Perspective of laser technology empowering lithium-ion batteries

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In current battery production, laser systems for bus-bar welding and electrode cutting have already achieved a high level of technical readiness (TRL). Laser cutting can be used to replace conventional mechanical punching of electrodes and is also used to slit wide coating sheets at processing speeds in excess of 100 m/min or to separate the current collector from the coated sheet by exposing the current collector tap contact (notching). It is worth noting that these established laser processes are not expected to have a significant impact on the electrochemical performance of batteries. On the other hand, laser structuring or modification of composite electrode materials is quite sophisticated because it is expected to directly affect the electrochemical properties and improve battery performance beyond the current technology. In particular, line patterns with spacings of several hundred micrometres have been shown to make the electrodes super-wicking for the liquid electrolyte. This accelerates the electrolyte filling process in battery production and avoids inhomogeneous wetting with dry electrode areas, which can lead to electrochemical degradation and cell failure. The novel 3D electrode architectures activate new diffusion pathways in the liquid electrolyte at high charge and discharge rates. The tortuosity of the electrode is reduced, the diffusion kinetics of lithium ions are significantly increased and overpotentials can be reduced [1].

Several research groups around the world, including Germany, the USA, Japan, and Korea, have recently started working on this relatively new research topic and manufacturing approach. So far, this technology has been at the experimental stage of proof of concept or validation under laboratory conditions. However, this type of laser process has great potential for future battery development. It can play a significant role in overcoming the technical challenges of state-of-the-art batteries by merging the concepts of three-dimensional electrodes (high power) and thick-film electrodes (high energy). The impact of high mass loaded electrodes on the electrochemical performance of lithium-ion batteries is significant. Thick film electrodes in high energy batteries can now be rapidly charged and operated at high power thanks to laser-generated 3D architectures. Laser structuring has been successfully developed for thick film composite electrodes based on advanced active materials and environmentally friendly water-based cathodes and anodes. Different structure types have been investigated for their positive impact on electrochemical performance in terms of high-rate capability, fast charging capability, lithium plating, cell degradation, safety, and cell lifetime [2]. Compared to cells with 2D electrodes, cells with 3D electrodes have always been found to be superior: cells with structured thick-film electrodes show excellent capacity retention for high-power operation, lithium plating can be suppressed during battery operation at high currents and low temperatures, and a doubling of battery life is possible.

At the Karlsruhe Institute of Technology (KIT), the complete manufacturing route and electrochemical and post-mortem analysis for lithium-ion batteries is being established, from slurry preparation and electrode coating to cell assembly of pouch cells with capacities of up to 20 Ah. This provides a unified approach to optimising the implementation of laser-based processes in battery manufacturing. Recently, machine concepts for upscaling ultrafast laser structuring of cathodes and anodes have been developed to advance this technology towards TRL6 and beyond [3]. To this end, roll-to-roll electrode laser processing machines have recently been implemented using ultrafast lasers with an average power of >300 W operating in the MHz range, enabling a significant step towards damage-free structuring of electrodes with a large footprint. In this exciting new research area, several basic research and industry-led European and national projects have been initiated to advance 3D battery technology to significantly higher cell capacities, cylindrical cell designs, and module level.

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[2] P. Zhu, B. Ebert, P. Smyrek, W. Pfleging, The Impact of Structural Pattern Types on the Electrochemical Performance of Ultra-Thick NMC 622 Electrodes for Lithium-Ion Batteries, Batteries 10(2) (2024) 58.

[3] A. Meyer, Y. Sterzl, U. Rädel, S. Xiao, M. Zenz, D. Schwab, W. Pfleging, Gaining a New Technological Readiness Level for Laser-Structured Electrodes in High-Capacity Lithium-Ion Pouch Cells, Batteries 9(11) (2023) 548.