.

Keywords: Lithium plating; phase field; dendrite growth; vibration frequency; Faraday calibration; LIB modelling.

Introduction: Lithium-ion batteries are used in many different fields, which has made their use more complicated. For example, they can be used in high and low temperatures, low pressure, and vibration. This is especially true because batteries are always exposed to vibration when they are used and moved around in the environment [1]. Recent studies have demonstrated that vibration accelerates degradation during cycling of lithium-ion batteries, with the influence of vibration frequency on cycling performance being non-linear [2]. Lithium dendrites make lithium-ion batteries less safe and useful, especially when they are charged quickly and it is a function of low temperature [3,4]. Monroe and Newman [5] assert that elastic deformation at the interface can dictate deposition stability; Jeon et al. [6] and Zhao et al. [7] demonstrate that phase-field electro-chemo-mechanical models can encapsulate the interrelated transport, kinetics, and mechanics that facilitate plating. Nonetheless, the function of vibration is still inadequately examined. Vibration can create local strain-energy hotspots by applying cyclic stress and strain. This can change the kinetics of ion transport, which can lead to uneven lithium plating and faster nucleation and growth. Furthermore, Kim et al. [8] assert that prolonged ultrasound exposure can elevate dead-Li levels, suggesting that mechanical forcing may yield either advantageous or adverse effects contingent upon the regime.

This study aims to fill the existing gap by creating a Multiphysics framework that enhances a traditional 1-D LIB model through specific couplings between the mechanical and electrochemical fields, as well as a phase-field depiction of anode morphology, in accordance with the modelling conventions established by Jeon et al. [6] and Zhao et al. [7]. Unlike MHz ultrasound, which is mostly made up of acoustic streaming by Kim et al. [8], we look at sub-kHz bulk vibration and do a causal frequency sweep to measure how it affects dendritic propagation. So, our results are meant to find frequency windows that speed up or slow down growth, and at the end, to help with vibration-aware battery design and testing.

2. Computational Methodology and Simulation Setup

To examine the combined influences of mechanical vibrations and electrochemistry on dendrite formation, a specialised Multiphysics model was created utilising the finite element software COMSOL Multiphysics. The simulation was conducted on a simplified one-dimensional geometry that depicted a cross-section of a lithium-ion battery cell. Intervals were used to define the geometry of the anode, separator, and cathode layers.

2.1 Geometry and Parameters

The model was made using the following materials and geometry settings. The global definitions node was used to set all the parameters so that they could be easily changed, and the units stayed the same.

Table 1: Key Simulation Parameters and Conditions

Parameter	Symbol	Value	Description
Anode Thickness	L_{neg}	70 [µm]	Thickness of the negative Electrode
Separator Thickness	L_{sep}	25 [µm]	Thickness of the separator
Vibration Amplitude	Vib_{amp}	1 [µm]	Amplitude of prescribed displacement.
Applied Current Density	I_{app}	-100 [A/m^2]	High rate charging current
Stress-Diffusion Coupling	α	1e-8 [Pa]	Strength of coupling.
Reference Stress	Reference Stress	1e8[Pa]	Reference stress for dimensionless coupling.

2.2 *Physics Interfaces and Equations:*

The model ties together three main physical interfaces:

2.2.1 Lithium-Ion Battery (Li-ion): This interface illustrates the way lithium ions move and how chemical reactions occur according to the Doyle-Fuller-Newman architecture[9]. The model estimates the lithium concentration within the solid phase ($c_{s)}$ and the electrolyte potential. The electrode's current density was set to -100[A/m^2] at the positive current collector border, and an electric ground was provided at the negative current collector.

2.2.2 Solid Mechanics: This interface illustrates how the anode and separator will behave when vibrated from the outside. The primary equation is the dynamic wave equation. It considers the evolving stress and displacement over time, as shown in equation (1).

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla S + F_v \; .... (1)$$

Where, ρ (rho) is the density, $\frac{\partial^2 u}{\partial t^2}$ is the acceleration that shows the motion of material, and it is dependent on time. F_v represents any external forces acting on the volume of the material, and vibrations were simulated by applying a prescribed displacement:

$u = Vib_{amp} \times \sin(2\pi \times Vib_{freq} \times t)$ to the anode boundary, where Vib_{amp} is the amplitude of the vibrations and Vib_{freq} is its frequency.

2.2.3 *Phase Field (ϕ)*: This interface employs the Cahn-Hilliard equation to track the evolving interface between the electrolyte (ϕ=0) and the lithium metal dendrite (ϕ=1). The initial condition for the phase field was set to a small positive value at the anode-separator interface to act as a nucleation site.

2.3 *Multiphysics Couplings*

The novelty of this work lies in the custom Multiphysics couplings that link these interfaces.

2.3.1 Stress-Enhanced Diffusion: To model how vibrations influence ion transport, the solid-phase diffusion coefficient (D_s) in the anode was modified. The standard concentration- and temperature-dependent diffusion from the material library $D_{s,0}(c, T)$, was augmented with a term dependent on the local von Mises stress (σ_{vm}), derived from the Solid Mechanics interface. This is implemented in the Particle Intercalation node of the Lithium Ion physics as a user-defined expression below as equation (2):

$$D_s = D_{s,0}(c, T) \, . \exp\, (\alpha \, . \frac{\sigma_{vm}}{\sigma_{ref}}) ...... (2)$$

In this case, σ_{ref} is a user-defined reference stress, and α is a coupling parameter that has no dimensions.2.3.2 *Electrochemical Dendrite Growth*: There is a source term that links the rate of the electrochemical reaction to the phase field variable. We added a custom source term to the Cahn-Hilliard equation that was based on the local electrolyte current density vector (i_s) and was adjusted by the Faraday constant (F) and the molar volume of lithium ($V_{m,Li}$). This source term drives dendritic growth in areas with high current density, which is like depositing lithium metal. The source term is shown below in equation (3):

$$\text{Source} = \frac{\phi(1-\phi) \, . i_s \, . V_{m,Li}}{F \, . v_{ref}} .... (3)$$

The terms $F \, . v_{ref}$, $\phi(1-\phi)$ is for unit normalization, and ensures the source is only active at the interface where ϕ is between 0 and 1. The parameter v_{ref} is a reference velocity used tomake the source term dimensionless.

2.4 *Simulation setup*

The simulation utilised a fully coupled, time-dependent analysis to resolve the system of Multiphysics equations. To make sure the starting point was stable, a preliminary stationary study was done first with all time-dependent loads and currents set to zero. The solution from that study was then used as the starting point for the main simulation. The time-dependent study was set up to last for 100 seconds.

3) Results and Discussion

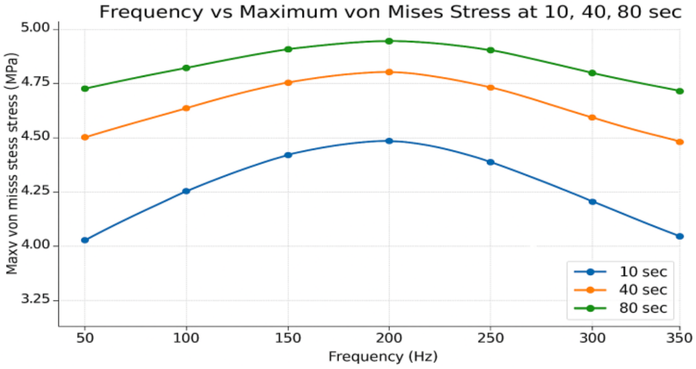

Figure 1. Frequency vs Von Mises Stress

Figure.1 shows a non-monotonic relation between vibration frequency and peak von Mises stress. Stresses are highest in the mid-band (~150–250 Hz) and lowest near 350 Hz, and they increase from 10 to 80 sec as deeper dendrite penetration develops. The stress hotspot consistently coincides with the advancing dendrite tip. In this sub-kHz regime, the response is most plausibly due to interfacial kinetics/mechanical coupling rather than acoustic streaming. The frequency ordering of stress agrees with the ordering of dendrite growth rate $v(f)$ and interfacial current, supporting a coherent cause–effect link.

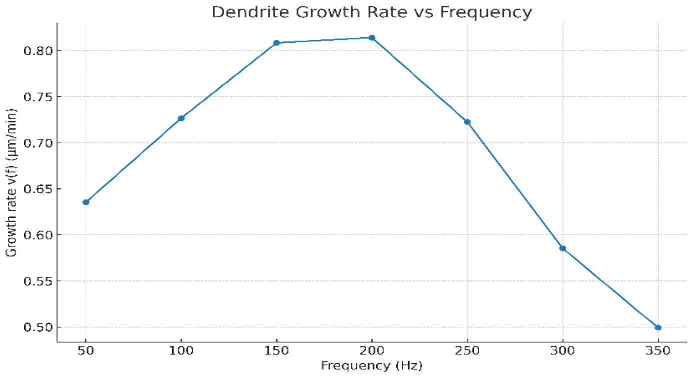

Figure 2 Dendrite Growth vs Frequency

The frequency curve (50–350 Hz) in Fig.2 shows dependence of dendrite growth rate on frequency. The mid-band (≈150–250 Hz) exhibits the highest average growth rates, whereas 350 Hz is the lowest, with 50–100 Hz intermediate. Practically, these results suggest avoiding the mid-band during cycling (or reducing amplitude/duty) and favouring higher sub-kHz settings that suppress growth in this configuration; limitations include the 1-D morphology and constant-amplitude loading, which we plan to address via 2-D checks and equal-acceleration sweeps.

Conclusion

This work advances the literature by introducing a calibrated, unit-consistent Multiphysics workflow that isolates the causal role of sub-kilohertz vibration on lithium plating the principal novelties are: (a) a unit-safe electro chemo-mechanical coupling suitable for routine studies; and (b) a parameter-invariant frequency sweep that reveals a practical "hot band". In addition, immediate applications include screening vibration windows for fast-charge operation and prioritizing damping or isolator strategies in test and pack environments. Finally, the approach is readily extensible—to 2-D/3-D morphology for branching, to equal-acceleration and amplitude sweeps for loading pathway disambiguation, and to benchtop validation in Lithium cells—thereby providing a clear path from diagnostic modelling to a deployable design tool for safer, vibration-tolerant battery systems.

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