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Energy Materials

He *et al*. *Energy Mater*. **2026**, *6*, 600061 **DOI:**10.20517/energymater.2026.81

Rethinking Li dendrites as strong brittle solids in Li metal batteries

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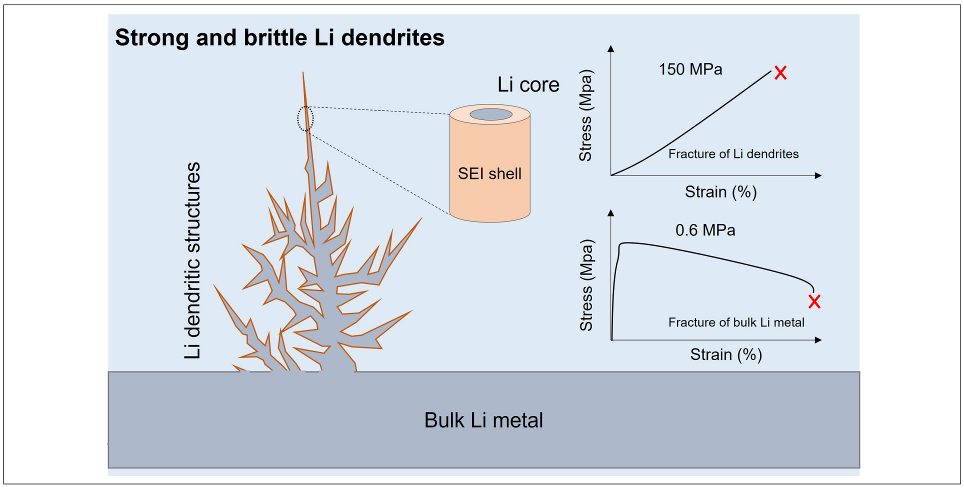
Citation: He, X.; Tan, P. Rethinking Li dendrites as strong brittle solids in Li metal batteries. *Energy Mater.* **2026**, *6*, 600061. https://dx.doi.org/10.20517/energymater.2026.81

Received: 18 Apr 2026
First Decision: 22 May 2026
Revised: 27 May 2026
Accepted: 5 Jun 2026
Published: 12 Jun 2026

Academic Editor: Yuping Wu
Copy Editor: Fangling Lan
Production Editor: Fangling Lan



The microscale is challenging to probe, inherently heterogeneous, and fundamentally important. Lithium-metal batteries are widely regarded as one of the most promising candidates for next-generation energy storage systems[1]. However, the uncontrolled growth of lithium dendrites has long remained a critical obstacle, leading to internal short circuits, electrolyte decomposition, safety hazards, and rapid capacity decay. For decades, the field has been guided by a central assumption: bulk lithium is a soft and ductile metal, and therefore rigid solid electrolytes with sufficiently high shear modulus can physically suppress dendrite penetration. Yet, extensive studies have demonstrated that even stiff inorganic solid electrolytes, such as garnet-type lithium lanthanum zirconate[2,3], fail to prevent dendrite propagation. This key contradiction has puzzled researchers worldwide. Recently, Ai *et al.* reported a study that directly quantifies the nanomechanical properties of individual lithium dendrites[4]. Their findings reveal that lithium dendrites exhibit unexpectedly high strength and pronounced brittleness at the microscale, fundamentally reshaping the mechanical understanding of dendrite behavior and resolving this long-standing paradox.

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Ai *et al.*[4] employed advanced micro-and nanoscale experimental techniques, including custom-designed air-free transfer systems, *in situ* scanning electron microscope (SEM) nanomanipulators, icro-electro-mechanical systems (MEMS)-based micro-mechanical testing chips, and Pt e-beam deposition [Figure 1A]. The e-beam in SEM enables direct observation of dendrite fracture during tensile testing. Interestingly, however, the e-beam itself can influence the measurement results [Figure 1B]. Beam irradiation may alter the physical properties of the sample, thereby affecting the measured fracture stress. Moreover, the thermal effects induced by e-beam exposure can even lead to partial recovery of fractured lithium dendrites [Figure 1C]. Therefore, this comparative result (highlighting the irradiation-induced artifacts and identifying the true modulus) serves as the primary support for central claims and conclusions. These findings highlight an important consideration: while direct characterization techniques provide intuitive observation of experimental phenomena, it is essential to carefully evaluate whether the probing method perturbs the intrinsic properties of the material[5]. This raises broader questions regarding *in situ* characterization techniques based on high-energy radiation. In contrast, certain indirect characterization approaches may better reflect realistic battery operating conditions[6]. Bulk lithium behaves as a soft and highly ductile polycrystalline metal. In contrast, body-centered cubic metals (such as Fe, Cr, and W) typically exhibit high strength and hardness. This difference originates from their intrinsic lattice resistance: for example, Fe possesses a relatively high Peierls stress[7], which imposes significant resistance to dislocation motion. In contrast, lithium, due to its weak metallic bonding, low atomic mass, large interplanar spacing, and high stacking fault energy, allows dislocations to remain compact and glide readily. However, in the study by Ai *et al.*, the fracture stress of a single lithium dendrite exceeds ~150 MPa, which is nearly 250 times higher than the yield strength of bulk lithium (~0.6 MPa) [Figure 1D and E]. More importantly, bulk lithium undergoes substantial plastic deformation and necking prior to failure [Figure 1F], whereas lithium dendrites exhibit fully brittle fracture with almost no observable plastic flow. This finding overturns the conventional perception of lithium dendrites as soft and deformable structures. Instead, they behave more like hard and sharp wedges, capable of penetrating rigid solid electrolytes by initiating and propagating cracks, thereby challenging the Monroe-Newman criterion that has guided electrolyte design for nearly two decades[8].

Through cryogenic transmission electron microscopy (cryo-TEM) and multiscale mechanical modeling, the authors uncover the structural origin of this anomalous mechanical behavior. Lithium dendrites exhibit a unique core-shell architecture, consisting of a nanoscale single-crystalline lithium core surrounded by a ~15 nm thick solid electrolyte interphase (SEI) layer. Two synergistic mechanisms give rise to their high strength and brittleness. First, the ultrasmall size of the lithium core significantly reduces the availability of dislocation sources, suppressing plastic deformation at room temperature[9]. Second, the rigid SEI shell imposes strong surface constraints, inhibiting dislocation nucleation and emission. Meanwhile, dislocation pile-up at the Li-SEI interface generates back stress, further increasing the effective yield strength. Together, these effects transform intrinsically ductile lithium into a high-strength, brittle material at the nanoscale. The authors propose the use of lithium alloy anodes, such as lithium-indium alloys, to introduce abundant dislocation sources, thereby restoring ductility and reducing brittle fracture and dead lithium formation. For solid electrolytes, they suggest shifting away from the singular pursuit of ultrahigh modulus and instead focusing on microstructural design strategies that enhance resistance to crack propagation. The differences in the mechanical behavior between bulk lithium and lithium dendrites are summarized in Table 1.

In the experiments by Ai *et al.*[4], tensile loading was applied to lithium dendrites, which effectively reflects their intrinsic mechanical properties. However, in practical battery systems, dendrite formation is more likely governed by compressive stresses and bending during electrochemical deposition. Therefore, incorporating additional loading modes, such as compression and bending, may provide a more comprehensive understanding of the mechanical behavior of lithium dendrites. Preventing dislocation in lithium dendrites requires the shell to possess sufficient strength. Therefore, this study indirectly demonstrates that the SEI

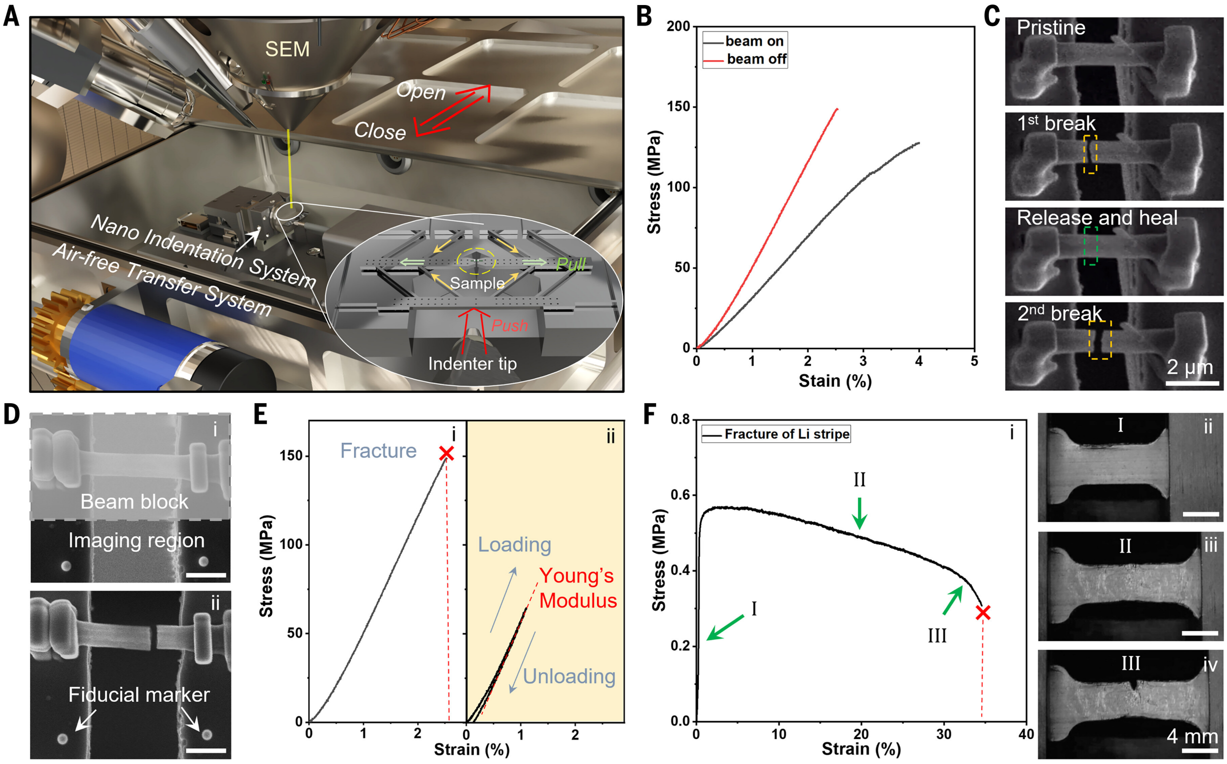

Figure 1. Mechanical properties of Li dendrites and bulk Li strips[4]. (A) Schematic illustration of a Li dendrite tensile test conducted in a scanning electron microscope (SEM). (B) Stress-strain curves of a Li dendrite with the electron beam (e-beam) turned on and off during the tensile test. (C) SEM images showing the e-beam healing effect on a Li dendrite: the first fracture was completely healed after e-beam treatment, while the second fracture occurred at a different location. (D) Typical tensile test of a Li dendrite; (i) and (ii) show the SEM snapshots of the Li dendrite before and after fracture, respectively. Scale bar: 1 μm. (E) Typical stress-strain curves of the fracture test and the loading-unloading test of Li dendrites, where Young's modulus is derived from the unloading segment. (F) Typical tensile test of a Li strip; (i) shows the typical stress-strain curve of the bulk Li strip, and (i-iv) illustrate the optical snapshots of the Li strip at different stages, as marked in (i).

Table 1. Mechanistic origins of mechanical behavior in bulk lithium *vs.* lithium dendrites

Mechanism category	Bulk lithium	Lithium dendrites
Dislocation sources	Abundant (grain boundaries, defects)	Extremely limited ("dislocation-starved")
Dislocation mobility	Enables easy plastic deformation	Strongly suppressed
Size effect	Negligible	Pronounced nanoscale strengthening
Surface/Interface	Free surface	Constrained by SEI shell
Role of SEI	Not applicable	Acts as a stiff confining layer
Dominant mechanism	Dislocation-mediated plasticity	dislocation nucleation-controlled and interface confinement-controlled
Fracture behavior	Ductile (void nucleation and growth)	Brittle (negligible plasticity)

SEI: Solid electrolyte interphase.

layer itself has relatively high stiffness and mechanical strength, enabling it to effectively act as a grain-boundary-like barrier, thereby suppressing dislocation activity. Furthermore, the work involves SEI formed in liquid electrolytes as well as passivation layers formed at solid-state electrolyte interfaces. Previous studies have shown that these two types of interphases differ significantly in structure, indicating the need for further investigation into their respective microscale mechanical properties.

In summary, this landmark study by Ai *et al.* redefines the mechanical behavior of lithium dendrites in batteries. It not only provides a fundamental resolution to a long-standing contradiction in the field but also opens up new research directions and prompts deeper reflection on the relationship between characterization methods and intrinsic material behavior.

DECLARATIONS

Author' contributions

Collected literature, organized viewpoints and wrote the original draft: He, X.
Put forward critical comments, guided the writing and polished the manuscript: Tan, P.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

Not applicable.

Financial support and sponsorship

This work was supported by National Natural Science Foundation of China (52561145238).

Conflicts of interest

Tan, P. is a Guest Editor of the Special Issue "Quasi/all-Solid-State Electrolytes for Advanced Batteries"in *Energy Materials*. He was not involved in any stage of the editorial process for this manuscript, including reviewer selection, manuscript handling, or decision-making. He, X. has declared that he has no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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