Laser Ablation of Electrodes for High-Throughput Manufacturing and Analytics of 3D Electrodes for Advanced 3D Battery Concept

Wilhelm Pfleging[1], Yannic Sterzl[1], Niclas Straßburger[1], Carolyn Reinhold[1], Penghui Zhu[1], Jhanis Gonzalez[2], Jong Yoo[2], Rick Russo[2].

[1] Karlsruhe Institute of Technology, IAM-AWP, Kaiserstraße 12, 76131 Karlsruhe, Germany
[2] Applied Spectra, Inc., 950 Riverside Pkwy Suite 90, West Sacramento, CA 95605, USA

* Correspondence: wilhelm.pfleging@kit.edu

Abstract

Laser material processing is becoming an increasingly vital component of the value chain in battery manufacturing and development. We differentiate between passive processes, which replace existing technologies without substantially affecting battery properties, and active processes, which specifically modify the architecture of electrodes and batteries, thereby altering and ideally significantly enhancing their electrochemical properties. Passive processes encompass laser cutting, slitting, notching for electrode processing, and busbar laser welding in module manufacturing, mainly utilized to optimize production economics [1]. Active laser processes involve directly structuring electrodes to enhance the active surface area or modifying current collectors, which serve as additional steps to improve diffusion kinetics or electrode layer adhesion [2]. A common characteristic of all laser processes is that their speeds must be substantially increased for successful integration into manufacturing to achieve throughput that aligns with battery production. We have made significant progress with the innovative approach of 3D electrode structuring and implemented roll-to-roll structuring for on-the-fly high-power laser ablation. This enables the prototype production of lithium-ion batteries (LIBs) with 3D electrodes, cylindrical cells, and pouch cells, preparing them for industrial modules [3]. This significant development step makes it possible, for the first time, to transfer the 3D battery concept from the laboratory to industrial production. Simultaneously, designs of laser-structured electrodes were optimized to significantly enhance battery properties concerning lifetime, high-rate capability, energy and power density, and cell safety by suppressing Li plating during fast charging [4].

A variety of electrochemical analysis techniques were employed to assess the electrochemical properties. These were complemented by laser-induced breakdown spectroscopy (LIBS) [5]. LIBS is a relatively new metrology approach for understanding and improving the chemistry of electrodes and electrolytes in LIBs [6,7]. LIBS for LIBs is a compelling value proposition. This all-optical technology (utilizing light for excitation and measuring spectra) measures the complete electrode chemistry (active material, binder, additives) and determines the quality (homogeneity/heterogeneity, purity) of the electrodes, thus implicitly indicating the reliability and accuracy of the various, and sometimes quite complex, production steps in electrode manufacturing. During LIBS, laser ablation of a small portion of the electrode material converts it into a transient high-temperature vapor plasma. The generated plasma spectroscopically encodes the battery chemistry. LIBS is performed at atmospheric pressure and provides micron spatial resolution, enabling 2D/3D elemental mapping; Figure 1 shows an example of 3D lithium distribution from one pristine and one degraded graphite anode. LIBS for LIBs allows standoff chemical analysis for laboratory or advanced manufacturing, enabling real-time monitoring of the battery chemistry (in-line metrology). A high-throughput technical approach is presented that is capable of elemental mapping of large footprint electrodes at high processing speeds. A suitable selection of laser beam wavelengths enables the investigation of binder distribution (after coating) and degradation processes (post-mortem), both

essential characteristics for electrode development through coating and subsequent laser structuring (3D battery concept). Preliminary studies of inline LIBS demonstrate its significant potential for controlling binder migration during coating and as a function of drying conditions.

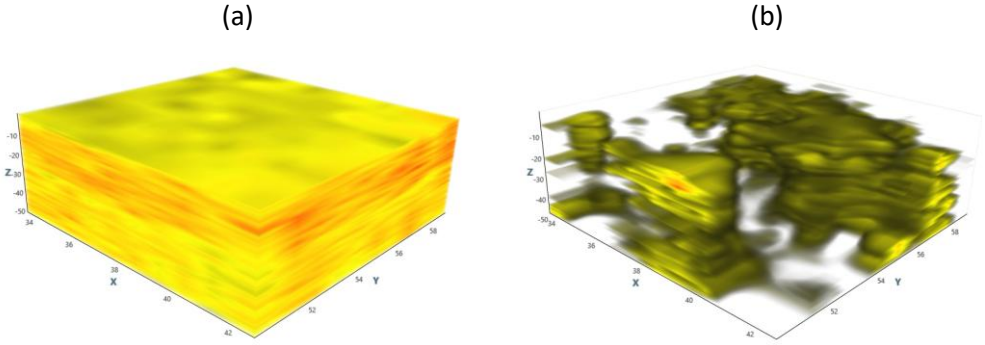

Figure 1: 3D elemental (Li) distribution in lithiated graphite anodes at different state of health (SOH), achieved from Laser-Induced Breakdown Spectroscopy ((a): SOH 100%, (b): SOH 0%, sample area: 9 mm²)

References

[1] W. Pfleging, A review of laser electrode processing for development and manufacturing of lithium-ion batteries, Nanophotonics 7(3) (2018) 549
[2] W. Pfleging, Recent progress in laser texturing of battery materials: a review of tuning electrochemical performances, related material development, and prospects for large-scale manufacturing, Int. J. Extrem. Manuf. 3 (2021) 012002
[3] A. Meyer, P. Zhu, A. Smith, W. Pfleging, Gaining a New Technological Readiness Level for Laser-Structured Electrodes in High-Capacity Lithium-Ion Pouch Cells, Batteries 9(11) (2023) 548
[4] Y. Sterzl, W. Pfleging, Optimizing Structural Patterns for 3D Electrodes in Lithium-Ion Batteries for Enhanced Fast-Charging Capability and Reduced Lithium Plating, Batteries 10(5) (2024) 160
[5] R. E. Russo, Laser ablation research and development: 60 years strong, Applied Physics A 129 (2023) 168
[6] Y. Zheng, D. Yin, H.J. Seifert, W. Pfleging, Investigation of Fast-Charging and Degradation Processes in 3D Silicon–Graphite Anodes, Nanomaterials 12(1) (2022) 14
[7] H. Hou, L. Cheng, T. Richardson, G. Chen, M. Doeff, R. Zheng, R. Russo, V. Zorba, Three-dimensional elemental imaging of Li-ion solid-state electrolytes using fs-laser induced breakdown spectroscopy (LIBS), J. Anal. At. Spectrom. 30 (2015) 2295

Keywords: laser ablation, anode, cathode, 3D battery, lithium-ion battery; laser-induced breakdown spectroscopy; electrode engineering, electrode manufacturing