



Advances and Challenges in Lithium Metal Battery Development: Part I. Metallurgy, Mechanics, and Non-Destructive Characterization

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The global energy transition is driving demand for advanced battery technologies, with lithium metal batteries (LMBs) emerging as a promising candidate to surpass the energy density limits of lithium-ion systems. However, commercialization of LMBs faces significant challenges. This first part of a two-part perspective sheds light on key developments and challenges in the domains of metallurgical properties of lithium anodes and their effect on plating/stripping behavior, the mechanical stability of lithium and stress relief mechanisms, and non-destructive characterization techniques for real-time monitoring. By integrating perspectives from academia, industry, and national laboratories, we highlight approaches to overcome these challenges.

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Manuscript submitted June 28, 2026; revised manuscript received September 13, 2026. Published October 12, 2026.

The energy transition or electrification of the world is driving up demand for battery electric storage. Lithium-ion (Li-ion) batteries have enabled widespread electrification due to their superior energy density (Wh l⁻¹), specific energy (Wh kg⁻¹), and declining cost (\$/kWh) compared to previous generations of batteries. Increasing market size and increasingly challenging performance requirements have brought the lithium metal anode back into the discussion, and several companies are working on its commercialization. Some benefits expected from the technology include improved specific energy and energy density, which can enhance electric vehicles, aircraft, and other high-performance equipment. However, industry is also interested in developing batteries that are less expensive and less dependent on battery material supply chains. So-called anode-less batteries or other technologies that eliminate the use of large amounts of anode-active materials, such as graphite, promise a pathway to lower cost. However, these batteries are also a type of Li metal battery, based on their working principle.¹ LMBs, by design, form metallic lithium from Li-ions during the charging process. The list of mechanical, chemical, and electrochemical issues that the battery cell system must be able to manage is extensive. This is also true for solid-state technology, as well as for hybrid or liquid electrolyte-based batteries. Additionally, Li metal is highly reactive, which adds to the list of challenges. Due to technical difficulties and additional challenges associated with scaling up manufacturing, LMBs are primarily used in applications with low production volumes today and are more expensive than Li-ion batteries. To address some of the fundamental challenges and to formulate the questions that must be answered to facilitate the broader adoption of Li metal batteries in commercial applications, the Lithium Metal Battery Workshop was established as an annual meeting in 2020. Numerous challenges associated with LMBs remain hidden from the community and need to be highlighted, as ignoring them could lead to economic and safety repercussions. To address the issue, we should gather critical questions, identify experts capable of solving them, foster productive collaborations between industry and academia, and

publish the findings. The 2024 workshop brought together participants from OEMs, cell manufacturers, universities, and U.S. national laboratories to discuss lithium morphology, diagnostics, metrology, non-destructive testing, insights from cell manufacturing companies, and perspectives on LMB cycling protocols, all in pursuit of that objective.

Current Status

From a metallurgy perspective, today, the impact of an anode's crystalline nature, texture, grain size, and purity on the evolution of Li plating/stripping in the formation and early cycling stages remains unexplored. Li metal used as the anode is manufactured through a variety of methods, including vapor deposition, extrusion, and cold rolling, or in slurry particulate forms.² The produced Li gets surface-treated to prevent its degradation during storage and shipping, wherein these methods can vary between manufacturers. Differences in the properties of the produced Li metal make it challenging to decouple the effects of substrate and electrolyte properties. To address the impact of Li metal substrate on Li plating/stripping morphological evolutions, knowledge gaps were identified in the workshop.

Collectively, the workshop discussions and subsequent literature highlight five connected gaps: (1) how Li production and processing govern purity, grain size, crystallographic texture, defect structure, surface topography, and passivation; (2) which Li attributes and processing histories must be reported to enable meaningful comparisons among studies; (3) how length scale, strain rate or current density, temperature, microstructure, constraint, and stack pressure govern the competition among stress generation, diffusion, creep, and dislocation-mediated plasticity; (4) when stress is relieved through Li deformation rather than interfacial separation or solid-electrolyte fracture; and (5) how non-destructive, *operando* measurements can connect evolving Li morphology, chemistry, stress, and inactive-Li formation to cell performance. Recent studies further emphasize the coupled effects of processing and chemical transformation across these gaps.

Mechanics is especially important at Li/solid-state electrolyte (SSE) interfaces, where spatially nonuniform Li⁺ transfer can force newly deposited Li into small, constrained volumes.^{3–8} If free expansion and dislocation-mediated plasticity are insufficient, continued

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plating produces nonuniform compressive elastic strain, locally decreases the Li lattice parameter, and establishes chemical-potential gradients that drive stress-directed diffusion.^{3,6,8} Bulk polycrystalline Li yields at stresses of order 1 MPa, depending on rate and temperature, whereas source-limited micron- and submicron-scale volumes can sustain local mean pressures on the order of 100 MPa.^{3,4,7,8} These constrained, multiaxial pressures are not equivalent to bulk uniaxial yield stress or ideal lattice shear strength and vary with stressed-volume size, strain rate/current density, temperature, crystallography, defect structure, and confinement. Stress may ultimately be accommodated by Li deformation, interfacial separation, or SSE fracture.⁶ In LLZO, an electrochemical reaction zone adjacent to a Li filament produces a constrained, contractive chemical eigenstrain that augments the crack-tip driving force and thereby reduces the Li pressure required for crack propagation.⁹

To gain insight into Li metal batteries, it is imperative to examine the morphology, microstructure, and chemistry of the lithium metal anode. Nevertheless, characterizing lithium metal presents significant challenges due to its inherent chemical reactivity, poor thermal stability, and low atomic number. These properties make lithium prone to contamination and melting while also displaying weak scattering capabilities for both electrons and X-rays.¹⁰

Cryogenic electron microscopy has played a crucial role in enabling atomic-scale characterization of lithium metal, significantly mitigating electron beam-induced damage.^{10,11} For example, cryo-transmission electron microscopy (cryo-TEM) can provide a detailed observation of lithium's structure and the distribution of unstable solid electrolyte interphase (SEI) components.¹² Furthermore, titration techniques, in which cycled anodes are digested by a reagent can be used to quantitatively resolve fundamental questions on the consumption of lithium. Fang et al., by leveraging lithium's reactivity with water, proved that the amount of dead lithium metal can be quantitatively and precisely measured using titration gas chromatography.¹³ Employing a similar approach, Hobold et al. were able to isolate various components of the SEI by taking advantage of their reactivity with acids.¹⁴ Those microscopic and analytical methods are now widely employed to elucidate the influence of morphology, electrolytes, and additives on the failure mechanisms of lithium metal electrodes.^{15–17}

However, a common limitation of these techniques is their destructive nature; they require disassembly of the cell both before and after the electrode reaction, preventing real-time insight into dynamic processes occurring within the system during operation.

Future Needs and Prospects

Metallurgy.—During the workshop, several questions were identified that require scientific investigation. These include:

- The significance of surface roughness and grain size
- Whether there are “bad” or “good” Li metal impurities
- Can an effective Solid Electrolyte Interphase (SEI) be formed in the presence of a Li metal passivation layer, whether this passivation layer interferes with Li metal nucleation, its impact, and if new Li passivation methods need to be developed?

To address these questions, careful, systematic studies aided by appropriate analytical tools are recommended to isolate each of these factors to some extent. Li metal handling, storage and cell integration preceding cell cycling can impact these factors and should be reproducibly captured and accounted for. For example, the vapor deposition method could produce Li substrates with comparable purity, texture, and grain size and thus may be an appropriate platforms for systematic studies that probe the impact of grain boundaries or surface roughness. One obvious challenge associated even with these carefully produced Li foils is caused by the highly reactive nature of Li metal, which immediately reacts upon contact with minimal amounts of gas impurities present in the tightly controlled

inert environments of research gloveboxes such as water and nitrogen. So, although the Li bulk produced through this method can be with high purity, its surface may not and therefore should be characterized and studied under reproducible conditions. Furthermore, the propensity of Li metal to creep under applied pressure can impact its morphological characteristics compared to those present in the originally deposited Li substrate. Accordingly, although it may not be feasible to isolate each contributing factor independently, a comprehensive understanding requires the identification and consideration of all contributing variables when a single factor is perturbed.

On the other hand, Li-metal-free anodes are ultimately desired to eliminate the use of excess Li metal, thus maximizing the specific and volumetric energy densities of the battery. In these cases, the cathode serves as the sole Li reservoir, where Li is electrodeposited on the current collector during battery charging. The metallic substrates used as anodes are typically polycrystalline with varying degrees of quality and purity depending on the metallurgical production processes. Although the morphological evolution of Li metal function of the anode properties, such as crystallographic nature, grain boundaries, and impurities, is not well known, the existing body of research does motivate systematic studies to capture and decouple these effects. For example, the crystallographic orientation of Cu is being shown to impact Li metal plating/stripping coulombic efficiencies, overpotentials, and SEI formation linked to differences in the surface energy of exposed planes, Li diffusion barriers, and facets lithiophilicity.^{18–20} In a similar manner, the presence of native oxides and other metallic species could induce discernible effects on the homogeneity and morphological evolution of Li caused by the lithiophobicity of the oxides or Li nucleation barriers.^{21,22} The distribution of these impurities can vary throughout the current collector, i.e. bulk vs grain boundaries, which could further complicate understanding their significance. To ultimately determine the impact of these factors on Li metal plating and stripping, systematic studies that capture their interrelation, aided by analytical tools, would be necessary.

Li mechanics.—Mechanically stable Li/SSE interfaces require stress accommodation to keep pace with stress generation before interfacial separation or electrolyte fracture occurs. This competition is governed by the size and geometry of the stressed volume; Li crystallography, defect and grain structure, thickness, alloying, and surface layers; temperature and current density; stack pressure and friction; and electrolyte and cell compliance.^{6,8,23} These variables should be reported and, where possible, one primary factor varied while important covariates are characterized.

Figure 1 provides one local mechanical illustration. For instrumented indentation, $S^2/P = (4\beta^2/\pi)(E_r^2/H)$, where S is elastic contact stiffness, P is load, E_r is reduced modulus, H is hardness, and β is the indenter-geometry factor. Because contact area cancels, S^2/P avoids explicit area-function and contact-depth determination and therefore avoids the additional area-estimation errors that pile up, surface roughness, and thermal drift introduce into separately calculated E_r and H . For specimens with similar E_r , a larger S^2/P corresponds to a lower hardness (mean contact pressure). Nevertheless, S^2/P is a depth-, rate-, microstructure-, defect-, and history-dependent contact metric, not an intrinsic material property or a unique mechanistic identifier. Figure 1 extends from approximately 50–800 nm; within the strongly differentiated 50–400 nm regime, corresponding to submicrometer-to-micrometer deformation volumes, S^2/P varies by approximately sixfold among the specimen conditions. As a point of reference, a representative value of S^2/P for pure, bulk polycrystalline Li metal is $\geq 71\,000\text{ GPa}$ ($E = 8\text{ GPa}$, $H = 3\sigma_y = 1.5\text{ MPa}$, and $\nu_s = 0.362$).

The nonmonotonic ensemble curves indicate distributed, stochastic changes in the available stress-relief mechanisms rather than unique critical depths. The Li–Ag minima are consistent with a crossover from diffusion-dominated to dislocation-mediated accommodation, whereas the melt-spun response suggests that dislocation

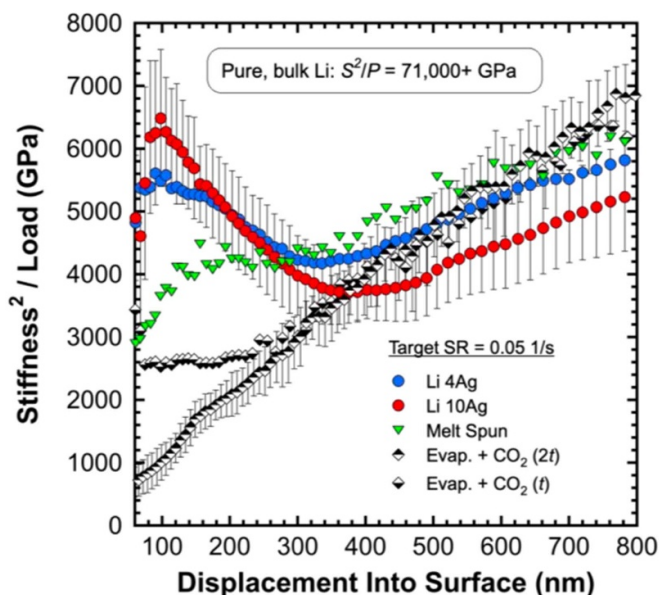


Figure 1. Depth-dependent S^2/P for five Li-based specimen conditions at a target indentation strain rate of 0.05 1/s. Symbols are means of at least 25 tests for each condition; error bars show ± 1 standard deviation for selected conditions. Nonmonotonic features in these average curves represent distributed crossovers rather than unique transition depths.

sources may become accessible at or below the earliest reliably measured depths. In prior individual indentations of high-purity Li, abrupt transitions occurred at local mean pressures of approximately 44–104 MPa, with lower transition pressures measured within approximately 1–3 μm of a grain boundary than within grain interiors. This supports a local source-access effect, not a general grain-size relationship. Likewise, the CO_2 -exposed response is consistent with the coupled behavior of hard-film/soft-substrate deformation.⁷ Beyond altering the stresses transmitted into Li and hence dislocation-source activation, the data do not support any conclusions about the possibility of dislocation blocking. Future studies should pair local mechanical measurements with microstructural, surface-chemical, and electrochemical characterization to determine whether stress is relieved by diffusion, dislocation-mediated flow, interfacial separation, or SSE fracture.

Non-destructive characterization of Li metal batteries.—In the context of commercial battery manufacturing and cycling, non-destructively characterizing the lithium metal anode throughout its lifecycle will be crucial for several reasons:

- To manage impurities and contamination during the qualification process
- To monitor and control lithium morphology during cycling
- To prevent thermal runaway and mitigate safety hazards²⁴

Additionally, the excess of lithium at the anodes in LMBs makes it difficult to properly evaluate the true lithium metal cycling behavior of a system as it can mask low CE and other shortcomings on the electrochemical curves.^{25,26} Therefore, it is necessary to employ advanced non-destructive techniques that can perform measurements on fully assembled batteries, either in “relaxed” states for *in situ* measurements or continuously in the case of *operando* characterization.

CT imaging—To track the morphological evolution of lithium in LMBs, computed tomography stands out as a powerful technique. Utilizing X-ray imaging, both *in situ* and *operando*, three-dimensional characterization of the formation of surface pits and the growth of mossy lithium deposits could be realized.^{27,28} However,

within the context of battery manufacturing, the significant costs, lengthy experimentation times, and complex data analysis required for synchrotron and neutron sources are often prohibitive. Moreover, while most computed tomography techniques are implemented using custom-made cell designs, replicating the operating environments pertinent to commercial cells frequently presents significant challenges.

Dilatometry—simpler methods have been developed to detect the presence of plated lithium through physical changes in the cell during cycling.²⁹ These techniques generally involve attaching a sensor either to the surface of the cell or within the cell itself. Notably, Louli et al. utilized a simple load cell apparatus for *operando* pressure measurement. Their observations highlighted both the reversible expansion of the cell stack associated with lithium plating and stripping, as well as the irreversible expansion resulting from parasitic processes like SEI growth and the accumulation of inactive lithium metal.³⁰

Calorimetry—isothermal heat flow microcalorimetry can provide highly sensitive *in situ* detection of lithium plating in both half and full cells, by identifying a distinct thermal heat flow signature at the onset of lithium plating on graphite electrodes.³¹

Optical sensor—notably, traditional microcalorimetry is generally limited to low rates and small cell formats. However, the recent advance of optical calorimetry, showed that heat flow could be measured in various cell designs.^{32,33} Interestingly, similar optical sensors have been employed to measure the chemo-mechanical stress occurring within the electrodes.³⁴ Moreover, Hedman et al. demonstrated that lithium plating detection is feasible through the measurement of light modulation by a fiber optic sensor placed on the surface of a graphite electrode.³⁵ Optical fibers could therefore offer new opportunities for *operando* characterization of LMBs through thermal, mechanical, and chemical measurements.^{32,33} Nevertheless, it is crucial to acknowledge that optical sensors only offer localized measurements of phenomena, which must be correlated with broader analyses to achieve a comprehensive understanding.

Acoustic monitoring—in this context, acoustic monitoring offers a promising approach for non-destructive characterization of LMBs. This technique is versatile, cost-effective, and capable of evaluating crucial battery properties such as wetting, SEI formation, and dead lithium, all without impairing the battery’s structural integrity.³⁶ Bommier et al. have shown that acoustic measurements can reliably detect Li metal plating within commercial lithium-ion pouch cells during operation. Using this method, they established a correlation between Li metal plating, current rate, and operational temperature, offering valuable insights into the dynamics of plating.³⁷ While this study utilized acoustic techniques for local diagnostics, Deng et al. employed an ultrasonic battery scanner to achieve 2D mapping of a commercial battery, enabling the visualization of electrolyte wetting, drying, and gas formation during cycling.³⁸

Interestingly, despite the existence of various non-destructive characterization techniques, there is a notable scarcity of *in situ* and *operando* data concerning LMBs thermal runaway and end-of-life. While thermal runaway events are inherently rare and unpredictable, we believe it is crucial to study these occurrences to ensure the safe usage of LMBs. It should be noted also that neither of the non-destructive techniques discussed enable direct insights into the chemistry of the cell, all of them merely observe physical parameters such as heat, volume, or density. This highlights the need for continued innovation in non-destructive characterization methods and workflows to address the challenges during LMB development.

Conclusions

The development of LMBs represents a transformative opportunity to meet the growing demands for high-energy-density storage. The 2024 Lithium Metal Battery Workshop brought together researchers from universities, national labs, and companies to

collectively identify key challenges and opportunities in LMB development. This perspective reflects the collaborative effort to connect academic research with the practical needs of industry and OEMs. Status and future needs with a focus on metallurgy, mechanics, and non-destructive characterization were outlined. Advancing LMBs requires more than new materials, it demands a system-level understanding of how lithium behaves during cycling, how mechanical stress develops at interfaces, and how safety risks evolve over time. Key takeaways from the workshop emphasize the critical role of lithium's metallurgical and mechanical properties in governing plating behavior and interface stability. Discussions also highlighted the need to improve lithium metal quality and handling, and to apply real-time, non-destructive diagnostics for monitoring degradation and failure modes throughout the battery's life cycle. Continued cross-sector dialogue will be essential for guiding research priorities, reducing scale-up risks, and enabling the safe and practical deployment of LMBs in electric vehicles and beyond.

Acknowledgments

Both parts of this two-part commentary are drawn from conversations at the lithium metal battery workshop (February 2024), which was jointly organized by University of California San Diego (UCSD) and Mercedes-Benz Research & Development North America (MBRDNA). MBRDNA was also the main sponsor for the workshop, with additional support from the Battery500 Consortium, which is funded by the US Department of Energy Office of Vehicle Technologies. R.M. acknowledges the support from Toyota Motor Engineering and Manufacturing North America to participate in the workshop. Oak Ridge National Laboratory acknowledges sponsorship by the US DOE, Vehicle Technologies Office's Advanced Battery Materials Research Program. The authors also acknowledge the following organizations that participated in the workshop: Columbia University, Oak Ridge National Laboratory, Penn State University, University of Houston, University of Texas at Austin, Drexel University, University of Chicago, Albemarle Corp, Applied Materials, Cuberg, Factorial Energy, LG Energy Solutions, Livent, Lyten, Our Next Energy, PolyPlus, Pure Lithium Corp, QuantumScape, SES AI Corp, Sion Power, Temasek, ULVAC Technologies Inc., Sepion, Hydro-Québec, Arcadium Lithium, Cummins, and Wildcat Discovery.

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References

1. K. B. Hatzell, *ACS Energy Lett.*, **8**, 4775 (2023).
2. K. Hatzell, W. Chang, W. Bao, M. Cai, T. Glossmann, S. Kalnaus, B. Liaw, Y. S. Meng, R. Mohtadi and Y. Wang, *Joule* (2024).

3. L. Zhang et al., *Nat. Nanotechnol.*, **15**, 94 (2020).
4. C. Xu, Z. Ahmad, A. Aryanfar, V. Viswanathan and J. R. Greer, *Proc. Natl Acad. Sci. U.S.A.*, **114**, 57 (2017).
5. W. S. LePage, Y. Chen, E. Kazyak, K.-H. Chen, A. J. Sanchez, A. Poli, E. M. Arruda, M. D. Thouless and N. P. Dasgupta, *J. Electrochem. Soc.*, **166**, A89 (2019).
6. M. Klimpel, H. Zhang, G. Paggiaro, R. Dubey, F. Okur, L. P. H. Jeurgens, K. V. Kravchik and M. V. Kovalenko, *Adv. Mater. Interfaces*, **11**, 2300948 (2024).
7. R. Saha and W. D. Nix, *Acta Mater.*, **50**, 23 (2002).
8. Z. Ning et al., *Nature*, **618**, 287 (2023).
9. C. D. Fincher, C. Gilgenbach, C. Roach, R. Osmundsen, A. Penn, M. D. Thouless, W. C. Carter, B. W. Sheldon, J. M. LeBeau and Y.-M. Chiang, *Nature*, **652**, 906 (2026).
10. D. Lin, Y. Liu and Y. Cui, *Nat. Nanotechnol.*, **12**, 194–206 (2017).
11. J. Z. Lee, T. A. Wynn, M. A. Schroeder, J. Alvarado, X. Wang, K. Xu and Y. S. Meng, *ACS Energy Lett.*, **4**, 489 (2019).
12. X. Wang, M. Zhang, J. Alvarado, S. Wang, M. Sina, B. Lu, J. Bouwer, W. Xu, J. Xiao and J.-G. Zhang, *Nano Lett.*, **17**, 7606 (2017).
13. C. Fang, J. Li, M. Zhang, Y. Zhang, F. Yang, J. Z. Lee, M.-H. Lee, J. Alvarado, M. A. Schroeder and Y. Yang, *Nature*, **572**, 511 (2019).
14. G. M. Hobold and B. M. Gallant, *ACS Energy Lett.*, **7**, 3458 (2022).
15. G. M. Hobold, C. Wang, K. Steinberg, Y. Li and B. M. Gallant, *Nat. Energy*, **9**, 580 (2024).
16. C. Gervillie-Mouravieff, L. Ah, A. Liu, C.-J. Huang and Y. S. Meng, *ACS Energy Lett.*, **9**, 1693 (2024).
17. B. Lu, W. Bao, W. Yao, J.-M. Doux, C. Fang and Y. S. Meng, *J. Electrochem. Soc.*, **169**, 070537 (2022).
18. Y.-J. Kim, S. H. Kwon, H. Noh, S. Yuk, H. Lee, H. Soo Jin, J. Lee, J.-G. Zhang, S. G. Lee and H. Guim, *Energy Storage Mater.*, **19**, 154 (2019).
19. Y. Gu, H. Y. Xu, X. G. Zhang, W. W. Wang, J. W. He, S. Tang, J. W. Yan, D. Y. Wu, M. S. Zheng and Q. F. Dong, *Angew. Chem., Int. Ed.*, **58**, 3092 (2019).
20. K. Ishikawa, S. Harada, M. Tagawa and T. Ujihara, *ACS Appl. Mater. Interfaces*, **12**, 9341 (2020).
21. S. T. Oyakhire et al., *Nat. Commun.*, **13**, 3986 (2022).
22. J. S. Yoon, D. W. Liao, S. M. Greene, T. H. Cho, N. P. Dasgupta and D. J. Siegel, *ACS Appl. Mater. Interfaces*, **16**, 18790 (2024).
23. W.-Y. Tsai et al., *ACS Appl. Mater. Interfaces*, **18**, 16338 (2026).
24. D. Ren, H. Hsu, R. Li, X. Feng, D. Guo, X. Han, L. Lu, X. He, S. Gao and J. Hou, *ETransportation*, **2**, 100034 (2019).
25. P. Albertus, S. Babinec, S. Litzelman and A. Newman, *Nat. Energy*, **3**, 16 (2018).
26. M. Genovese, A. Louli, R. Weber, S. Hames and J. Dahn, *J. Electrochem. Soc.*, **165**, A3321 (2018).
27. O. O. Taiwo, D. P. Finegan, J. Paz-garcia, D. S. Eastwood, A. Bodey, C. Rau, S. Hall, D. J. Brett, P. D. Lee and P. R. Shearing, *Phys. Chem. Chem. Phys.*, **19**, 22111 (2017).
28. H. Pan, T. Fu, G. Zan, R. Chen, C. Yao, Q. Li, P. Pianetta, K. Zhang, Y. Liu and X. Yu, *Nano Lett.*, **21**, 5254 (2021).
29. B. Bitzer and A. Gruhle, *J. Power Sources*, **262**, 297 (2014).
30. A. J. Louli, M. Genovese, R. Weber, S. G. Hames, E. R. Logan and J. R. Dahn, *J. Electrochem. Soc.*, **166**, A1291 (2019).
31. L. Downie, L. Krause, J. Burns, L. Jensen, V. Chevrier and J. Dahn, *J. Electrochem. Soc.*, **160**, A588 (2013).
32. J. Huang, L. A. Blanquer, J. Bonefacino, E. R. Logan, D. A. D. Corte, C. Delacourt, B. M. Gallant, S. T. Boles, J. Dahn and H.-Y. Tam, *Nat. Energy*, **5**, 674 (2020).
33. C. Gervillie-Mouravieff, L. A. Blanquer, C. Alphen, J. Huang and J.-M. Tarascon, *J. Power Sources*, **580**, 233268 (2023).
34. L. A. Blanquer, F. Marchini, J. R. Seitz, N. Daher, F. Bétermier, J. Huang, C. Gervillie and J.-M. Tarascon, *Nat. Commun.*, **13**, 1153 (2022).
35. J. Hedman, R. Mogensen, R. Younesi and F. Björefors, *Adv. Mater. Interfaces*, **10**, 2201665 (2023).
36. C. Gervillie-mouravieff, W. Bao, D. A. Steingart and Y. S. Meng, *Nat. Rev. Electr. Eng.*, **1**, 547 (2024).
37. C. Bommier, W. Chang, J. Li, S. Biswas, G. Davies, J. Nanda and D. Steingart, *J. Electrochem. Soc.*, **167**, 020517 (2020).
38. Z. Deng, Z. Huang, Y. Shen, Y. Huang, H. Ding, A. Luscombe, M. Johnson, J. E. Harlow, R. Gauthier and J. R. Dahn, *Joule*, **4**, 2017 (2020).