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Rethinking dendrite growth in solid electrolytes

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Developing solid-state electrolytes that enable fast charging, long cycle life, and high safety remains a central challenge for solid-state lithium batteries. Ceramic solid-state electrolytes are often expected to suppress lithium dendrite penetration by acting as mechanical barriers. In this view, dendrite growth is primarily treated as a fracture process, in which lithium plating generates stress at a flaw until the local stress intensity reaches the fracture toughness of the electrolyte, thereby driving crack propagation. This mechanistic theory has been highly influential. Earlier studies established the importance of pre-existing defects, current density, and crack propagation in lithium penetration through inorganic solid electrolytes[1]. Subsequent studies in garnet-type electrolytes showed that nanoscale cracks and stress concentrations can strongly regulate the initiation of lithium intrusion[2]. More recent works have further distinguished dendrite initiation from dendrite propagation, proposing that these two steps follow different mechanical rules[3]. However, a key uncertainty has remained unresolved, namely whether electrochemistry merely loads a passive crack, or instead actively changes crack tip resistance during dendrite growth.

Now, writing in *Nature*, Fincher and colleagues provide direct evidence that the latter scenario can occur[4]. Using operando birefringence microscopy on translucent Ta-doped lithium lanthanum zirconate ($Li_{6.6}La_3Zr_{1.6}Ta_{0.4}O_{12}$, LLZO), they directly mapped the stress field around growing dendrites and extracted the corresponding stress intensity factor during dendrite propagation. The key observation was striking. At the lowest current examined, Fincher and colleagues reported that the steady-state stress intensity factor approached the fracture toughness of LLZO measured without electrochemical polarization, which is broadly consistent with the conventional fracture-based framework[4]. However, as the current increased, the stress intensity factor decreased monotonically, even when the dendrite velocity increased. More surprisingly, at the highest current examined, Fincher and colleagues found that dendrites could propagate at a stress intensity factor up to 75% lower than that expected for purely mechanical fracture[4]. In other words, the faster the dendrite

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grew, the less mechanical driving force appeared to be required. This trend is difficult to explain by a traditional model in which lithium deposition simply accumulates stress until a chemically unchanged ceramic fractures.

The behavior of the lithium filament and the after current was switched off and lithium plating ceased is also revealing. During open-circuit holds, neither dendrite length nor the measured stress intensity factor changed appreciably. The reduction in apparent fracture resistance therefore does not appear to arise from passive relaxation after growth. Instead, it is specifically coupled to active electrochemical propagation. This finding marks an important conceptual shift. Previous models have generally emphasized the geometry of flaws, the role of current focusing, or the mechanics of wedge opening[1-3]. These studies are essential for understanding how mechanical defects guide dendrite initiation and propagation. However, they did not resolve how Li^+ reduction is electronically enabled at or near the advancing crack tip. Electronic leakage in solid electrolytes has been proposed to promote internal Li deposition and filament formation, especially at electronically defective regions such as grain boundaries[5,6]. The present study does not directly address bulk electronic conduction in LLZO. Instead, it identifies a more localized process. The dendrite tip behaves as an electrochemically active region, where Li^+ transport, electron supply from the metallic dendrite, interfacial reaction, and fracture resistance are coupled.

Cryogenic scanning transmission electron microscopy provides a mechanistic bridge for this reinterpretation. Near rapidly growing dendrite tips, Fincher and colleagues identified a nanometer-scale degraded interfacial region and detected multiple crystalline phases, including tetragonal LLZO, $Li_6Zr_2O_7$, and $LiLa_2TaO_6$. These observations indicate that local electrolyte decomposition occurs during dendrite growth. The authors further propose that the tip region behaves as a Faradaic reaction front, in which Li^+ ions are provided by the electrolyte, whereas electrons are supplied by the metallic dendrite. This process can induce local corrosion around the tip and drive the electrochemical transformation of the solid electrolyte. More importantly, Fincher and colleagues linked the transformed interfacial region to a net molar-volume contraction relative to pristine LLZO. This conclusion was supported by the calculated molar volumes of the proposed product phases and HAADF-STEM analysis of the degraded region[4]. Such a volume-contracting transformation can reduce the effective resistance against crack propagation, offering a natural explanation for why propagation occurs at unexpectedly low stress intensity. Therefore, the key advance of this work lies not only in demonstrating that corrosion occurs near the dendrite tip, but also in showing that such corrosion can directly weaken the electrolyte during dendrite growth.

This insight broadens dendrite resistance from a purely mechanical concept to a coupled electrochemical and mechanical property. This perspective aligns with the growing recognition that interfacial stability is a critical challenge in solid-state batteries[7]. During stable operation, the electrolyte/electrode interface must be either thermodynamically compatible or kinetically self-passivating. If neither condition is satisfied, interphase evolution can dominate cell failure. Fincher and colleagues now show that such interfacial instability is not limited to planar electrode contacts. It can also develop at the most highly stressed and electrochemically active region of the cell, namely the dendrite tip, where it directly influences fracture behavior. This point is particularly provocative because LLZO is widely regarded as a relatively stable solid electrolyte against lithium metal. If electrochemically induced embrittlement can occur even in this system, similar or even stronger effects may occur widely in less reduction-tolerant electrolyte families. Despite these important advances, several questions remain open. First, the experiments were performed in a model Ta-doped LLZO system with optical access, and it remains unclear whether the same stress-corrosion relationship quantitatively applies to sulfide, halide, or argyrodite electrolytes. Second, although the work reveals electrochemical decomposition near the dendrite tip, it does not fully decouple the relative contributions of electronic leakage, local Li^+ flux, current focusing, pre-existing defects, and stack pressure.

Third, the proposed volume-contraction mechanism provides a compelling explanation for electrochemical embrittlement, but direct operando quantification of the local thickness, composition, and mechanical properties of the transformed region is still needed. Therefore, this study does not overturn mechanical dendrite models, but provides an important extension by incorporating crack-tip electrochemistry and mixed transport into the failure framework.

This work also inspires new design principles for robust solid electrolytes. Fracture toughness, elastic modulus, and defect density and distribution will remain important descriptors, but more electrochemical factors must also be considered. The lower bound of the electrochemical stability window, the chemistry of reaction products, and the sign and magnitude of transformation-induced volume change may be equally decisive. Looking forward, the field should move beyond identifying dendrites after failure and toward quantifying the local conditions that make a crack tip electrochemically active. First, electronic conductivity and band-structure variations should be mapped at grain boundaries, pores, reduced regions, and crack tips, because even small electronic leakage may enable internal Li deposition. Second, researchers may consider combining operando stress mapping with cryogenic electron microscopy, tomography, and local spectroscopy, so that stress intensity, reaction-front chemistry, and transformed-zone geometry can be measured in the same experiment. Third, materials design should explicitly account for electrochemical stability under reducing conditions and for the mechanical consequences of decomposition reactions. Robust solid electrolytes should not only be stiff and tough, but also remain electronically insulating under reducing potentials, and if decomposition occurs, capable of forming products that are mechanically neutral or even crack-arresting. Finally, interphase engineering should be reconsidered. The ideal interphase should conduct Li^+, block electrons, suppress reduction at the crack tip, and avoid volume-contracting reactions that lower the resistance to crack advance.

DECLARATIONS

Authors' contributions

Literature review, manuscript drafting, and editing: Lin, T.
Conceptualization, supervision, and manuscript review and editing: Wu, H. B.

Availability of data and materials

No new datasets were generated or analyzed during this study. All data and information discussed in this commentary are available from the cited literature.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool DeepSeek (version 2.0.4) was used solely for language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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